JPL PUBLICATION 77-40

Compendium of Critiques of JPL Report SP 43-17

Automotive Technology Status and Projections Project

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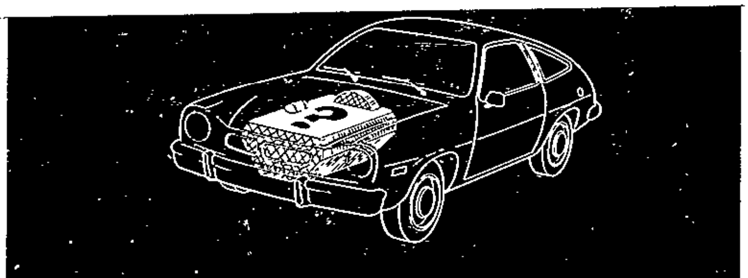

Should We Have a New Engine ?

An Automobile Power Systems Evaluation

prepared for
Energy Research and Development Administration

by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

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16. Abstract

Almost 50 critiques of the Jet Propulsion Laboratory report SP-43-17, "Should We Have A New Engine?" were received and are published in this document together with the JPL responses. These critiques and responses should serve as a catalyst for discussions of automotive issues vital to the national interest.

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EXHIBIT A

ENCLOSURE TO JPL LETTERS IN RESPONSE TO CRITIQUES OF AUTOMOTIVE POWER SYSTEMS EVALUATION STUDY (APSES)

As Reported in SP 43-17 "Should We Have a New Engine?"

Introduction

The automotive study activities at JPL have entered a new phase. Upon completion of the APSES study, the analysis team was partially disbanded during the period August 1975 to September 1976 and another team was formed to conduct the follow-on study work under the sponsorship of the Energy Research and Development Administration (ERDA). Included among the follow-on tasks is the formal response to each of the critiques of the 1975 APSES study. ERDA has requested early attention to the critiques response task.

The purpose of this enclosure is to summarize information on: (1) the time lag between receipt of the critiques and the response letters, (2) the productive utilization of the critiques in more detailed assessments, and (3) the content of the current automotive technology study effort.

Background

In August 1975, the JPL Report SP 43-17, "Should We Have a New Engine?", was published. The purpose of the document, sometimes called the APSES Report (Automotive Power Systems Evaluation Study), was to assess automotive improvements that could be expected in the next decade. In addition to widespread distribution of the report, a series of oral presentations was conducted by members of the APSES study team. Critiques of the report from interested individuals of organizations were solicited. At that time, however, there was neither funding nor mechanism for responding to the many and extensive comments received The critiques were simply compiled and given limited distribution.

Current Program

In May of 1976, JPL was selected by the ERDA Division of Transportation Energy Conservation to conduct a follow-on automotive assessment effort. The approval for this project, called Automotive Technology Status and Projections (ATSP), was received in September 1976. The principal activities and outputs of the ATSP effort are:

- A continuing assessment of highway transportation technology and of the potential advantages of new propulsion concepts.
- Fact finding visits to assess the state-of-the-art in selected areas of automotive technology.
- An annual report which surveys and assesses progress toward meeting ERDA goals and objectives for highway transportation vehicles.
- A longer term product consisting of a source book on automotive technology. Assessments of alternative power plants and major vehicle subsystems will form the basis of the source book. The individual assessments, called Technical Task Summaries (TTS), will be published separately as they are completed.
- In the near term, and as an integral part of the ATSP effort, responses have been prepared to the APSES critiques. This was done using the existing data base. Further analysis resulting from the critiques will be done downstream as part of the on-going studies discussed below.

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Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

ACKNOWLEDGEMENT

Almost 50 critiques of JPL Report SP 43-17, "Should We Have a New Engine" have been received and are published herein. JPL/Caltech is grateful for the interest of the many organizations and individuals, as manifest in the thoughtful and substantive critiques and for their patience in awaiting our response. We trust that this compendium of critiques and responses will be of benefit to all interested parties, and serve as a catalyst for discussion of automotive issues so vital to the national interest.

The efforts of the JPL critique response team are acknowledged with appreciation. The team consisted of:

H. E. Cotrill
B. Dayman, Jr.
S. P. DeGrey
Dr. M. W. Dowdy
J. G. Finegold
Dr. G. Gigas
F. W. Hoehn
Dr. G. J. Klose
Dr. N. R. Moore
T. W. Price
Dr. P. R. Ryason
H. W. Schneider
Dr. R. R. Stephenson
A. N. Williams

FOREWORD

In August 1975, the Jet Propulsion Laboratory (JPL) California Institute of Technology (Caltech) completed an assessment of the benefits that could be realized with alternate engines and related vehicle improvements in automobiles of the next decade. This major systems study, entitled "Automobile Power Systems Evaluation Study (APSES)," was funded under a public-interest grant to Caltech from the Ford Motor Company. The results, documented in JPL Report SP 43-17* "Should We Have a New Engine?", stirred nationwide interest and JPL has received thoughtful comments and critiques from many interested organizations. For a dynamic subject area of this breadth and scope, it is not surprising that certain of the study's conclusions and recommendations are somewhat controversial. Until recently, however, there were neither funds nor a mechanism available to JPL whereby these comments and critiques would be addressed in appropriate depth. The Energy Research and Development Administration (ERDA) has now provided the necessary mechanism through their sponsorship of a follow-on study.

ERDA recognized that the APSES study report has served as a common basis for constructive dialogue in industry and government circles. The broad utility of that assessment motivated the ERDA Division of Transportation Energy Conservation to continue such work in support of its Office of Highway Vehicle Systems. JPL was selected to conduct the follow-on project, called Automotive Technology Status and Projections (ATSP).

The ATSP Project is a multitask effort which embraces all of the facets of the original APSES study, and more. The general objective of the ATSP project is to carry on a continuing assessment of current automotive technology development programs and of prospects of new concepts. The study embraces alternate engines and power train components, related energy-conserving vehicle modifications, and fuel alternatives which could be implemented by the end of this century. Early phases of the study will focus upon passenger cars, with possible subsequent expansion to include trucks, buses and other highway vehicles.

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*Now available as SAE Publication SP 400s.

One of the major products of this project is to be a series of annual reports on ERDA's advanced automobile program. These documents will assess progress made in the prior year toward meeting ERDA's objectives in ongoing automotive development, and the potential impact of new developments. This assessment will be made against the backdrop of revised fuel supply projections, changing regulatory standards, and National priorities.

A longer-term output of the ATSP project will be a comprehensive Sourcebook on Automotive Technology. Its revisable sections will summarize pertinent technical data on alternative automotive powerplants (heat engines, electric and hybrids), transmissions and other power train components, related vehicle structure and packaging improvements, and fuels. It is intended that this sourcebook serve as a convenient and self-consistent desk reference for interested users.

Since the ATSP Project is building upon the original APSES data base, one of the early tasks assigned by ERDA was the compilation and publication of the critiques of the APSES report. This document is intended to satisfy that requirement. JPL responses are included for most of the critiques. For some of the critiques, a response is not required. In these cases the incoming letter is included, but without a corresponding response letter. Most of the responses are interim in nature, and considerable work must be done to properly address the many aspects of the APSES study which are discussed in the critiques.

Applicable portions of the various critiques will be incorporated in the appropriate ATSP study tasks (e.g., all the critiques, or portions thereof, pertaining to gas turbine power systems will be addressed under the "Brayton Power Systems" study task). Technical Task Summaries will be published as public documents. They will subsequently serve as the basis for various sections in a Sourcebook on Automotive Technology, and for the annual reports.

APPROACH

Each critique of JPL Report SP 43-17, "Should We Have a New Engine" is preceded in almost all cases by the corresponding JPL response letter. Included with each response letter was a standard enclosure. In the interest of bervity, the enclosure is not included with each response letter herein, but is presented as Exhibit A.

EXHIBIT A

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The ATSP activities that are currently underway include the following

- Responses to the APSES critiques are scheduled for completion in late July 1977.
- Analyses of selected technical issues, brought out in the APSES critiques, will be compiled and addressed on a generic basis without further reference to individual sources. A letter-by-letter response is not planned
- A review of the alternate engine installed-horsepower scaling that was used in the APSES report is scheduled for completion early in CY 1978.
- Development of JPL's simulation computer program, Vehicle Economy, Emission, and Performation (VEEP), is continuing. Phase I, for conventional heat engined cars, is scheduled for completion in October 1977.
- A review of the APSES projections relative to the catalytic controlled Otto cycle engines is particularly pertinent in view of the recent Volvo announcements in this area. It is scheduled for completion during the fourth quarter of CY 1977.
- A reassessment of the state of development of Brayton cycle engines is scheduled for completion in late CY 1978.
- A reassessment of the state of development of Stirling cycle engines is scheduled for completion in late CY 1978.

In addition to the above tasks which are in progress, there are several other tasks scheduled to begin later in CY 1977 These include reassessments of Diesel cycle engines, Rankine cycle engines, advanced transmissions, and potential vehicle modifications other than to the drive train. Each of these tasks will include recognition of appropriate issues raised in the critiques. Completion of these last four items range from mid CY 1978 to early in CY 1979 .

CONTENTS

CONTENTS (cont)

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Critique by

General Motors Corporation
General Motors Technical Center
Environmental Activities Staff
Warren, MI 48090

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

34LPE-77-224-1

June 29, 1977

Dr. David S. Potter, Vice President
Environmental Activities
Executive Offices
General Motors Technical Center
Warren, Michigan 48090

Dear Dr. Potter:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

General Motors' comprehensive analysis of the subject report obviously required a significant expenditure of engineering man-hours and management time for its preparation. JPL wishes to express our sincere thanks to GM for providing this evaluation of the study. Both the timing of our response and a summary of our restructured program are explained in the enclosure.

JPL is pleased that GM concluded that the report "is a good technological review of the state-of-the-art in alternate power plant development, identifying the pertinent characteristics of the various engines studied as well as many of the obstacles which must be overcome. Certainly this type of report is useful at any time". Mr. Starkman also stated in his cover letter, "I offer this document to you (JPL) in an intent to be constructive rather than critical". It is in this same spirit that we now provide a partial response to the major GM concerns. Unfortunately, this type of exchange has a natural tendency to emphasize the limited areas of disagreement between the parties at the expense of the larger areas of agreement.

The GM critique consists of a cover letter, summary, and eight attachments. The attachments were apparently written by different GM technical experts who reviewed selected chapters of the JPL report. The summary and cover letter appear to represent a GM senior management perspective of the overall study. We want to respond here primarily to the GM concerns expressed in the summary and cover letter. Clearly a complete point-by-point response to all of the items raised in the Attachments is neither appropriate nor feasible in a letter; it would, in essence, be another study. Only two issues from the GM Attachments are commented on below. Our ERDA-sponsored on-going work calls for continuing technology assessment studies. One of the outputs of this project is a series of Technical Task Summaries (TTS) on selected alternate engine types which update and expand the work in the subject report. The detailed GM comments and suggestions on these engine types will be incorporated in these TTS reports as appropriate.

Telephone 354-4321 *Telex 675421* *Twx 910-588-3294*

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Before leaving the Attachments, two areas warrant specific JPL comment as follows: (1) GM's Attachment 8 summarizing the conclusion of 21 alternate power plant studies, and (2) the Otto cycle comments. JPL objects to the inferences drawn in Attachment 8, "Conclusion from 21 Contemporary Alternate Power Plant Studies". The listing of conflicting conclusions from many studies that were performed under differing conditions of objective, scope, time frame, funding and vested interest in the outcome is simply an irrelevant compilation at best. The JPL report emphasizes the first word of its title - Should - and considers the potential of the alternatives. It is in no way a prediction of what will be; JPL claims no special clairvoyance in predicting the future. We feel that it is necessary to assess the potential objectively and strive to achieve it.

Attachment 1 gives GM's comments on the Otto cycle with respect to the prospects for meeting the Statutory emission standards (.41 g/mi HC/3.4 CO/0.4 NO_x) without degrading fuel economy. An October 3, 1975 letter to Mr. Jensen of Ford amplified the JPL position as of that date. The letter supported the position taken in the subject study. Looking at that situation today with the benefit of almost 2 years elapsed time, JPL still concludes that given adequate development the statutory emission standards can be met across the fleet without degrading (and, in fact, slightly improving) fuel economy. The question of the certification margin for the "large" (5000 lb curb weight) car is now moot as the legislated fuel economy standards will result in "large" cars of significantly lower weight.

Turning now to the summary and cover letter, GM's "major concerns with the JPL report relate to its scheduling of technological breakthroughs ... as well as its apparent lack of recognition that the ultimate success of an alternative engine must be determined in the marketplace". Also the summary, cover letter and one of the Attachments dwell heavily on the subject of risk - technical, market and financial. Regarding the "scheduling of technological breakthroughs", JPL, of course, agrees that true research breakthroughs cannot be scheduled. However, JPL has not, as GM concluded, scheduled research breakthroughs in formulating the report's conclusions and recommendations. In our judgement, research breakthroughs are not required to implement the Mature configuration engines upon which the JPL conclusions were based. What is needed is a technical development program which, of necessity, requires firm management commitment and adequate funding. The JPL scheduling of this development effort is a success-oriented path, as it should be when setting project goals. Failure to reach the scheduled goals would be attributed to frailty of man, not fundamental scientific limitations.

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We are quite frankly puzzled by GM's major emphasis that the JPL report "has an apparent lack of recognition that the ultimate success of an alternate engine must be determined in the marketplace". We are not aware that the JPL report or verbal presentation, either in 1975 or now, disagree with this statement. The central thesis of the JPL report is that several of the alternative engines have sufficient potential to warrant their vigorous development to provide the nation the option of their subsequent introduction. The JPL study did not by its scope address the possible introduction strategies that could be employed after a successful technical development. The risk, of any type, to GM (or the infra-structure supporting it) of carrying out the JPL research and development recommendations is affordable. Since the public at large benefits from reduced emissions and improved fuel economy, the JPL report stated that government assistance (of an unstudied and unspecified type) could be employed to further reduce the risk.

This critique has been most helpful to JPL, and we sincerely appreciate the time spent by General Motors' Staff in its preparation.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:tm

Enclosure (1)

Environmental Activities Staff
General Motors Corporation
General Motors Technical Center
Warren, Michigan 48090

December 1, 1975

Dr. R. Rhoads Stephenson
Investigator, Auto Power Systems Investigation
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

Dear Rhoady:

Attached you will find a copy of General Motors analysis of the JPL report, "Should We Have a New Engine?"

This is transmitted to you in accordance with our discussion of September 18, 1975, at which time you and members of your staff briefed us on the contents of that report.

The attached critique represents the input from many individuals and staffs within General Motors. Each of the people involved in the analysis is an expert in the particular portion of your document which he reviewed. Environmental Activities Staff has acted as a collating organization in order to put the resulting discussion into context.

As noted in the GM summary, we have generally concluded that the report is a good technical review of the state of the art in alternate power plant development. Our major concerns with the report relate to its "scheduling" of technological breakthroughs to occur within the next few years (such as the assumption that the statutory emission standards will soon be met), as well as its apparent lack of recognition that the ultimate success of an alternative engine must be determined in the marketplace. As you know, major technological advances must occur in several areas, before any alternate power plant will be able to offer a serious challenge to the conventional Otto cycle engine. Our points of disagreement and agreement are addressed more precisely and completely in our critique.

On behalf of General Motors, I offer this document to you in an intent to be constructive rather than critical. We trust it will be of value to you and your task force personnel. Thanks for the opportunity to evaluate your report and its contents.

Very truly yours,

Ernie

E. S. Starkman
Vice President

mb
att.

SUMMARY

The Jet Propulsion Laboratory (JPL) report entitled "Should We Have a New Engine? An Automotive Power Systems Evaluation", dated August, 1975, has been reviewed by several interested research and engineering groups within General Motors. Generally, they concluded that the Report is a good technological review of the state of the art in alternate power plant development, identifying the pertinent characteristics of the various engines studied as well as many of the obstacles which must be overcome. Certainly, this type of report is useful at any time.

One of the major GM concerns with the Report centers on its assessment of all of the various technical interactions and, from these, the probable resulting characteristics of the various alternate power plants. This process depends heavily on the reliability of the predictions made for overcoming the technical obstacles, and the associated impact on the total design development and production capabilities of the industry. To illustrate this concern, a review of the conclusions reached in a number of similar alternate power plant studies made by "contemporaries" of JPL shows that they reached widely different conclusions even though they used essentially the same set of facts. There is certainly no consensus in the conclusions reached by these studies.

The JPL Report, as with most other studies of the alternative power plant situation, contains an array of assumptions concerning how and when various obstacles will be overcome. Included is the tacit assumption that all of these problems will be solved "on schedule" with adequate funding. Thus, the assumption is made that it is possible to "schedule" technological breakthroughs. Past experience does not support this, and GM engineers and scientists are not able to find support for this critical assumption in any of the past history of alternative power plant development.

A second major GM concern is that the Report fails to recognize that the ultimate success of any alternative power plant must be determined in the marketplace. The economic and market risks cannot be "assumed away," as is the case in almost all technological-fix studies. Before any precisely stated conclusions such as those included in the JPL Report can be formulated, the total area of technological and economic risks, manufacturability and materials must be effectively evaluated. This should occur both in terms of the organizations which are required to take the risk, and acceptance of the results in the marketplace. Without this type of sensitivity study, no realistic actions may be taken regarding the conclusions.

In summary, while the study is interesting, there does not appear to be any significant new information contained in it, and the conclusions appear to be highly speculative.

Specific comments as they relate to the Otto cycle, diesel, stratified charge, Stirling and gas turbine engines, as well as transmission selections, are contained in Attachments 1 through 5 of this statement. Comments on the subjects of financial risk, manufacturability and materials are in Attachments 6 and 7. Attachment 8 summarizes the conclusions of the 21 alternate power plants studies made by "contemporaries" of JPL.

ATTACHMENT 1

OTTO CYCLE ENGINE

The following comments relate to Volume II, Chapter 3, of the JPL Report, which addresses the Otto cycle engine. This was reviewed with the JPL project team during their visit to GM on September 18, 1975.

The JPL Report concluded that with some additional development, the Otto cycle engine can meet the 1978 statutory standards (.41 gpm HC, 3.4 CO, .4 NOx) with some improvement in fuel economy. Excerpts from the Report which state this conclusion and the rationale for this conclusion are shown in Figures 1 and 2. The major supporting points are:

1. low mileage vehicle data with 3-way catalyst systems;
2. high mileage conversion efficiencies of 3-way systems, of 77% for HC and NOx;
3. engine-out emission levels for HC and NOx of 1.73 gr/mi. which, when combined with the above efficiency, would allow this system to meet the statutory standards; and
4. fuel economy equal to the best 1975 oxidizing converter systems with some improvement through better mixture control, optimized EGR and spark timing.

General Motors engineers have experimented extensively with both the 3-way catalyst system, including closed-loop control of the fuel metering, as well as open-loop dual catalytic converter systems. Shown in Figure 3 are results from 5 current GM development cars targeted toward the 1978 statutory standards utilizing these types of emission control systems. The first 2 vehicles in the figure are closed-loop, electronic fuel injection, 3-way converter systems. The third vehicle employs a closed-loop carburetor system with a 3-way converter, followed by an oxidizing converter with additional secondary air. The last 2 vehicles are open-loop, dual converter vehicles. Consistent with the JPL findings, all of these vehicles achieved the statutory levels at low mileage. However, this type of information in itself does not demonstrate capability to achieve the standards for the required 50,000 miles.

Shown in Figure 4 are additional test results for the same 5 vehicles discussed in Figure 3, showing engine-out emission levels and the overall conversion efficiency on the Federal emission test. These data indicate that at low mileage, conversion efficiencies on the order of 77% for HC and NOx are achievable. Again, however, these conversion efficiencies are not demonstrative of the capability of the system to meet the 50,000 mile requirement.

GM is continuing to develop comprehensive system durability data on advanced emission control systems, since this is of primary importance in determining system potential. Figure 5 shows system durability data to date for the first vehicle listed in Figure 3. These data indicate that at 5,000 miles, this vehicle is already exceeding the CO standard (which JPL stated as being no problem), and is marginal for NOx control.

This test is being run with Indolene clear fuel which has a low contaminant level (.009 gr/gal. lead and .0004 gr/gal. phosphorus) to enhance the probability of this system achieving durability requirements. Figure 6 shows conversion efficiencies for this test vehicle. The overall test efficiency for all 3 constituents at the 5,000 mile test point was 78%.

Durability results obtained to date on the dual converter open-loop system (4th vehicle in Figure 3) are shown in Figure 7. These data show that at 10,000 miles, the vehicle is exceeding the HC standard, and is marginal on both CO and NOx control.

Figure 8 shows durability results for a number of other dual converter system vehicles, with each curve representing a different catalyst formulation. These data indicate that although low NOx levels can be achieved at low mileage, the systems deteriorate rapidly. The maximum mileage for which all 3 constituents were below the statutory standards (.41 HC, 3.4 CO, .4 NOx) was 16,000 miles, with most of the systems failing at less than 10,000 miles. Thus, our vehicle system data indicate that NOx catalyst durability with either 3-way or dual converter systems is a major problem. It appears to require a technological breakthrough.

One of the important assumptions involved in the JPL conclusions concerning the capability of 3-way and dual catalysts, is that 1.73 gr/mi. of HC and NOx can be simultaneously obtained as engine-out or feed-gas levels to the catalytic converter. As shown in Figure 9, it is the original reference used for the basis of this assumption. The vehicles in this reference used AIR, and had a/f ratios considerably leaner than stoichiometric. The use of AIR and the lean a/f ratios would not provide an acceptable feed-gas for a reducing converter. Thus, these data are not usable as a basis for the JPL assumption that emission levels of less than 1.73 gr/mi. of HC and NOx out of the engine can be simultaneously and readily obtained.

Shown in Figure 10 are test results from the experimental system vehicles listed in Figure 3, indicating the feed gas levels to the catalytic converter of these systems. These data show that levels on the order of 1.7 HC and 1.7 NOx were achieved with these experimental systems. However, the achievement of these emission levels at stoichiometric or rich a/f ratios compatible with 3-way or dual converter systems requires spark retard, particularly for the control of HC. Thus, a loss in fuel economy of 12.9% to 23.5% results when compared with comparable 1975 Federal certification vehicles. As indicated above, with feed gas levels as shown on this chart, adequate system durability has not been achieved. In order to obtain acceptable durability, lower feed gas levels may be required which will probably result in a larger fuel economy penalty.

The data referenced in the JPL report which was used to indicate that the statutory standards can be met at low mileage, with no loss in fuel economy when compared with 1975 vehicles, do not support the conclusion reached. These referenced data are shown in Figure 11. Engine-out emission levels of this vehicle at 0 miles were 2.4 HC, 28.3 CO and 1.2 NOx. The emission results of the total system considerably exceed both the statutory HC and NOx requirements at 4,000 miles.

Shown in Figure 12 is the GM assessment of the impact of more stringent emission standards on vehicle fuel economy, including the test data source. The penalty of 20% for meeting the statutory standards (.41 HC, 3.4 CO and .4 NOx) is based on the 3-way catalyst and dual catalyst systems shown in the previous figures. It is important to note that this assessment may not be valid since viable technology has not been developed to meet the statutory standards.

Contrary to the JPL report, the 3-way catalyst system does not represent existing technology for meeting the statutory standards, and will require some major technological breakthroughs to accomplish that task. As already demonstrated, the 3-way system has poor catalyst durability. In addition, the simultaneous clean-up of all 3 constituents at the stoichiometric a/f ratio inherently results in a lower conversion efficiency for each constituent than if individual oxidizing and reducing catalysts were used. The "window" for simultaneous conversion is very narrow, drifts with age and temperature, and decreases with miles.

In order to achieve significantly lower engine-out levels that appear to be a necessity in improving the overall performance of such emission control systems as 3-way or dual catalyst, significant fuel economy penalties can be expected. Wide experience obtained in developing emission control systems to different emission control standards clearly supports this premise. Figure 13, which includes a comparison of 1975 Federal and California certification data vehicles, is one example of fuel economy impact with lower emission standards. This shows a 9.3% fuel economy penalty at the more stringent California standards.

Figure 14 shows the results of the GM 1977 practice fleet targeted for the original 1977 emission standards of .41 HC, 3.4 CO and 2.0 NOx. For the 18 cars in this fleet that reached 30,000 miles, the average fuel economy penalty compared with comparable 1975 Federal certification cars, was 13.5%. Of the 18 cars, only 8 were still within the standards at 30,000 miles. With a catalyst change, these 8 cars would have a reasonable probability of meeting the standards at 50,000 miles.

Figure 15 shows two development cars which are being tailored for the 1977 California standards of .41 HC, 9.0 CO and 1.5 NOx. These vehicles are showing an 18 to 24% loss in fuel economy compared with comparable 1975 certification cars, and both are exceeding the emission targets which would be required to have reasonable probability of meeting the certification and end-of-line requirements.

Utilizing these test results, an illustration of the process for stating low mileage emission requirements for potential certification can be developed. This process is outlined in Figure 16. The data shown in this figure represent our experience in meeting the 1975 certification requirements at the 1975 Federal standards of 1.5 HC, 15 CO and 3.1 NOx. An average of the actual certification data cars at 4,000 miles shows that the emission levels were .5 HC, 6.0 CO and 2.2 NOx. These levels were 34% of the HC standard, 40% for CO, and 70% for NOx. These 4,000 mile emission levels were required to assure that these vehicles would meet the certification requirements and represent the design margin required to include the deterioration factor, as well as car and test variability.

Assuming that there would be no significant change in our technology with respect to the catalyst system in terms of efficiency and deterioration (which is at this time a reasonable assumption when considering the statutory standards) and assuming that we could reduce car and test variability proportional to the reduction in standards, the average certification car at 4,000 miles would have to be at .14 HC, 1.4 CO and 1.4 NOx to meet standards of .41 HC, 3.4 CO and 2.0 NOx. The lower margin for NOx results from the lower deterioration factor with the EGR type of control used to meet that standard, as opposed to the converter system required to meet the HC and CO standards. If we were required to meet a .4 NOx standard, this would also require a converter system. Assuming that we could achieve the same level of conversion efficiency as currently being achieved for HC with oxidizing converters (which we have not been able to achieve to date), then the average certification car would have to be at a .14 NOx level to meet this standard.

Low mileage emission performance data for 3-way and dual catalyst systems are above the levels which appear to be required to meet the certification requirements at statutory levels. Moreover, the durability data indicate poor durability and higher deterioration rates than were assumed in the calculation above, which would mean even lower emission requirements and low mileage. These data also indicate that a substantial loss in fuel economy will result at the current level of technology for both 3-way and dual catalyst systems.

A number of other assumptions included in the JPL analysis of the Otto cycle engine are also of concern. These are listed in Figure 17 to indicate our belief that these assumptions are not valid based on our test experience. Detailed comments on these assumptions have not been included since the above discussion has covered much more important areas which require attention, first.

In summary, our review of the JPL conclusion that potential exists for the Otto cycle engine to achieve both statutory emission control levels and maximum fuel economy indicates that existing information does not support such a conclusion. Major problem areas must be solved, and significant technological breakthroughs must be achieved, before support for such an optimistic conclusion can be stated. No precise schedule for such improvements can be predicted because the experimental development progress curve to date has been very low, compared with the progress that must be achieved in order to meet the conclusions stated by JPL. This time-scheduling is particularly important in the JPL analysis, since it assumes very-near-future utilization of emission control systems such as 3-way and dual catalyst, in order to allow achieving both the statutory emission standards and significant fuel economy gains. Extensive development efforts to achieve this improvement in technology would certainly impact ability to maintain an all-out research and development effort toward a totally different power plant.

FIGURE 1

JPL - OTTO CYCLE ENGINE SUMMARY

. EMISSIONS

"GIVEN SOME ADDITIONAL DEVELOPMENT, CARS WITH CATALYTICALLY CONTROLLED OTTO ENGINES DO NOT HAVE TO GIVE UP FUEL ECONOMY TO COMPLY WITH THE STRICTEST LEGISLATED EMISSION STANDARDS. IN FACT, SOME IMPROVEMENT IN EFFICIENCY OF SUCH ENGINES CAN BE OBTAINED WITHOUT RELAXATION OF THOSE EMISSION STANDARDS."

(SUMMARY PG. 3)

RATIONALE --

--- 3-WAY SYSTEMS AT LOW MILEAGE HAVE HC AND CO EMISSIONS LARGELY BELOW .41 HC AND 3.4 CO, WITH NOx IN THE RANGE OF .2 TO .9 WITH THE HEAVIER CARS ALL ABOVE .4.

--- "A REASONABLE HIGH MILEAGE CONVERSION EFFICIENCY FOR 3-WAY SYSTEMS IS 77% FOR HC AND NOx, WITH CO NOT BEING A PROBLEM, ACCORDING TO DEVELOPERS OF SUCH SYSTEMS."

--- WITH 77% EFFICIENCY, .41 HC AND .4 NOx STANDARDS ARE ATTAINABLE WITH A FEED GAS OF 1.73 FOR HC AND NOx.

--- "EMISSIONS OF LESS THAN 1.73 G/MI OF HC AND NOx HAVE BEEN SIMULTANEOUSLY OBTAINED ..., AS REPORTED BY GUMBLETON."

--- THEREFORE, A 3-WAY CATALYST SYSTEM WITH ADVANCED CARBURETION AND PROPORTIONAL EGR IS PROJECTED TO RESULT IN A FEED GAS SUFFICIENTLY LOW IN HC AND NOx TO ALLOW VEHICLE EMISSION STANDARDS OF .4 HC AND .4 NOx TO BE MET.

(3-17)

FIGURE 2

JPL - OTTO CYCLE ENGINE SUMMARY (CONT'D)

. FUEL ECONOMY

--- 3-WAY SYSTEM EQUAL TO THE BEST '75 OXIDIZING CONVERTER SYSTEM.

--- 5% IMPROVEMENT FOR SUPERIOR MIXTURE CONTROL OF ADVANCED CARB., OPTIMIZED EGR AND SPARK TIMING.

--- "MATURE UC CARS," YIELD A SALES WEIGHTED IMPROVEMENT IN ECONOMY OF ABOUT 9 TO 10% OVER MY '75 CARS.

(3-16)

. DRIVEABILITY

3-WAY SYSTEMS WILL PROVIDE DRIVEABILITY EQUAL TO OR POSSIBLY SOMEWHAT BETTER THAN UNCONTROLLED CARS. NO STARTING OR WARM-UP PROBLEMS ARE ANTICIPATED.

(3-18)

'78 FEDERAL DEVELOPMENT CARS

EMISSION STANDARDS .41/3.4/.4

Make/ Inertia Wt.	Engine Description	Emission Control System	Low Mileage Emissions
Chevrolet 3000#	140 - EFI	C/L - 3 Way Cat EGR	.19/2.4/.26
Chevrolet 3000#	140 - EFI	C/L - 3 Way Cat EGR	.27/1.7/.15
Chevrolet 4000#	350 - 4 bbl	C/L - 3 Way Cat + Oxid Cat - CAIR - EGR	.33/1.9/.39
Chevrolet 4500#	350 - 4 bbl	Dual Cat AIR - EGR	.33/1.3/.27
Chevrolet 4500#	350 - 4 bbl	Dual Cat AIR - EGR	.28/2.5/.32

FIGURE 3

'78 SYSTEMS - ZERO MILES

MAKE/ INERTIA WT.	ENGINE DESCRIPTION	EMISSION CONTROL SYSTEM		HC	CO	NOx
CHEVROLET 3000#	140 - EFI	C/L 3-WAY EGR	T	.19	2.4	.26
			E	1.3	14.7	1.8
			%	87	88	88
CHEVROLET 3000#	140 - EFI	C/L 3-WAY EGR	T	.27	1.7	.15
			E	1.9	11.5	1.6
			%	84	85	89
CHEVROLET 4000#	350 - 4 BBL	C/L 3-WAY + OXID. CAT. AIR-EGR	T	.33	1.9	.39
			E	2.0	19.4	1.3
			%	83	88	73
CHEVROLET 4500#	350 - 4 BBL	DUAL CAT. AIR-EGR	T	.33	1.3	.27
			E	2.8	58	1.0
			%	89	98	73
CHEVROLET 4500#	350 - 4 BBL	DUAL CAT. AIR-EGR	T	.28	2.5	.32
			E	1.6	69	.9
			%	83	97	66

FIGURE 4

EMISSION SYSTEM DURABILITY

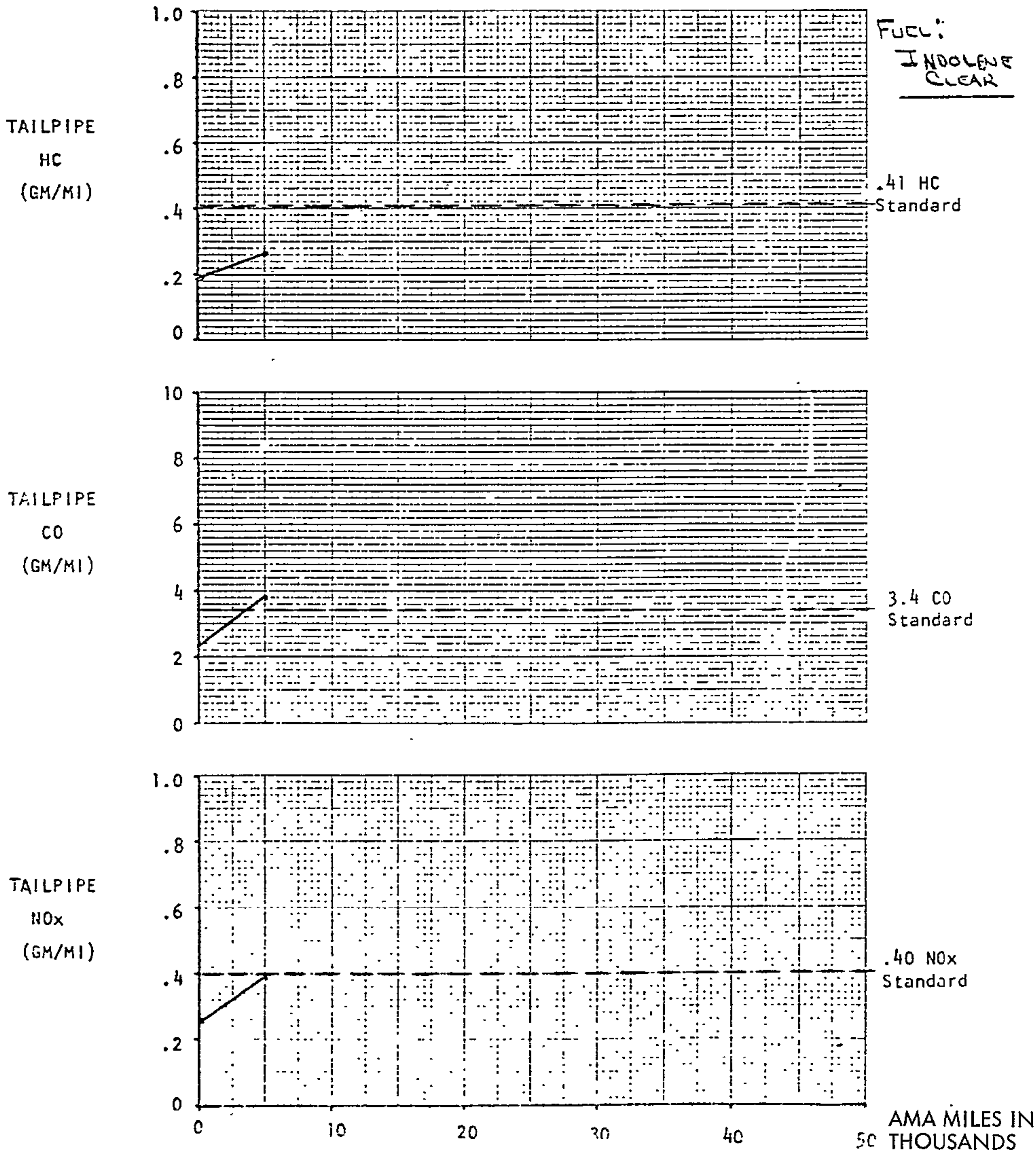
FIGURE 5

System description: Closed Loop EFI 3-Way Catalyst

Catalyst type: HN-3032 160 in³ Bead .03 T.O. 5:1 Pt/Rh

Vehicle No. 65375 Type Vega Inertia wt. 3000#

Engine displ: 140 Trans. Auto. Axle 3.36



EMISSION SYSTEM DURABILITY

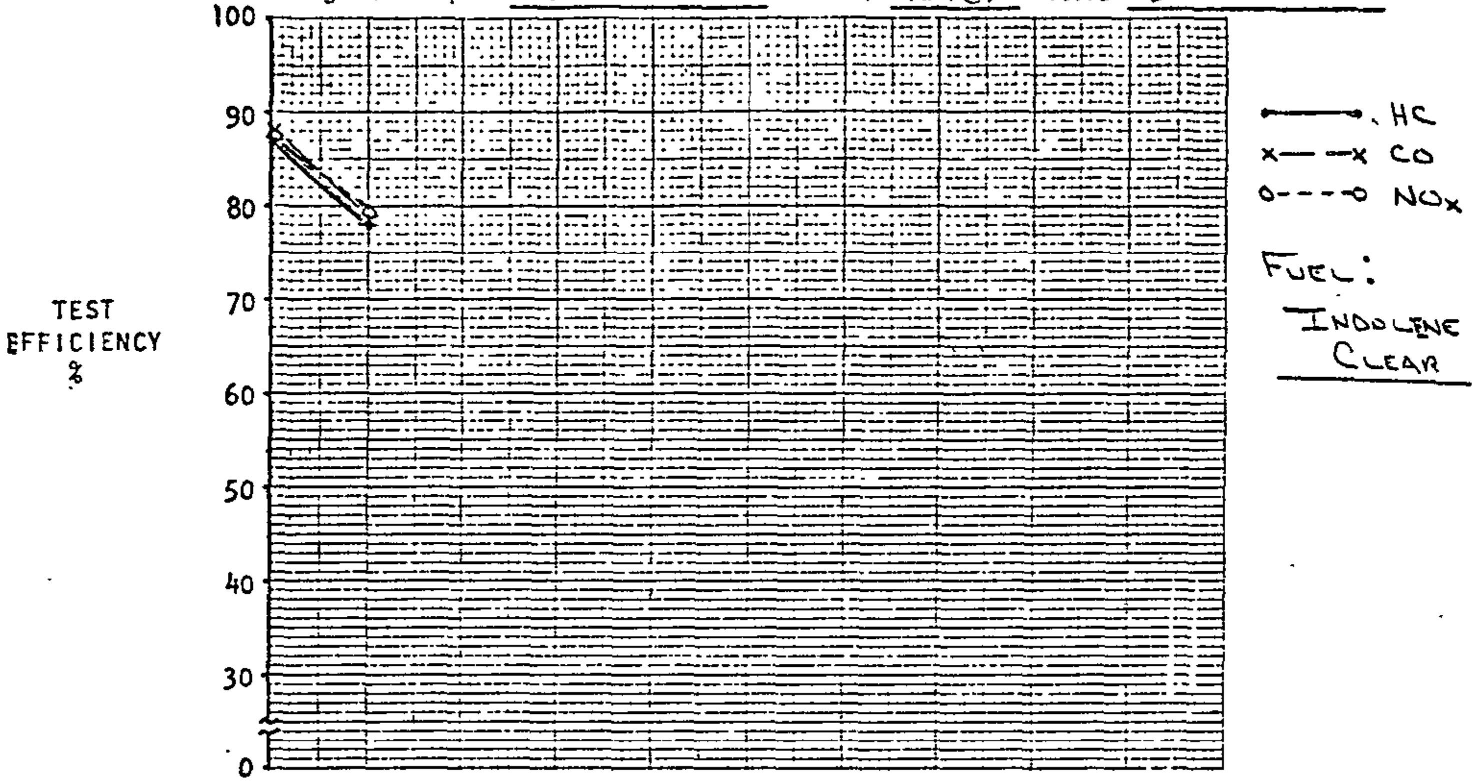
FIGURE 6

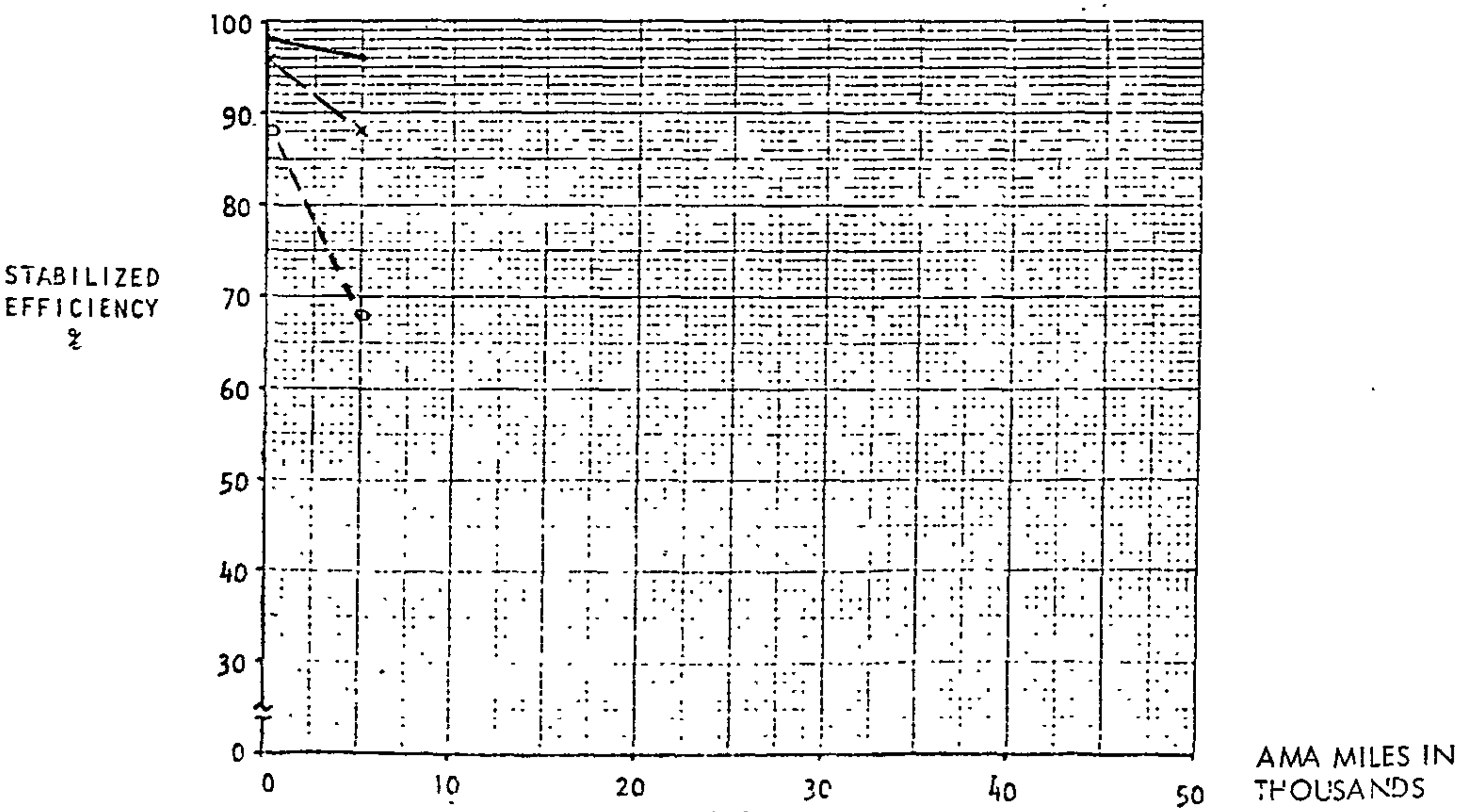
System description: CLOSED LOOP EFI 3-WAY CATALYST

Catalyst type: HN-3032 160 IN^3 BEAD .03T.O. 5:1 PT/RH

Vehicle No. 65375 Type VEGA Inertia wt. 3000#

Engine displ: 140 Trans. AUTO. Axle 3.36





EMISSION SYSTEM DURABILITY

FIGURE 7

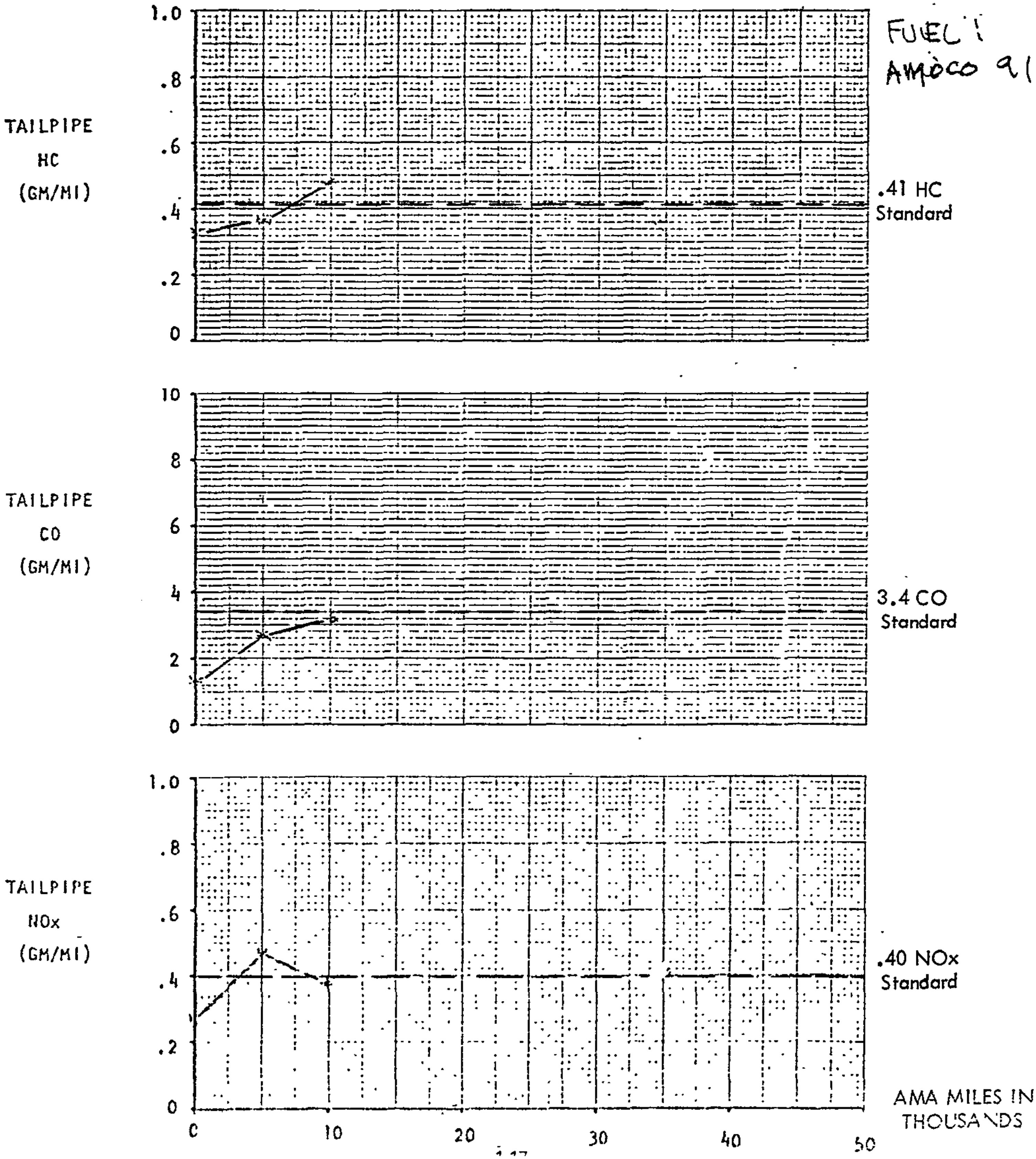
System description: DUAL CONVERTER OPEN LOOP

Catalyst type: GOULD GEM 68 + PRODUCTION U/F

Vehicle No. 65336 Type MALIBU Inertia wt. 4500

Engine displ: 350 Trans. THM Axle 2.73:1

FUEL: AMOCO 91



EXPERIMENTAL DUAL CATALYTIC CONVERTER
DURABILITY RESULTS

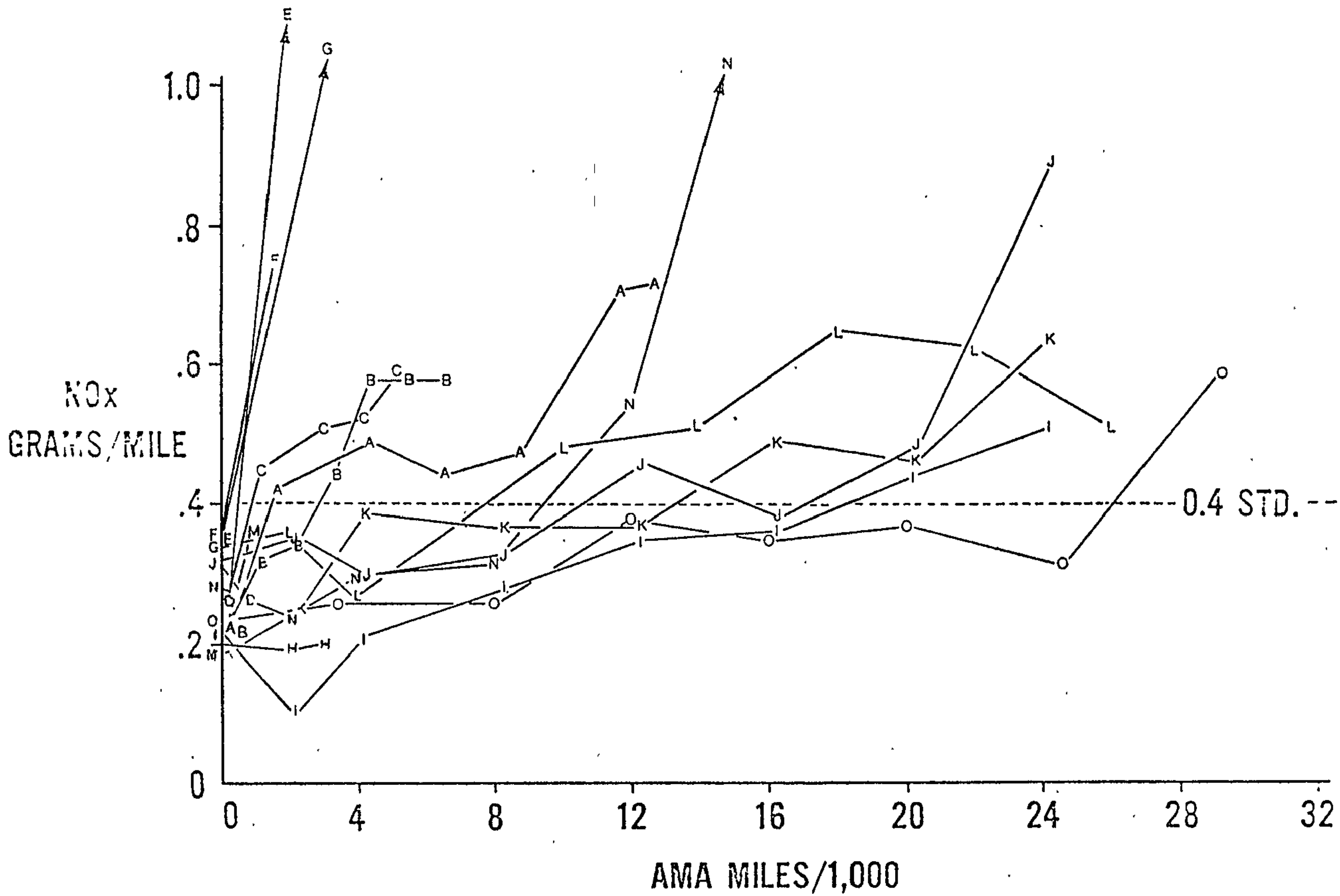


FIGURE 8

FIGURE 9

'78 SYSTEMS (FEED GAS)

Table I - Experimental Control Systems (350 CID-V8 with AIR, 5000 lb Inertia Weight, 1975 EPA Test Procedure)

Car	System	HC g/mile	CO g/mile	NO_x g/mile	Economy, mpg	A/F*
A	Transmission controlled spark	1.1	12.8	3.3	11.1	16.8
B	Proportional EGR–ported spark	1.7	15.8	1.3	11.5	15.7
C	Proportional EGR–ported spark	1.7	15.4	1.1	12.2	16.0
E	Proportional EGR–ported spark	2.0	20.0	1.1	12.8	15.6

* WITHOUT AIR

- AIR AND LEAN A/F DOES NOT PROVIDE ACCEPTABLE FEED GAS FOR REDUCING CONVERTERS

REF. - GUMBLETON, J.J.; BOLTON, R.A.; LANG, H.W. - (G.M. CORP.) "OPTIMIZING ENGINE PARAMETERS WITH EGR", SAE PAPER No. 740104, FEBRUARY 1974.

'78 SYSTEMS - ZERO MILES

(FEED GAS)

MAKE/ INERTIA WT.	ENGINE DESCRIPTION	EMISSION CONTROL SYSTEM		HC	CO	NOx	CITY MPG	% LOSS
CHEVROLET 3000#	140 - EFI	C/L 3-WAY EGR	T	.19	2.4	.26	17.6	12.9
			E	1.3	14.7	1.8		
			%	87	88	88		
CHEVROLET 3000#	140 - EFI	C/L 3-WAY EGR	T	.27	1.7	.15	17.3	14.4
			E	1.9	11.5	1.6		
			%	84	85	89		
CHEVROLET 4000#	350 - 4 BBL	C/L 3-WAY + OXID. CAT. AIR-EGR	T	.33	1.9	.39	10.4	23.5
			E	2.0	19.4	1.3		
			%	83	88	73		
CHEVROLET 4500#	350 - 4 BBL	DUAL CAT. AIR-EGR	T	.33	1.3	.27	9.9	23.2
			E	2.8	58	1.0		
			%	89	98	73		
CHEVROLET 4500#	350 - 4 BBL	DUAL CAT. AIR-EGR	T	.28	2.5	.32	10.0	22.5
			E	1.6	69	.9		
			%	83	97	66		

77-40

FIGURE 10

FIGURE 11

'78 FEDERAL DEVELOPMENT CAR
EMISSION STANDARDS .41/3.4/.4

Table 3
Closed Loop - Dual Converter Durability
1975 FTP Emission Data
350 CID, 5000 Lb. Inertia Weight

Miles	HC	CO	NOx	MPG	'75 Fed. Car MPG
0	.27	.78	.27	11.9	
	(2.4)	(28.3)	(1.2)		
4,000	.54	2.2	.60	12.5	12.6
	(2.6)	(22.6)	(1.1)		
8,000	.64	3.3	.77	12.1	
	(2.8)	(26.1)	(1.2)		
12,000	.96	7.2	1.1	12.2	
	(3.0)	(25.7)	(1.2)		

( ) = Engine Out

Ref. - Genslak, S. L., Zahorchak, J. A.
(General Motors Corporation)
"Dual Catalytic Converters,"
SAE Paper No. 750176,
February, 1975

FIGURE 12

EFFECT OF EMISSION STANDARDS ON FUEL ECONOMY

EMISSION STANDARDS	FUEL ECONOMY	DATA SOURCE
HC/CO/NOx	'75 FTP-URBAN	
1.5/15.0/3.1	BASELINE	'75 FED. CERT. DATA CARS
.9/ 9.0/2.0	-9%	'75 CALIF. CERT. DATA CARS
.41/3.4/2.0	-14%	'77 PRACTICE FLEET
.41/9.0/1.5	-20%	'77 CALIF. DEV. CARS
.41/3.4/ .4	-20%*	'78 FED. DEV. CARS

* ASSESSMENT MAY NOT BE VALID SINCE VIABLE TECHNOLOGY HAS NOT BEEN DEVELOPED.

FUEL ECONOMY COMPARISON

1975 Federal (1.5 HC; 15 CO; 3.1 NOx) vs. 1975 California (0.9 HC; 9.0 CO; 2.0 NOx)

		Fuel Economy*				Percent Difference	
	Engine	Federal		California			
Make	Description	City	Highway	City	Highway	City	Highway
Chevrolet	140-2bbl	20.8	29.8	18.5	28.3	-11.0	-5.0
Chevrolet	250-1bbl	15.8	21.9	15.1	19.8	-4.4	-9.6
Chevrolet	350/400-4bbl	12.5	17.1	11.5	15.5	-8.0	-9.4
Pontiac	350/400-4bbl	11.4	16.8	11.2	15.3	-1.8	-8.9
Pontiac	455-4bbl	11.2	16.2	10.0	13.2	-10.7	-18.5
Oldsmobile	350-4bbl	14.0	18.7	11.9	16.8	-15.0	-10.2
Oldsmobile	455-4bbl	12.1	16.8	10.8	16.4	-10.7	-2.4
Oldsmobile	260-2bbl	14.8	19.6	12.6	16.4	-14.9	-16.3
Buick	231-2bbl	17.3	24.7	15.2	20.9	-12.1	-15.4
Buick	350-4bbl	12.7	17.5	11.8	16.3	-7.1	-6.9
Buick	455-4bbl	11.1	15.3	9.9	13.9	-10.8	-9.2
Cadillac	500-4bbl	10.9	14.3	10.3	13.3	-5.5	-7.0
Average of Comparable Cars		13.2	18.3	12.0	16.5	-9.1	-9.8
55% City + 45% Highway		15.1		13.7		-9.3	

*Includes certification data and supplemental fuel economy cars

Ref. - General Motors Request for Suspension of 1977 Federal Emission Standards, January 10, 1975

FIGURE 13

1977 PRACTICE FLEET - CATALYTIC CONVERTER SYSTEMS
EMISSION STANDARDS - .41/3.4/2.0

Make/ Inertia Wt.	Engine Description	No. of '77 Cars	Fuel Economy - '75 FTP - Urban: '77 Practice Fleet @ 5K	'75 Fed. Car @ 4K*	Percent Difference
Chevrolet 3000#	140 - 2 bbl AIR - EGR	2	19.3	20.2	- 4.5
Chevrolet 4000#	250 - 1 bbl AIR - EGR	2	14.7	15.8	- 7.0
Chevrolet 4500#	350 - 2 bbl AIR - EGR	2	10.0	13.3	-22.6
Chevrolet 4500#	400 - 4 bbl AIR - EGR	2	10.8	13.1	-17.6
Chevrolet 4500#	400 - 4 bbl Lean Burn	1	11.5	13.1	-12.2
Pontiac 4000#	350 - 4 bbl AIR - EGR	1	12.0	13.2	- 9.1
Pontiac 4500#	400 - 4 bbl AIR - EGR	1	11.0	13.0	-15.4
Oldsmobile 4000#	260 - 2 bbl CCS - EGR	2	12.5	14.8	-15.6
Oldsmobile 4500#	350 - 4 bbl CCS - EGR	3	11.3	14.6	-22.6
Buick 4000#	350 - 2 bbl CCS - EGR	1	11.8	13.6	-13.2
Buick 4000#	350 - 2 bbl AIR-EGR	1	12.5	13.6	-18.8
		18**			-13.5

* Includes certification data and supplemental fuel economy cars.
** Only 8 of 18 cars were below standards @ 30K miles.

77-40

FIGURE 14

'77 CALIFORNIA DEVELOPMENT CARS - CATALYTIC CONVERTER SYSTEM

EMISSION STANDARDS - .41/9.0/1.5
EMISSION TARGETS - .20/5.0/1.0

Make/ Inertia Wt.	Engine Description	"Best Effort" HC/CO/NOx	Fuel Economy - '75 FTP - Urban '77 Dev. Car	'75 Cert. Car	Percent Difference
Chevrolet 3000#	140 - 2 bbl AIR - EGR	(.27)/3.8/1.01	15.4	20.2	-23.8
Chevrolet 4500#	350 - 4 bbl AIR - EGR	.19/4.7/(1.16)	10.6	12.9	-17.8

( ) Over Target

FIGURE 15

FIGURE 16

CERTIFICATION REQUIREMENTS*

(BASED ON 1975 CERTIFICATION VEHICLES)

	HC	CO	NOx
1975 FEDERAL STANDARDS	1.5	15.0	3.1
AV. CERT. CAR @ 4K	.5	6.0	2.2
PERCENT OF STANDARDS	34%	40%	70%
PROPOSED FEDERAL STANDARDS	.41	3.4	2.0
ASSUME 1975 PERCENT OF STANDARDS	34%	40%	70%
REQUIREMENT FOR AV. CERT. CAR @ 4K	.14	1.4	1.4

* BASED ON CHEVROLET & BUICK DATA

FIGURE 17

OTHER JPL ASSUMPTIONS

- THAT CONVERTERS ALLOW FOR OPTIMUM TUNING OF SPARK AND AIR/FUEL IRRESPECTIVE OF THE LEVEL OF HC CONTROL REQUIRED.
  (3-4)
- IMPROVEMENT IN HC/CO CONTROL THROUGH IMPROVED MIXTURE DISTRIBUTION -- PARTICULARLY DURING WARM-UP
  (3-5)
- ATTRIBUTES ADVANCE CARBURETORS (DRESSER - VARIABLE VENTURI ULTRASONIC - EFI) AS REDUCING HC AND CO EMISSIONS BY A FACTOR OF 1.6 TO 2.0 (4500# CAR .7 - 1.48/3.9 - 10.3/ 1.8 - 2.7/ 10.7 - 11.2)
  (3-8, 3-9)
- ACKNOWLEDGES HIGHER HC AND CO IN FEED STREAM TO A DUAL CONVERTER DUE TO RICH AIR/FUEL -- SOLUTION LARGER VOLUME OF CATALYST OR MORE NOBLE METAL.
  (3-12)
- 3-WAY CATALYST SYSTEMS
  - RAPID PROGRESS IS BEING MADE ON DURABILITY PROBLEM
    (3-12)
  - DUE TO THE VIRTUALLY STEP CHANGE IN OUTPUT VOLTAGE OF THE O_2 SENSOR (900 MV), "SETTING THE CONTROL POINT @ 500 MV OR LESS ELIMINATES TEMPERATURE SENSITIVITY."
    (3-12)
- $40 COST DIFFERENTIAL BETWEEN SYSTEMS TO MEET .41/3.4/2.0 AND .41/3.4/.4
  (3-15)
- ASSUMES THAT BASIC WANKEL ENGINE FUEL ECONOMY CAN BE MADE EQUAL TO PISTON ENGINE @ .41/3.4/.4 OR 2.0 EMISSION LEVELS (BY RESOLUTION OF THE ROTOR/HOUSING SEAL DIFFICULTIES).
  (3-16)

ATTACHMENT 2

DIESEL AND STRATIFIED CHARGE ENGINES

Diesel Engines

JPL's general conclusion on diesel engines is that continued development is not warranted primarily because: (1) the diesel offers little fuel economy advantage over a comparable gasoline engine; and (2) known NOx emission reduction techniques cannot meet the .41/3.4/.4 standards without an unacceptable compromise in performance.

This second item is a very important criterion for this engine since existing technology has not clearly demonstrated even experimental capability of achieving the .4 NOx standard. Whether this NOx standard will indeed remain as a long term emission requirement is certainly of question, making this less than a solid criterion for rejection of the diesel. Because this .4 NOx standard currently exists, there has been relatively little concentrated development effort on achieving low NOx levels from the diesel -- much more is required to determine the ultimate capability and associated trade-offs of the diesel engine.

Discussing the first item above, it is based on energy equivalent fuels and performance equivalent vehicles. In concept, this is the proper method to compare power plants although there is some question concerning the method used to size the power plants. This would have some, although probably little, effect on the diesel-gasoline comparison.

Fuel economy potential of the diesel is of prime importance in its evaluation. JPL claims a sales-weighted 19% increase in urban fuel economy, and a 5% increase on the highway. For the mature diesel as compared with the mature Otto-cycle engine (page 4-33, Volume II), the 19% fuel economy increase appears consistent with data based on our current vehicles but the 5% highway economy appears low. Our vehicle data show about a 10% highway fuel economy gain, but these evaluations do not include the mature configuration (turbo-charged, EGR). These comparisons are made at current emission levels, making it difficult to project the fuel economy differential between gasoline and diesel engines since the statutory emission requirements (particularly NOx) are considerably below current standards.

An additional energy saving can be realized at the refinery if a 50-50 gasoline/diesel fuel split (by energy) is produced. JPL quotes an Exxon report (reference 17-35) which states that a 2% saving in total refinery input energy can be achieved at the 50-50 fuel split point, in addition to savings in refinery investment. This gain in refinery efficiency can be added to the gain in diesel engine fuel economy to find the total gain in miles driven per barrel of crude oil when switching to the 50-50 split. Other reports by Mobil and Texaco have shown from 0 to 1% gain in refinery efficiency, respectively. The JPL mature diesel data from Table V of the JPL Volume I Summary is shown on the attached Figure 1, along with the 20% urban gain. The range of these data show a gain in miles driven per barrel of crude oil from 2.7% (0% refinery, 7% diesel) to 12% (2% refinery, 20% diesel).

This potential improvement in miles driven per barrel of crude oil, the current uncertainty in the long term emission standards, along with less refinery investment costs, make the diesel an attractive power plant in an area between all gasoline engines and some other engines such as the turbine or Stirling. This is based on the ability to meet emission and other requirements in that time frame.

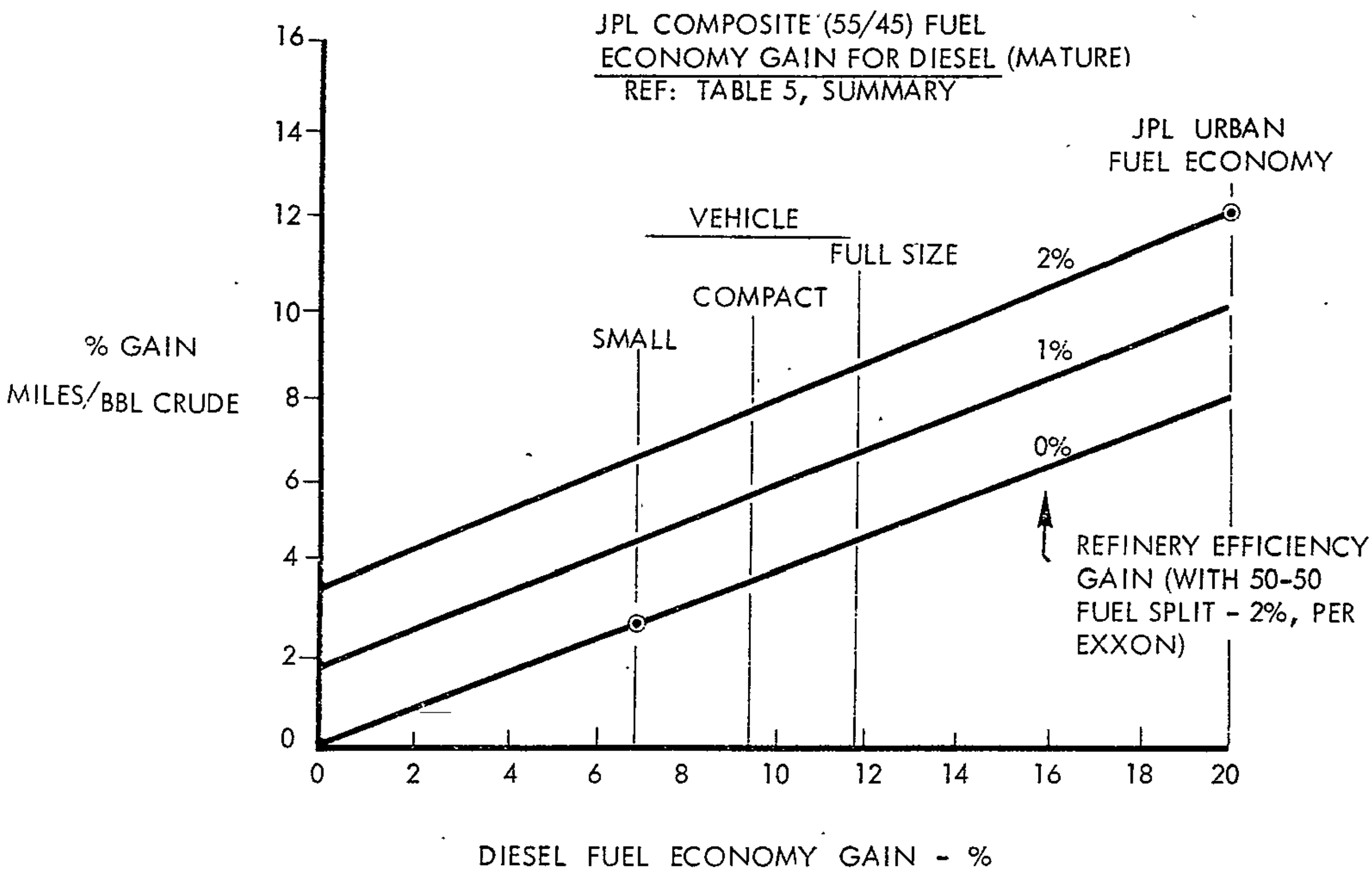
Stratified Charge Engines

JPL has concluded that the open chamber, direct-injected stratified charge engine can achieve the statutory emission standards, and has better fuel economy than the pre-chamber type engines. The PROCO engine was selected as being the most highly-developed engine of this type. The mature configuration which appears identical to the current configuration is credited with a 12% urban and a 3% highway fuel economy gain over the conventional engine (sales-weighted). The section on stratified charge appears to be consistent with current data except for the advanced configuration. A ceramic rotary stratified charge engine is proposed, which appears to be a very unlikely engine.

Several areas in the stratified charge section have direct implications to the Honda CVCC system. JPL states that the CVCC system achieves fuel economies equivalent to the 1973-1974 levels. This is not unexpected, they state, because of the delayed burning which results in higher exhaust gas temperatures, but poorer fuel economy than is possible with the conventional gasoline engine.

The CVCC engine system can also be evaluated using the calculated results of Blumberg, as shown in the JPL Report, at a lean overall a/f ration of 18.4 without EGR. Stratified charge offers no reduction of NOx emission, while there is a loss in fuel economy compared with a homogeneous engine. These results agree with our conclusions on stratified charge vs. homogeneous engines. The Blumberg calculations do indicate that stratified charge is most effective in reducing NOx with EGR at stoichiometry. This is the approach used with the PROCO engine. The NOx control achieved with stratified charge along with loss in fuel economy can also be achieved with spark retard of the homogeneous engine, according to JPL.

DIESEL FUEL ECONOMY ADVANTAGE AND REFINERY EFFICIENCY GAIN EFFECTS ON INCREASED MILES DRIVEN PER BARREL OF CRUDE OIL



BASE CASE

90% - 10% GASOLINE-DIESEL FUEL ENERGY SPLIT

60% REFINERY OUTPUT TO AUTOMOTIVE FUEL

MAINTAIN NON-AUTOMOTIVE REQUIREMENT

94% REFINERY EFFICIENCY

NEW SITUATION

50% - 50% GASOLINE-DIESEL FUEL ENERGY SPLIT

REFINERY SAVINGS GO TO DIESEL FUEL

FIGURE 1

ATTACHMENT 3

STIRLING ENGINE COMMENTS

The JPL Report on the above study is a good review of the current literature on Stirling, and other, powerplants which JPL chose as possible alternatives to present production automobile powerplants. It is valuable as a source list for current literature and includes new information gleaned from JPL "Fact-Finding Visits" that otherwise does not exist in the public literature. It also contains a large amount of similar reference material on subjects peripheral to automotive powerplant.

A major conclusion of the study is that an extensive research and development program should be undertaken to ready Stirling and Brayton engines for broad use as automotive powerplants in the 1980's. With respect to the Stirling engine, this conclusion is based upon an initial finding that the developed "Mature" Stirling engine will operate consuming only 68% as much fuel as a similarly "Mature" Otto cycle engine and that the Stirling engine will meet statutory emission standards of 0.41 HC/3.4 CO/0.4 NO_x.

With the specific Stirling fuel consumptions from the initial findings as major predicates, the study proceeds to draw conclusions and make recommendations with respect to allowable Stirling vehicle selling prices, customer break-even and ownership costs over 10-year vehicle lifetimes, United States petroleum requirements to the year 2000, multimillion-dollar Stirling research and development programs "which the (automotive) industry inself can pay for," and a recommended strategy for integrating the development, manufacturing, and introduction of the alternative powerplant vehicles through the 1980's and 1990's.

Since the fuel economy findings for the "Mature" cars are major foundations of the subsequently-developed material, JPL checked the fuel economy projections of "Present" Otto engine vehicles against current production vehicle averages, and the "Mature" Otto engine vehicles were assigned modest 5% improvements. The fuel economy projections for "Mature" Stirling vehicles were assigned 12% improvements over "Present" Stirling vehicles, and the "Present" vehicle fuel economy projections are not given in the report. There is no present Stirling vehicle test data against which the projections could have been checked. The report thus provides reason to believe that the Otto cycle projections may be accurate, and it also provides reason to believe that the Stirling fuel consumption projections contain appreciable uncertainties.

The uncertainties of other major elements of the JPL projections and conclusions are discussed. Some of these uncertainties are errors in projecting the kinds of fuels that will be used in the future, errors in projecting fuel prices, errors in projecting future emission standards, errors in projecting changes in vehicle use patterns, and others. The sensitivity of the study conclusions to possible errors in the projections of vehicle fuel economies was not evaluated.

In many respects the JPL Report appears to be an excellent and valuable piece of work; but the major conclusions that have strong dependence upon highly uncertain fuel economy projections suggest a pyramid precariously perched upon its apex.

A more objective discussion of the JPL Stirling fuel economy and performance data follows.

FUEL ECONOMY AND PERFORMANCE

The conclusions of the JPL Automobile Power System Study are based upon characteristics attributed to "Mature" versions of the engines which were considered. The efficiency of the Mature baseline Otto cycle engine was considered to be 5% better than Present Otto cycle engines, and the efficiences for the Mature Stirling engine were increased 12% over those projected by Philips for the engine currently being installed in the Ford Torino experimental car. JPL concludes that various size class Mature Stirling vehicles will perform Highway and Urban driving cycle tests with fuel consumptions from 27% to 35% lower than those of comparable Mature Otto engine vehicles. If the 5% Otto engine improvement and the 12% Stirling engine improvement were eliminated, the 27% to 35% range for the Stirling-Otto fuel economy comparisons would have been 21% to 30%. It will be seen that the differences between 27/35 and 21/30 are not significant to the results, so the Fuel Economy discussion which follows simply compares present Otto cycle engine performance with the Stirling engine projections.

Data from Chapters 3 and 6 of the JPL Report were compared with data generated for comparable Stirling and Otto cycle vehicles by the General Motors General Purpose Simulation computer program (GPSIM). The following conclusions were reached.

1. The Stirling and Otto engine sizes given in the JPL Report did not give equivalent 0 to 60 mph performances for the Small, Compact, and Large vehicles. In the Small vehicles both the Otto and Stirling engines were too small; and in the Compact and Large vehicles the Stirling engines were too small and the Otto engines too large.

2. In order to have equal performing cars in the Compact and Large size classes where V-8 Otto engines would be used, the Stirling and Otto engines should have about equal maximum power ratings. In the Small cars where an in-line Otto engine might be used, the Otto engine should be about 20% larger than the Stirling.

3. Changing the engine sizes to give equal performing vehicles alters the fuel economy projected for the urban and highway EPA test cycles, but the Stirling still appears to retain an appreciable advantage in fuel economy over the Otto engines. Power-to-weight ratios, rear axle ratios, and vehicle weight all influence the fuel economy

comparison somewhat; but the principal reason for the Stirling advantage is that the Stirling engine map used in both the JPL and GPSIM simulations postulates higher engine efficiencies than do the engine maps used for the Otto engines.

4. The credibilities of the JPL and GPSIM projections for the Stirling engine vehicles are in doubt, because of the omission of known transient engine effects and, more particularly, because these programs project fuel consumptions 21% to 39% lower than Ford/Philips published projections.

GPSIM Simulation Program

This vehicle simulation considers most of the definable components of a vehicle and its powerplant. Engines are represented by performance tables entered into the program, and the accessories, transmissions, drivelines, rear axles, and wheels are described in terms of efficiencies and inertias. Vehicle road load is represented by a typical formula based upon the vehicle weight, frontal area, and drag characteristics. Given accurate data, GPSIM has demonstrated the ability to simulate vehicle operation accurately when compared with carefully controlled road tests.

For the purposes of evaluating the JPL Report findings, studies were made of the Small, Compact, and Large Stirling and Otto-engined vehicles. The Small and Compact cars were represented by Vega-sized vehicles with typical Vega road load, torque converter, and driveline characteristics. The Large vehicles were represented by Impala characteristics. For the Small vehicle Otto engine, the performance map of the 1975 Vega, 140 CID engine with a two-barrel carburetor was scaled to a displacement that would give the desired maximum horsepower. Similarly the 1975 350 CID, two-barrel Chevrolet engine was scaled for the Compact cars; and the 1975, 500 CID, four-barrel, Cadillac engine was scaled for the Large cars. Allowances were made for the usual engine accessories. The Stirling map given as Figure 6-13 and Figure 10-4 of the JPL Report was scaled for all of the Stirling cars. Since Philips has stated that engine accessories were included in this map, no additional allowances were made for Stirling engine accessories.

As in the JPL study, three-speed automatic transmissions were used for all vehicles. The gear ratios were 1.00, 1.52, and 2.52. In the initial evaluation of the JPL cars rear axle ratios giving N/V (Engine rpm/Vehicle mph) ratios from 20 to 60 were examined; but changes resulting from different rear axle ratios do not influence the overall findings of this study, so the data presented here are only for rear axle ratios near 3.0 to be comparable with the ratios used by JPL.

The vehicle maneuvers of interest, a zero to 60 mph maximum power acceleration, the EPA Urban test cycle, and the EPA Highway cycle, were simulated as though the vehicle were running on the road; and the data given here for the EPA Urban cycle are for a hot start test. No effort was made to simulate the cold start condition.

In the zero to 60 mph acceleration maneuver the program selected transmission gear ratios that gave maximum engine power; but in the EPA Urban and Highway tests, the program selected the transmission ratios that gave the maximum engine efficiency.

Study Results

The significant data from the study are given in Table 1. Columns 1 through 5 contain data from the JPL Report for the Mature Stirling and Otto-cycle vehicles. Columns 6 through 10 contain the results of the GPSIM simulation of the JPL vehicles. Columns 11 through 14 contain the data for the JPL vehicles with the engine maximum power ratings changed so that the vehicles gave the 0 to 60 mpg performance postulated by JPL. The vehicle weights were not changed through all of these simulations and remained at the JPL test weights of 300 pounds plus the curb weight.

Comparing Columns 8 and 3 shows that the GPSIM simulation did not verify the performance projected by JPL for the six vehicles. Comparing Columns 9 and 4 shows that the GPSIM Urban fuel economies were generally within two mpg of the JPL projections, but that the GPSIM Stirling economies were always better than JPL Stirling and the GPSIM Otto were always poorer than JPL Otto. Comparison of Columns 10 and 5 shows that the GPSIM Highway fuel economies were poorer than the JPL projections with rather large differences from 4 to nearly 10 miles per gallon.

In the last four columns, the GPSIM engine maximum power outputs have been adjusted in an effort to give actual performance equal to those postulated by JPL in Column 3. Inspection of Column 12 indicates that this was achieved reasonably well; and comparison of Column 11 with Column 2 shows that the Small car needed larger Otto and Stirling engines than those given by JPL; and that the Compact and Large Stirling engines of JPL were too small and that the corresponding Otto engines were too large.

The economy effects of making the vehicles equal performers can be seen by comparing Columns 9 and 10 with Columns 13 and 14, respectively. In order to make equal performance, it was necessary to increase the power output of the Stirling engines in each case and this resulted in a loss of both urban and highway fuel economy amounting to 0.2 to 0.7 miles per gallon. To achieve equal performance, the Otto engine for the Small car was increased in output with losses of 1.5 and 1.3 miles per gallon on the Urban and Highway cycles, respectively. For the Compact and Large cars, the Otto engines were reduced in maximum power with resulting increases in the miles per gallon ranging from 1.2 to 2.3 miles per gallon.

The matter of most interest is the relative fuel consumption of the Stirling and Otto-engine vehicles, and ratios of these values are given in rows D, E, and F of the table. Columns 4 and 5 in rows D, E, and F show that the JPL Report projects Stirling vehicle consumptions from 65% to 83% of the Otto vehicle consumptions. In the same rows, but Columns 13 and 14, it is seen that the equal performing vehicles give somewhat more consistent ratios, but with the Stirling consumption still only 60% to 82% that of the Otto vehicles.

Table 1

		JPL Report Mature Engines					GMR GPSIM Simulation: JPL Power					GMR GPSIM Simulation: Corrected Power			
		Test Weight Lb	Max Hp	0-60 Time Sec	Urb F.E. mpg	Hwy F.E. mpg	N/V	Max Hp	0-60 Time Sec	Urb F.E. mpg	Hwy F.E. mpg	Max Hp	0-60 Time Sec	Urb F.E. mpg	Hwy F.E. mpg
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	Small Stirling	2440	57	17	33.9	47.2	43	55	21.2	35.8	37.4	67	16.0	35.4	36.7
	Small Otto	2400	70	17	25.8	39.0	43	70	19.2	24.8	31.3	82	15.1	23.3	30.0
B	Compact Stirling	3350	99	13.5	26.3	37.0	43	95	14.2	27.9	30.8	100	13.5	27.7	30.4
	Compact Otto	3400	125	13.5	18.3	27.3	43	124	11.1	14.8	18.2	102	14.0	16.7	20.5
C	Large Stirling	5120	177	10.5	17.2	25.8	40	170	11.4	17.9	21.6	182	10.5	17.7	21.2
	Large Otto	5300	230	10.5	11.2	16.8	40	229	8.6	9.7	12.6	188	10.6	10.9	14.0
D	Small $\frac{\text{Otto mpg}}{\text{Stirling mpg}}$				0.76	0.83				0.69	0.83			0.66	0.82
E	Compact $\frac{\text{Otto mpg}}{\text{Stirling mpg}}$				0.69	0.74				0.53	0.59			0.60	0.67
F	Large $\frac{\text{Otto mpg}}{\text{Stirling mpg}}$				0.65	0.65				0.54	0.58			0.61	0.66
G	Small Stirling													29.8%	28.7%
	Small Otto													20.9%	24.6%
H	Compact Stirling													28.6%	27.0%
	Compact Otto													17.5%	19.3%
I	Large Stirling													29.1%	27.7%
	Large Otto													17.0%	18.6%

The final data in rows G, H, and I identify the basic reason for the Stirling fuel economies appearing better than the Otto. The data in Columns 13 and 14 of rows, G, H, and I are the effective overall efficiencies of the engines in the respective vehicles during the urban and highway simulations. It is seen that the Stirling engine was considered to have been operating at a higher efficiency than the Otto in each instance. Thus, the better fuel economies that this study and the JPL study show for the Stirling are principally the result of postulating a higher efficiency for the Stirling engine in the performance maps that were used as bases of the simulations.

Credibility - Engine Size

The JPL Report explained the use of smaller engines in the Stirling vehicles by saying that the Stirling engine had a "fatter" speed-power curve when "Per Cent Power" was plotted against "Per Cent Speed." Figure 10-1 of the JPL Report gives data pertaining to this observation, and Table 2 below shows the comparison between the Stirling and Otto engines provided by the respective curves of the JPL figure.

Table 2
(After Figure 10-1; JPL Report)

Per Cent Speed	Otto Engine Per Cent Power	Stirling Engine Per Cent Power	Stirling % Power / Otto % Power
20	22.6	30.8	1.36
40	52.7	63.0	1.20
60	80.5	86.3	1.07
80	97.3	98.6	1.01
100	100.0	100.0	1.00

In a maximum power acceleration like the 0 to 60 mph maneuver, the engines are operating near the top end of the power-speed curves most of the time. For example, with the GPSIM cars that had engines sized to perform that maneuver in the times specified by JPL (Columns 11 to 14, Table 1), all except the Small car Otto engine were above 75% power after the first second. The Small Otto had reached nearly 50% power at the one second time interval and both the Compact Stirling and Compact Otto had reached 85% power in this time. Thus well over 90% of the time in the maneuver was spent at speeds where the engines produced more than 80% of their maximum power.

Returning now to Table 2 and the JPL observation that this Stirling power-speed characteristic allows the use of a smaller Stirling engine. The JPL data show that their Stirling and Otto engines perform at nearly identical portions of their full power capabilities at all points above about 70% power. Thus in the regime of engine operation in the performance maneuver, the JPL data show the Stirling and Otto engines to have nearly equal characteristics. These JPL data thus do not support the JPL contention that smaller Stirlings can give performance equal to the Otto engines.

With the engines used in the GPSIM simulation, the 500 CID Otto engine and the Stirling engine have the same full load power-speed characteristic up to about 80% power after which the Otto rises above the Stirling until the Otto peaks at about 75% of maximum speed. The 350 CID Otto engine is about 10% below the Stirling power-speed curve until they become equal near 75% power with the Otto then rising above the Stirling to peak at about 80% of maximum speed. The small 140 CID Otto engine is about 20% below the Stirling up to about 70% speed, and the curves converge with full power for both engines at full speed. These engine characteristics are clearly reflected in the engine sizes shown for equal performance in Table 1, Column 11.

In this context of comparative engine sizes between the Stirling and Otto, it is also interesting to note that the Ford/Philips experimental program has replaced a 161 horsepower Otto engine with a nearly equal 170 horsepower Stirling engine to obtain equal performance in approximately equal weight vehicles (JPL Reference 6-6). This relationship of equal maximum power ratings for equal performance from Stirling and Otto cycle V-8's also tends to agree with the GPSIM conclusions for the equal performing Large and Compact cars.

Credibility - Fuel Economy

Upon first examination the credibility of the JPL conclusions about the superior fuel economy of Stirling vehicles in comparison with Otto vehicles was suspect, because JPL provided much lower power-to-weight ratios for the Stirling vehicles than for the Otto vehicles while postulating equivalent performance. The discussions given above show that GMR would prefer to tend toward the evident Ford/Philips conclusion that approximately "equipotent" engines are needed in similar sized vehicles for equal performance.

The original conclusions of the JPL Report and of the GMR GPSIM study both show substantial fuel economy advantages for the Stirling. This is a direct consequence of the fact that both studies were based upon the same postulated performance for the Stirling engine. However, the Stirling advantages appear so large that they transcend smaller effects like power-to-weight ratios, transmission shift points, and other inadequacies in the use of simulations for estimating vehicle fuel economies. The main item influencing the credibility of the findings is whether or not the steady state Stirling performance map can be used in the manner of the "VEEP" or GPSIM simulations to estimate transient performance in the environment of the vehicle.

Ford and Philips have, in effect, undertaken to make an assessment of this matter by constructing a Stirling vehicle for test purposes, and the definitive answer will not be known until a properly-built vehicle has been tested. However, there are some matters which bear consideration in the meantime.

While it is presented as an analytical projection, and not as test data, the Philips performance map is probably an acceptably close approximation of how the Stirling engine with its accessories would operate at steady state and at the temperature conditions for which the map was drawn.

The most serious deficiency of the GPSIM and VEEP vehicle simulations is that the engine cooling system is not considered. The Philips performance map was made for an ambient temperature of 100°F (JPL Reference 6-40), and some temperature difference was probably allowed between the engine cooling water and the ambient to provide for operation of a radiator system. However, Stirling engines reject about twice as much heat to the cooling water as do Otto engines and a passenger car would be severely cramped for space in which to install the larger capacity cooling system required by this added heat rejection. Otto cycle engines in vehicles typically operate with the radiator coolant more than 100°F above the ambient, and the radiator space available is matched to the Otto cooling load with these high water temperatures. If the cooling water temperature of the Stirling engine were increased 100°F above that for which the performance map was drawn the efficiency advantage of the Stirling (rows G, H, I of Table 1) would be nearly halved.

Another transient phenomenon which should be considered in the simulation is the operation of the Stirling controls. The pressure level control to regulate power is probably the most important of these. As stated in the JPL Report the mass of working gas in the engine must be changed to effect a steady state change of power. It has been demonstrated that power changes can be effected rapidly enough to give rapid response of the engine torque, but pumping of the gas during transients requires some engine power. This pumping power is expected to have less than a 5% effect on fuel consumption on the Urban driving cycle; but an accurate simulation should include consideration of this pressure control system.

The fuel and temperature controls can likewise introduce distortions during transients that will make the engine perform differently than it does in steady state conditions. Because of the relatively high heat capacity of the combustion system and the heater assembly, these effects are smoothed for short transients; but the requirements for combustion blower power and the effects of heater temperatures which vary from those of the steady state performance map should be considered. A 100°F drop in heater temperature would reduce the efficiency advantage of Table 1 by about 25%.

It is conceivable, indeed probable, that Philips has simulated the operation of their engine in a vehicle giving consideration to the above effects as well as to others which may require attention. On the supposition that a Philips vehicle simulation would be more accurate than the GPSIM or the JPL VEEP simulation, some fuel economies were projected with GPSIM for a vehicle like the Ford Torino for which Philips have published projected performance and fuel economy figures (JPL Reference 6-6). The performance and fuel economy results are given in Table 3.

Table 3

	GMR GPSIM	Ford/Philips
Test Weight	4841	4541
0-60 mph, seconds	11.4	11.1
Urban Test, mpg	18.7	11.4
Highway Test, mpg	22.7	17.9

While the vehicle weights are slightly different, it is seen that the performance predictions agree very well. However, the fuel economy data give little support to the credibility of the GPSIM simulation which, it should be recalled, gives results similar to those of the JPL "VEEP" simulation.

ATTACHMENT 4

GAS TURBINE ENGINE COMMENTS

The recommendations of the JPL report that the development effort on Brayton cycle powerplants be increased greatly is based on the lower fuel consumption projected for the mature Brayton powered vehicles compared to the mature Otto engined vehicles.

The projected fuel consumption of the mature Brayton-engined vehicles depends on projected component efficiencies, the proposed engine operational modes, and advantageous speed + power characteristics of the engines which result in lower power to weight ratios for the same vehicle performance.

The projected efficiencies are higher than those measured on GM component test rigs today but they represent target efficiencies that we believe to be attainable with diligent effort. The effectiveness of the regenerator for the mature engine is attainable, based on demonstrated ceramic (Cercor(R)) matrix data but GM computations indicate the size of the component would be at least 50% larger than indicated in the JPL analysis. Furthermore, it has been our experience that the theoretical increase in effectiveness at part load is not fully attained in practice. Continued material development is required to attain the necessary thermal and chemical stability of this component. The GM gas-turbine design-point cycle-analysis program, using the mature-engine component efficiencies and losses confirms the design point thermal efficiency indicated in Figure 5-5 of the JPL Report.

Both the engine performance and the operating modes of the JPL Brayton engines are based on earlier work by AiResearch (1). The operating mode for the mature free-turbine engine results in a very flat curve of minimum bsfc vs. power which can be deduced from Fig. 5-5. At 15% of design point power the bsfc is only 12% higher than at design point. This characteristic is much flatter than that of current GM turbine engine designs. There are three separate but compatible operating modes for achieving these results. At high power levels (100% to 80% power) the engine is operated as a fixed geometry engine, i.e., gasifier speed determines power level and turbine-inlet temperature decreases with power and gasifier speed. In the mid-power range (80% to 35% power) the variable power turbine nozzles are used to maintain constant turbine-inlet temperature and power decreases as gasifier speed is decreased. In the low power range (35% to idle power) the gasifier speed is held constant at about 73% speed and engine airflow and output power are controlled by variable compressor inlet guide vanes (VIGV). The engine flow with the VIGV set to their minimum flow position is reduced 50% compared to the flow with zero guide-vane effect. In this third mode of operation, thermal efficiency is sacrificed in order to reduce the engine response time. Because of its excellent torque/speed characteristics, the free-shaft turbine can use a 3-speed automatic transmission.

The operating mode of the single shaft gas turbine also comprises three phases. Both engine speed and turbine inlet temperature are reduced as power is reduced from 100% (used for acceleration) to 75%. From 75% to about 10% power, turbine inlet temperature is held constant, as is VIGV setting as engine speed is reduced to 55% of design. From 10% to idle power, speed is held constant and the engine airflow is reduced by means of the VIGV. Idle fuel flow is projected to approach 6 to 7% of max fuel flow. Because of its unique torque speed characteristics the single-shaft engine requires a continuously variable transmission. While a variable-stator type is recommended for control purposes, the efficiency characteristics of a hydromechanical type were used for the JPL analysis of the single-shaft turbine.

The GM gas-turbine part-load cycle-analysis program was run with component performance suggested by AiResearch (1) and the minimum bsfc vs. hp charateristic was calculated for the free-turbine engine. The results of these calculations appear in Figure 1 and are compared with those inferred from Figs. 5-4 and 5-5 of the JPL report. The GM part-load computation shows approximately 10% higher bsfc than the mature JPL free-turbine engine with inlet guide vanes. The variation of compressor characteristics with inlet guide vane setting that we assumed reduces power and raises bsfc more at the low power end than JPL indicates. Internal tests of inlet guide vanes on a GM compressor indicate that these effects should be even more deleterious than we assumed for this calculation. Our experience indicates that bsfc levels predicted by part-load cycle analyses are not fully achieved in hardware, especially at very low power.

The part-load fuel consumption projected for the upgraded Chrysler engine (2) being developed under ERDA contract is 20% higher than that projected by JPL. The upgraded Chrysler-designed engine incorporates advanced compressors and turbines developed with NASA assistance, as well as inlet guide-vane flow control.

The power to weight ratio required to attain the performance targets of 440 feet in 10 seconds and 0 to 60 miles per hour in 13.5 seconds with the AiResearch single-shaft engine has been analyzed by several investigators. Bowlin of Mechanical Technology Incorporated (3) showed that with a continuously variable transmission (CVT) of the hydromechanical type, a power to weight ratio (hp/100 lbm) of 3.5 would provide the desired performance in a 4200 lbm curb weight vehicle. Fuel economy on the urban Federal Driving Cycle (FDC) was 14.5 mpg with air conditioning. Cordner and Grim (4) investigated both hydromechanical and traction type CVTs for the same engine and the same size vehicle. They found that a power to weight ratio of 3.5 with the hydromechanical transmission would meet the performance targets and provide a FDC fuel economy of 12.9 mpg. A power to weight ratio of 3.7 was required with the traction drive CVT which resulted in a FDC fuel economy of 12.0 mpg. The JPL report proposes that a power to weight ratio of 3.6 in a large (4220 lbm) car would exceed the EPA performance spec for distance in 10 seconds (440 ft) by 60 ft and would provide FDC fuel economy of 15.8 mpg. In the studies by Bowlin (3) and Cordner and Grim (4) the effect of engine inertia was taken into consideration. The significant performance increase of the large vehicle would indicate that the inertia effect was not fully considered in the JPL analysis.

The power-to-weight ratios suggested by JPL in table 5-10 (Vol. II) are below the ranges calculated by GMR for free-turbine engines having a response time of 0.85 second needed to meet the ten-second distance requirement. GM experience with free-turbine engined vehicles has indicated that they require the same power-to-weight ratio as conventionally powered vehicles for the same performance. In addition, GMR calculations indicate that single-shaft engines starting from 50% idle would require higher installed power than a free-turbine engine to provide performance matching that of conventional vehicles (5).

In summary, we believe that the JPL mature-engine design-point efficiencies may be attainable but the predicted engine part-load efficiencies are optimistic by over 10%. Approaching these efficiencies will require diligent efforts to improve component efficiencies to the projected values. The gas turbine vehicle fuel economies projected by JPL are optimistic because of optimistic part load bsfc and low power to weight ratios predicted for meeting the performance targets. Other investigators have projected fuel economy figures for both single and free-shaft turbine powered vehicles with less performance that were as much as 20% poorer than the JPL projected mature Brayton vehicles.

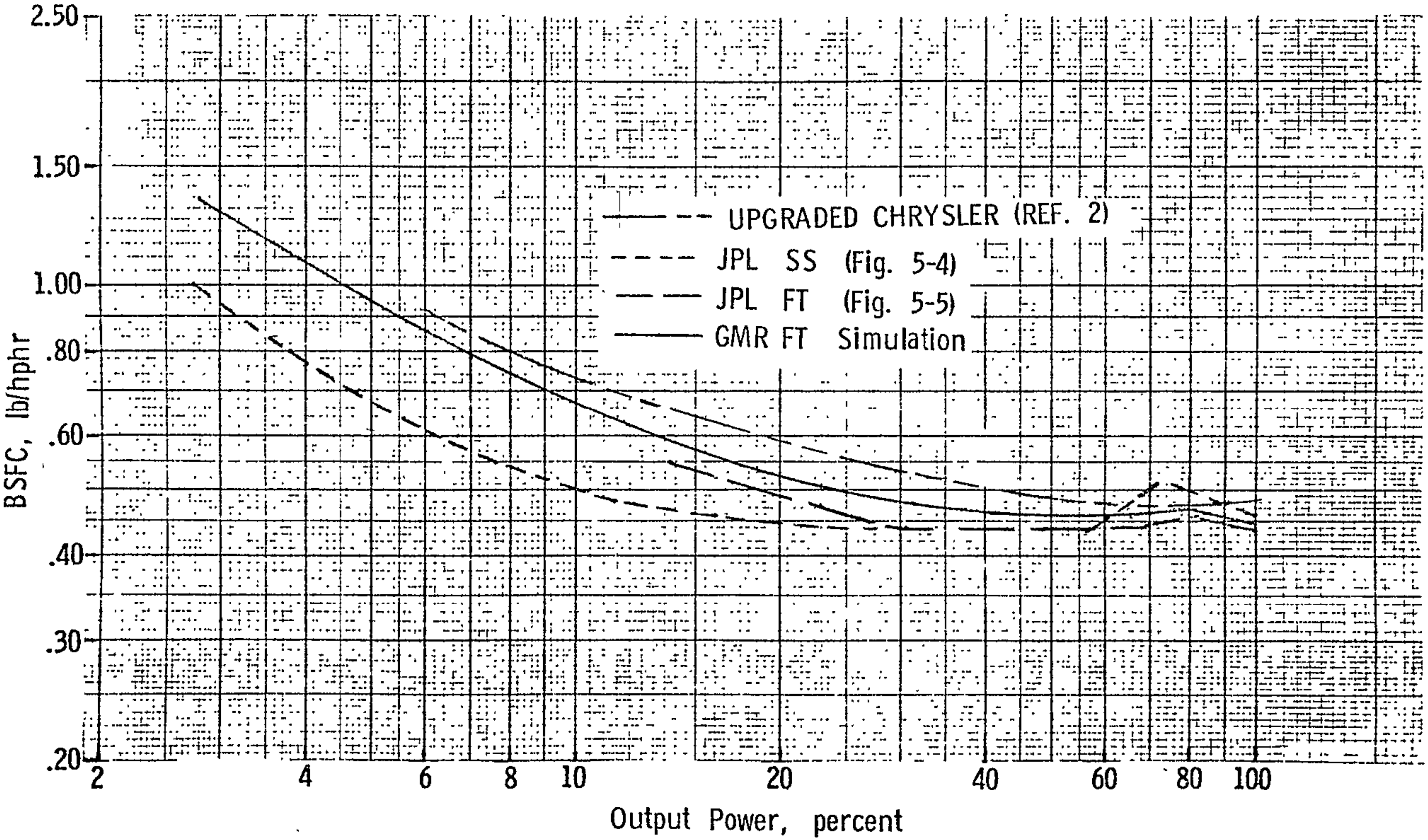
(1) "Automotive Gas Turbine Optimization Study", AiResearch Manufacturing Company of Arizona, EPA Report AT-6100-R7, 1972.

(2) Schmid, F. W., and Wagner, C. E., "Tenth Quarterly Progress Report, Baseline Gas Turbine Development Program, Contract No. 68-01-0459", April 30, 1975.

(3) Bowlin, R. C., "Transmission for Advanced Automotive Single-Shaft Gas Turbine and Turbo-Rankine Engine", USEPA Report APTD-1517, 1973.

(4) Cordner, M. A., and Grim, D. H., "Transmission Study for Turbine and Rankine Cycle Engines", USEPA Report APTD-1558, 1972.

(5) Liddle, S. G., Sheridan, D. C., and Amann, C. A., "Acceleration of a Passenger Car Powered by a Fixed-Geometry Single-Shaft Gas Turbine Engine," SAE Paper No. 720758, September 11-14, 1972.



UPGRADED CHRYSLER (REF. 2)
JPL SS (Fig. 5-4)
JPL FT (Fig. 5-5)
GMR FT Simulation
BSFC, lb/hphr
2.50
1.50
1.00
.80
.60
.40
.30
.20
2
4
6
8
10
20
40
60
80
100
Output Power, percent

ATTACHMENT 5

TRANSMISSION SELECTION COMMENTS

An important feature which analysis has shown to benefit the fuel economy of the mature Uniform Charge (UC) Otto engine baseline vehicle was not considered in the fuel economy comparison with Otto Engine Equivalent Vehicles of the JPL report. Beachley and Frank* of the University of Wisconsin investigated the effect of a toroidal (traction-drive) transmission on vehicle performance and economy. They found that the engine size for a specific performance objective (time and distance for a 50 to 70 mph accel) could be reduced 11 to 20%. In addition, fuel economy on the Federal Driving Cycle increased 18% to 28% for the two cars considered.

Beachley and Frank point out that these projections must be used with caution since the benefits may not be fully realized in practice. However, since the JPL study recommendations are based on computer modeled engines and transmissions, the application of a computer modeled transmission on the mature Uniform-Charge Otto engined vehicle (baseline) seems justifiable.

The JPL investigators did consider the work of Beachley and Frank (JPL reference 10-29). In section VIB of the Summary (Volume I), the CV transmission is proposed as a "longer term" (probably producible by 1985) vehicle improvement. They project improved composite fuel consumption of 10 to 15% (increasing with car size). However, the baseline vehicle used for the fuel economy comparison of Section VIIB of the JPL Summary (Fig. 13 and Table 5) does not have the benefit of the CVT. If the JPL estimates of fuel economy improvement with a CVT (which are more conservative than those projected by Beachley and Frank) were applied to the UC Otto (baseline) vehicles, the fuel economy advantage of the free-turbine Brayton would disappear and the advantage of the single-shaft Brayton would be reduced to a level where the accuracy of the computed turbine economy could not justify claiming a significant advantage.

* Beachley, N. H., and Frank, A. A., "Increased Fuel Economy in Trans portation Systems by Use of Energy Management. Volume I - General Results and Discussion," Report DOT-TST-75-2, 1974.

ATTACHMENT 6

FINANCIAL ESTIMATES

Ability to develop detailed comments on the financial information contained in the JPL Report is somewhat limited due to lack of specific definition of many of the assumptions and application of methodology within the report. Extensive time would be required to study those items, when defined, as well as to evaluate how modification in these assumptions and application of methodology would change the conclusions. Therefore, it is not possible to make a comprehensive critique of the financial evaluation processes used by JPL. However, a few major areas of the financial considerations of this study do merit general comment, as follows:

1. The JPL Cost Findings Summary (11.5.3, Item 6) states that a vehicle with a Brayton or Stirling engine will cost about 10% more than a vehicle of equivalent performance with an Otto cycle engine.

   Comment - GM's most recent estimates (early 1974) on the turbine engine indicate considerably greater cost penalty over the conventional engine. For sake of discussion, even the impact of the 10% increase is significant as evidenced by the resulting adverse consumer resistance to our recent 1975 vehicle price increases of about 8%. New engines would have to compete with the conventional engine at at least a 10% first cost penalty. Recent experience would indicate that this could be prohibitive unless significant consumer value could be demonstrated.

   One of the critical assumptions in this type of analysis is that an alternate engine can, because of improved fuel economy, be sold at a premium that would provide the necessary revenue to provide for development and facilities investments. This is an assumption that can and should be tested in the marketplace. It is a question of the extent to which two cars that are identical in all respects except that they are different power plants, can have different prices and survive in a competitive market. If an individual firm were to test the validity of this assumption in the marketplace, it must be recognized that there would be substantial financial, technological and market risk, with great potential for substantial losses. It is not apparent that these risks and uncertainties were incorporated into the JPL financial analysis in such a manner as to make a marketplace-oriented evaluation of the "potential for increased profits". This is required to warrant the level and timing of expenditures estimated in the Report. Since the financial analysis has not fully addressed the inherent technological and economic risks, the Report as a result infers a degree of predictability that does not appear justified as a basis for making public policy decisions.

2. The methodology to JPL's discussion (11.2) states, "A key assumption is that the R & D program has been successfully completed and a production prototype engine is in hand." This is indeed a key assumption since this assumes that this configuration will be available several years from now. Many outside factors, political, economic, etc. may significantly influence these estimates. This type of assumption is very important in evaluating whether or not to commit massive expenditures for both capital facilities and research talent exclusively toward an unproven goal, based on cost estimates for 10 years in the future. In addition, these cost estimates are predicted on the fact that there will be adequate material, technical and capital resources available. The availability of these items is not clearly demonstrated in the Report in such a manner to justify the risk of the future health of the auto industry and the Nation's economy.

3. Following are a few other assumptions, included in the statistical data of the Report, with which we are concerned as to their validity and their impact on the overall study conclusions:

    a. Overhead expense is assumed to be the same for all studied engines regardless of production configuration or support requirements.

    b. The general relationship of engine cost as a function of horsepower appears to be a gross oversimplification. Our experience definitely does not substantiate that engine costs vary directly with horsepower.

In general, we are very concerned with the validity of a number of key assumptions included in the Report, and therefore their impact on the conclusions. A much clearer definition of the extent of these assumptions and their potential impact on the conclusions must be completed, in order to remove the extensive doubt of the validity of the conclusions. Of major importance in this area is the necessity to adequately comprehend and evaluate the risk involved in all of the assumptions.

ATTACHMENT 7

MANUFACTURABILITY AND MATERIALS

Only a very limited discussion of manufacturability is included in the JPL Report. For example, Chapter 11 on Manufacturability and Costs contains practically no information on manufacturability considerations -- mainly it is devoted to cost information. Manufacturing and production considerations are very important, and could have serious impacts on material and process availability as well as on production costs.

For example, machining rate comparisons on components for all but the Brayton engine are based on using high speed tooling, whereas carbide tooling is applied to the Brayton estimates. A significant amount of carbide tooling is already being utilized for engine machining, which therefore was not comprehended in the cost comparison.

Other sections of the Report emphasize the necessity of developing ceramic technology for the Brayton and Stirling engines, but practically no attention is given to the necessity to develop manufacturing techniques for these ceramic components. This type of cursory analysis of the manufacturability of the components proposed, and the manufacturing processes which might need to be developed, contributes to the overly-optimistic conclusions of the Report.

The information included in the Report concerning availability of materials concentrates on nickel, chromium, cobalt and tungsten. It appears to be handled quite effectively. However, since the future engines proposed are heavily dependent on ceramics, more attention should be given to the selection of ceramic materials and to the development of reliable and usable sources.

ATTACHMENT 8

CONCLUSIONS FROM 21 CONTEMPORARY ALTERNATE POWER PLANT STUDIES

There have been a large number of studies made within the last few years by various groups, concerning alternative automotive power plants. One measure of the value of the JPL report, then, can be judged by a comparison of the various conclusions. Such a comparison, from 21 different studies, is attached.

It is readily apparent from a review of these conclusions that even though the various study groups used essentially the same set of facts, the studies reached quite different conclusions with respect to the potential of the various power plants. It is remarkable that such a wide disagreement exists. According to these studies, the best alternate engine for the future ranges from steam, to a gas turbine, to a fuel injected, stratified, turbo-charged rotary engine. Since all of these studies are generally evaluating the same technology, these differences in conclusions clearly point out the considerable uncertainty in forecasting future engine development.

Many of the differences relate to a marked over-optimism with regard to technological advances which are predicted to occur during the next few years. If the results of these reports are to be utilized by policy makers, the studies need to clearly define the amount of time and effort required to solve the problems based on some supportable information on which technological advances can reasonably be expected to occur.

Such studies, in order to reasonably reflect projections that are probable, as well as possible to achieve should maintain a strong sensitivity to the free market choice. Otherwise, selection of the characteristics of the transportation system will not be responsive to the public interest. Past history has demonstrated that the free market, if allowed to operate, will select future automotive power plants by trial and error, or survival of the fittest, a ruthless optimizer.

Such reports as the JPL Report are certainly worthwhile to describe the state of the art in automotive power plants, but projections into the future need to be strongly tempered by the associated uncertainties and risks involved.

CONCLUSIONS QUOTED ARE ARRANGED UNDER THE FOLLOWING HEADINGS:

<u>GENERAL</u>

<u>GAS TURBINE</u>

<u>STIRLING</u>

<u>STRATIFIED-CHARGE</u>

<u>DIESEL</u>

<u>ROTARY</u>

<u>RANKINE OR STEAM</u>

<u>ELECTRIC</u>

<u>MISCELLANEOUS</u>

Hybrid

Lean Burn

Warren Engine

(Bibliography is shown at rear of section)

GENERAL

JPL	vol. I. p. v par. 4	"...the safest prediction...[is] that the engine powering our cars in the future will be an improved version of the conventional Otto cycle engine. ...the final outcome will depend on the actions of ...ultimately, the auto-buying public."
	vol. I. p. vi par. 2	"Our study...involved...analytical extrapolations of engine and vehicle performance into the future. This ...step was of critical importance. Many of the engines currently undergoing tests are deficient in one or more areas...and are not ready for widespread introduction. Fortunately, the time frame of the study allows up to 10 years of research and development (R&D), through which much can be accomplished."
BJERK-LIE	p. 4 par. 1	"...the real competitor against which all candidate alternative power plants must be matched--the spark ignition, gasoline powered, Otto cycle engine...meets all of the above requirements except emissions."
	p. 5 par. 1	"...spark-ignition engines with much improved combustion, diesel engines with improved combustion and an approach to lightweight design...gas turbines with improved combustion and high temperature materials, and Stirling engines with high temperature materials are the potential automobile heat engines of the future...."
NAS PANEL 1974	p. 4 par. 1	"The current status of development of alternative, non-internal-combustion engines is such that at least another generation of development will be required before any of these will have reached the stage of being considered a suitable prototype for manufacture.... that 1982 is the earliest one of the alternate engines, the gas turbine, would be ready for limited production, and even then only if several technological advances are achieved."
AERO-SPACE	p. S-50	see attachment, Figure S-18
NAS PANEL 1974	p. 213	see attachment, Figure 12.3
STERN-LICHT	p. 22 par. 7	"...the reciprocating piston engine will remain dominant at the turn of the century. However, it will probably change from internal to external combustion...."
HITT.	p. 104 par. 3	"Government funding of external combustion systems should receive low priority."

*Bibliography at rear of section.

GENERAL continued...

HITT.	p. 46 par. 3	"If one were to poll a group of experts to decide which advanced propulsion system would emerge as the replacement for the ICE after 1976, it is nearly certain that the conclusions would not converge. ...reviewers' comments of our draft final report reveals that these choices are still the greatest area of controversy."
MIT	p. 32 par. 4	"We have therefore concluded that whether the optimum powerplant for the last two decades of this century will be the ICE, an alternative, or whether it will even be a single system for all passenger cars, cannot now be confidently forecasted."
EATON	p. 17	"The overall conclusion...is that there still is considerable uncertainty as to the choice and rate of commercialization of specific engines,...."
AERO-SPACE	p. S-53 par. 3	"At this time no alternative engine development appears to have progressed to a point where sufficient data are available to substantiate any claim of superiority over other engines."
NAS PANEL 1974	p. 211 par. (8)	"None of the alternative heat engines have been shown conclusively to have a suitable cost structure for use in conventional automobiles."
BJERK-LIE	p. 4 par. 2	"Admitting the various alternative power plants into the system in limited quantities as they are each brought near to economic viability can sift out the viable alternatives over the next 15 to 30 years.... More rapid conversion is not a real possibility.... Nor is it a real possibility that a single alternative power plant will be adopted by the system."
AYRES	p. 219	"...it seems that the industry has a very strong incentive to obtain the widest possible consensus on the optimum technological choice prior to undertaking any major investment commitments."
	p. 220	"...it is not suggested that a government mandate of a specific technology is desirable."

GENERAL continued...

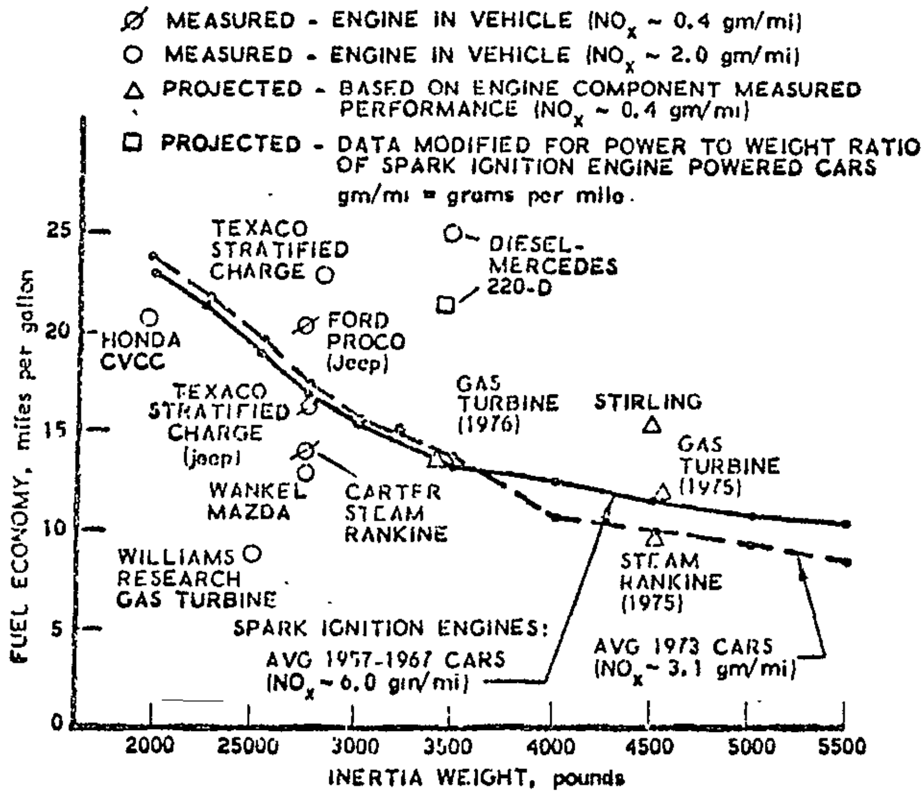


Figure S-18. Fuel Economy Over the Federal Emissions Test Driving Cycle

(AEROSPACE) S-50

(NAS PANEL 1974)

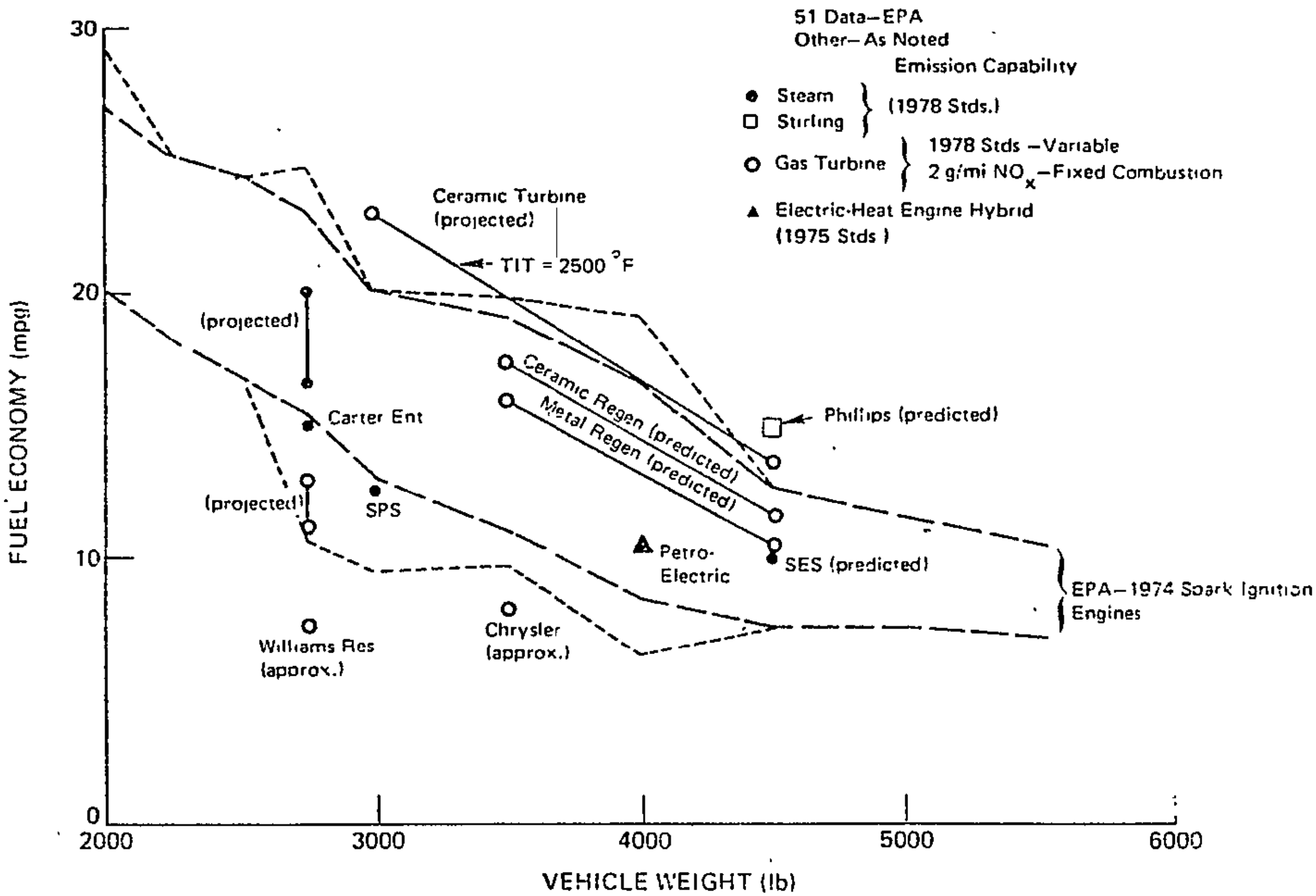


FIGURE 12.3 Fuel Economy - Alternative Engines. All Data Are Measured Except: Predicted from Dynamometer and Projected from Extrapolation.

GAS TURBINE

JPL	vol. I. p. 76 2.	"Mature Brayton fuel economy will be second only to that of the Stirling....Braytons also offer very low emissions, low scheduled maintenance, and fuels adaptability. They are the lowest in cost of the continuous-combustion powerplants. Hence, they are also leading candidates for introduction in the next decade. Insufficient data are available to decide between the 'single-shaft' and 'free-turbine'...."
	vol. I. p. 61 par. 5	"A significant observation is the small cost differential for a Mature single-shaft Brayton power system (engine plus CV transmission) which, within the uncertainties of the analysis, may be considered manufacturing-cost-competitive with the baseline...Otto."
HITT.	p. 38 par. 1	".... It is estimated that a 150-hp gas-turbine power system including transmission will cost approximately $2220 compared to $910 for an ICE of similar power."
	p. 103 par. 6	"Both capital and labor requirements are more than twice those projected for the baseline ICE. The initial price of the gas-turbine vehicle is $800 more than a comparable advanced Otto cycle car and its marketplace acceptability must be questioned."
WmRES.	p. 1-1/1-2 par. 4	"The results of this analysis indicate that the net cost of ownership of gas turbine powered automobiles should be substantially lower than current and future internal combustion, piston engine powered passenger cars."
AERO-SPACE	p. H-2 par. 4	"GAS TURBINE ENGINES...Estimated High production costs continue to be a major factor inhibiting the implementation of the automotive gas turbine engine."
RAND	p. 7 par. 2 Ex.Sum.	"Neither the gas turbine nor the Rankine ("steam") cycle engine appear to offer as good fuel economy or cost reduction,..."
NAS PANEL 1973	p. 60	"Within this decade the automobile gas turbine of over 150 HP has a good probability of substantially matching or bettering the spark-ignition engine in first cost, running costs, emissions, reliability, driveability, and maintenance."

GAS TURBINE continued...

AYRES p. 220 Tab. I

	OC-Engine Case OC-70	OC(2)	Standard Turbine Engine Case RFT(4)
Fuel economy (mpg)	11.4	9.1	12.4

OC-70 - Otto Cycle 1970

OC(2) - OC-70 plus Exhaust Gas Recirculator, plus Dual Catalytic Convertor and miscellaneous

RFT(4)- Regenerative Free Turbine with ceramic burner parts, with a stainless steel regenerator

HITT. P. 103 par. 4 ".... The gas-turbine system....suffers from a fuel economy penalty (25 percent increase over the ICE by the year 2000)...."

MIT p. 27 par. 2 "The major problem areas [of the turbine] are:

* Part-load fuel economy--a major problem with metallic components, a lesser problem with ceramic components.
* High manufacturing costs...."

RAND p. 40 3rd dot "The Rankine engine appears to offer somewhat better fuel economy than the gas turbine...."

AERO-SPACE p. H-2 par. 5 "While demonstrated fuel economy is low for gas turbine engine-powered cars (about eight to nine miles per gallon for an intermediate-size car over the Federal Emissions Test Driving Cycle), it is estimated that fuel economy for improved engines will rise to about 12 miles per gallon and be competitive with that of current spark ignition engine-powered cars."

p. H-2 par. 6 "In the future, if ceramic turbines are developed, a substantial rise in turbine operating temperature will be possible, leading to a significant reduction in fuel consumption."

UNAIR CRAFT p. 2 par. 6 "...the simple-cycle engine is predicted to fall short of the EPA goal of 10 miles per gallon over the Federal Driving Cycle,...."

GAS TURBINE continued...

NAS PANEL 1973	p. 51	"The...single-shaft...gas turbine...engine...can give good full-load specific fuel consumption. However, the part-load, part-speed performance of high-pressure-ratio compressors is very poor, and essentially rules this engine out of consideration for automobiles...."
RAND	p. 40 4th dot	"...compared with other types of gas turbines, a free turbine system offers the greatest fuel economy, ..."
UNAIR-CRAFT	p. 4 par. 1.	"...the simple-cycle, single-shaft engine...is clearly the best solution for a low-emissions automobile power-plant, this engine offering the highest probability of meeting all systems requirements, including low cost, low pollution, and satisfactory fuel economy."
	p. 2 par. 2.	"The single-shaft simple-cycle gas turbine has the best potential of meeting the 1976 [1978] Federal NO_x emission standards but careful combustor development is required to establish the fact."
	par. 3.	"The single-shaft engines...require an advance in transmission capability to provide adequate driving characteristics."
BJERK-LIE	p. 9 par. 3	"In the last few years, there has been increased study of[18] and acceptance of the single-shaft gas-turbine concept[3,10] ....However, some form of infinitely variable transmission is required...none has yet been demonstrated with a single-shaft gas turbine."

[3] GM [10] Ford [18] GM

GE	p. 2 par. 4	"The single-shaft engine...with the regenerator bypass for the primary combustor air was recommended for the advanced automobile gas turbine engine...."
AiRES.	p. 1-2 par. 4	"...a relatively low pressure ratio, single-shaft engine with regeneration (either a fixed-boundary recuperator or a rotary regenerator, driving the vehicle through an infinitely variable speed-ratio traction transmission) is the system most capable of meeting or exceeding the optimization criteria."

GAS TURBINE continued...

NAS PANEL 1973	p. 58	"The proponents of the use of single-shaft gas turbines have claimed that the elimination of a separate power turbine and its bearings will result in a substantial cost saving, while an infinitely variable transmission can be developed which will cost no more, and perhaps less, than existing automobile automatic transmissions. Such claims have been met with some skepticism, but they are not beyond possibility."
NAS PANEL 1973	p. 56	"There seems to be an excellent chance that the static [ceramic] parts of experimental gas turbines will be successfully tested by 1974, and perhaps [ceramic] turbine rotors by 1978."
BJERK-LIE	p. 11 par. 1	"The design of gas turbines for the high inlet temperatures required to achieve competitiveness with gasoline engines is a new science that is some years away from maturity...There is no established certainty that any of these methods of utilizing high turbine-inlet temperatures can be developed for a low-cost engine. ...the potential performance gains associated with higher turbine inlet temperatures could be dissipated by increased viscous losses due to the reduced Reynolds numbers.[24]" [24] VW
	par. 2	"The use of ceramic rotary regenerators has encountered serious problems."
NAS PANEL 1973	p. 8	"Those candidates that appear to merit earliest consideration are as follows: Diesel.... Advanced diesel.... Advanced gas turbine.... Advanced Stirling.... Advanced battery...."
STERN-LICHT	p. 22 par. 6	"The author does not believe that the Wankel, Rankine, or the gas turbine are likely to become automotive power plants with impact by the year 2000."

GAS TURBINE continued...

EATON p. 17 "Turbine engines have greater long range potential in both cars and heavy duty applications and the Stirling engine probably even greater potential."

[illegible]RK-LIE p. 9 par. 1 "The most significant change in the outlook for the gas turbine over the last five years results from the general agreement among U. S. manufacturers[3,10,11,12] that it can be a technically superior engine to the spark-ignition engine at least down to 75kw (100 hp), and probably to 55kw (75 hp)."

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[3] GM [10] Ford [11] Chrysler [12] Williams Research

STIRLING

JPL	vol. I. p. 76 1.	"The Stirling powerplant offers the lowest fuel consumption of all the Mature alternates, low emissions, and fuel adaptability. These characteristics, coupled with its long-range potential, make it a primary candidate for introduction in the 1980's."
BJERK-LIE	p. 15 par. 3	"The Stirling engine must still be regarded as an experimental engine for automobiles."
EATON	p. 17	"Turbine engines have greater long range potential in both cars and heavy duty applications and the Stirling engine probably even greater potential."
NAS PANEL 1973	p. 8	"Those candidates that appear to merit earliest consideration are as follows: Diesel.... Advanced diesel.... Advanced gas turbine.... Advanced Stirling.... Advanced battery...."
STERN-LICHT	p. 22 par. 5	"The Stirling engine is the most likely candidate, although the diesel or the Warren engine show considerable promise at this time."
BJERK-LIE	p. 15 par. 1	"What is now apparent for Stirling engines is that by modifying the efficiency slightly an engine of appropriate power for an existing automobile can be of low enough weight and size to be acceptable."
NAS PANEL 1973	p. 108	"The engineering problems remaining to be solved before it [the Stirling engine] could be adopted as a practical engine for limited application relate to the reliability of the heater assembly, sealing of the working fluid, and to the development of a simple, versatile power-output-control system. Considerably more engineering is necessary before the engine can be considered a suitable automobile power plant." "Of the alternative heat engines potentially suitable for automobiles, the Stirling engine can have the fewest limitations in all-around future applications, but it is the least well developed and will require the longest to develop at the existing rate."

STIRLING continued...

NAS PANEL 1973	p. 117	"If Stirling engine development were to cease, the existing engines would not be good candidates now for automobiles. However, the amount of improvement possible by a more generalized approach than heretofore taken is great in terms of increased reliability and lower cost. It is this possibility that makes the Stirling engine a 'dark horse'...."
HITT.	p. 40 par. 2	".... At 150 bshp, the engine [Stirling] weight with transmission is projected to be in excess of 1500 lb; the cost, at over $3000."
	p. 47 par. 8	"The Stirling-cycle system would be too costly ($5000 for the engine alone) as a production vehicle unless a major breakthrough were achieved in its materials and production technology."
	p. 102 par. 4	".... The stratified-charge engine....if successful, would be a better option than either the advanced Otto cycle with catalytic controls, the Rankine engine, or the gas turbine."
MIT	p. 89 par. 1	"The Stirling cycle engine...is unlikely to ever be mass produced, however, unless a suitably inexpensive design for the heater head is developed. An effort to supplement the Ford-Philips-United Stirling program should be considered."
RAND	p. 38 3rd dot	"...its [the Stirling] equivalent gasoline fuel economy does not appear to match that of the supercharged stratified rotary.... Because the Stirling engine is much heavier, auto size and weight are increased. For example, the full-size auto with the Stirling and stratified rotary SIE are 4,600 and 3,000 lb, respectively;...."
AERO-SPACE	p. H-3 par. 1	"The Stirling engine has the potential for demonstrating excellent fuel economy, multifuel capability, very low noise and vibration, and [low] emissions...."
	p. H-4 par. 3.	"Primary problem areas...are: ...radiator size.... ...the array of heater tubes...now made of nickel-chrome alloys...."
	p. H-4 par. 4	"Other problems...include inadequate piston seal life, hydrogen diffusion through the cylinder walls and seals, and the need for low-cost power control...."

STRATIFIED-CHARGE

JPL	vol. I. p. 10 (5)	"...the Stratified-Charge...and the Diesel do not offer enough advantage over the improving conventional Otto engine, in vehicles of equivalent performance, to warrant their widespread introduction in general-purpose automobiles."
NAS PANEL 1974	p. 1 par. 1	"From the viewpoint of fuel economy, at least on an urban-type driving cycle, the diesel and stratified-charge engines appear most attractive."
	p. 2	STRATIFIED CHARGE

Emission Levels		Fuel Economy (relative to 1967)
0.41 - 3.4 - 2.0	Carbureted Pre-chamber	0% - 10% Penalty
0.41 - 3.4 - 1.0	"	10% - 20% Penalty
0.41 - 3.4 - .4	"	25% - 30% Penalty
0.41 - 3.4 - 2.0	Direct Injected	25% - 40% Gain
0.41 - 3.4 - 1.0	"	15% - 20% Gain
0.41 - 3.4 - .4	"	0%

DOT/EPA p. 40 Tab. 7 — "...1980 Compared to 1974...

	Full Size	Mid-Size	Small Size
	(Fuel Economy Improvement in % of MPG)		
∘ PROCO stratified charge,or	25	25	15

SwRI p. 126 par. 4, vol.IIA — "The open chamber stratified charge engine...appears to be a viable candidate for a low emission, low fuel consumption replacement for the conventional engine."

STRATIFIED-CHARGE continued...

SwRI	p. 226 vol.IIB	"Stratified Charge Engine....The fuel economy calculations for this design result in a composite improvement of 55 percent in mileage [relative to 1973 production vehicles] after correction for emission controls."
	p. 227 vol.IIB	"The principal deterrent to the development of the stratified charge engine is that when it is fully emission controlled (0.4 g/mile-NO_x), in most cases, the fuel economy suffers severely to the point that it is virtually no better than a conventional carbureted engine in terms of fuel economy."
HITT.	p. 102 par. 4	".... The stratified-charge engine....if successful, would be a better option than either the advanced Otto cycle with catalytic controls, the Rankine engine, or the gas turbine."
	p. 102 par. 5	"A major government program should be conducted for the development of a stratified-charge engine."
ADL	p. 29 par. 1	"Improved Engine Efficiency [mass-producible by 1980]. Extend the concept of the conventional piston engine for light-duty passenger car use by developing the stratified-charge engine and particularly a light-weight diesel engine. We believe that the stratified charge engine is less viable than the diesel because of a lack of proven road flexibility, increased complexity, and lower potential for fuel economy gain; i.e., 17 (standard) to 18 (compact) % mpg gain for the stratified charge versus 20 (standard) to 25 (compact) % mpg gain for the diesel."[relative to 1973 production vehicles]
EATON	p. 17	"In the near term, the stratified charge engine looks potentially very attractive...."
STERN-LICHT	p. 22 par. 2	"In the near term, the stratified-charge engine looks potentially attractive, offering required low emissions without sacrifice in fuel economy."

DIESEL

JPL	vol. I. p. 10 (5)	"...the Stratified-Charge...and the Diesel do not offer enough advantage over the improving conventional Otto engine, in vehicles of equivalent performance, to warrant their widespread introduction in general-purpose automobiles."
NAS PANEL 1974	p. 1 par. 1	"From the viewpoint of fuel economy, at least on an urban-type driving cycle, the diesel and stratified-charge engines appear most attractive."
NAS PANEL 1973	p. 8	"Those candidates that appear to merit earliest consideration are as follows: Diesel.... Advanced diesel.... Advanced gas turbine.... Advanced Stirling.... Advanced battery...."
	p. 37	"A general consensus was that eventually...[diesel] engines should be used in specialty vehicle applications having a high-load factor and used mostly in urban areas, such as taxis, light pickup and delivery trucks, and some cars."
STERN-LICHT	p. 22 par. 5	"The Stirling engine is the most likely candidate, although the diesel or the Warren engine show considerable promise at this time."
NAS PANEL 1974	p. 1 par. 3	"Regarding standards for 1978, lowering of NOx emission levels from 1.0 to 0.4 g/mi appears to exact a penalty in fuel consumption of up to 35% by excluding the diesel engine."
	p. 2	DIESEL

Emission Levels	Fuel Economy (relative to 1967)
0.41 - 3.4 - 2.0	25% - 40% Gain
0.41 - 3.4 - 1.0	20% - 35% Gain

DIESEL continued...

DOT/EPA p. 40 Tab. 7

"...1980 Compared to 1974...

	Full Size	Mid-Size	Small Size
	(Fuel Economy Improvement in % of MPG)		
∘ turbo-charged Diesel**	50 (37)	45 (33)	35 (23)

**Numbers in parenthesis show the fuel economy improvement percentage on a mile per unit energy basis, since diesel fuel has greater density than gasoline."

SwRI p. 228 vol.IIB

"Turbocharged Diesel Design....The fuel economy calculations when adjusted on a Btu-basis...result in a 70-percent improvement in mileage...." [1973 production]

DOT/EPA p. 49 par. 3

"The range of economy improvements that have been estimated for the conversion to naturally-aspirated diesel engines from gasoline engines on an equal performance basis is shown as a % change in miles per gallon as follows:

Vehicle Type	Data From Ref (1)	Data From Ref (2)	Data From Ref (3)
Large	+20%	+35%	--
Mid-size	+25%	--	+46%

[1]op. cit., ADL Report

[2]op. cit., SWRI Report

[3]Monaghan, M.L., C.C.J. French, and R.G. Freese. A Study of the Diesel as a Light-Duty Power Plant. Report prepared by Ricardo and Company Engineers, Sussex, England, for the U.S. Environmental Protection Agency, July 1974."

ADL p. 29 par. 1

"Improved Engine Efficiency [mass-producible by 1980]. Extend the concept of the conventional piston engine for light-duty passenger car use by developing the stratified-charge engine and particularly a light-weight diesel engine. We believe that the stratified charge engine is less viable than the diesel because of a lack of proven road flexibility, increased complexity, and lower potential for fuel economy gain; i.e., 17 (standard) to 18 (compact) % mpg gain for the stratified charge versus 20 (standard) to 25 (compact) % mpg gain for the diesel."[relative to 1973 production vehicles]

DIESEL continued...

AERO-SPACE	p. H-4 par. 3.	"The fuel economy of diesel-powered vehicles over the Federal Emissions Test Driving Cycle is between 50 percent and 70 percent better than that achieved by the average 1973 model...."
	p. H-5	"...On an equivalent performance basis, the fuel economy advantage...would be smaller."
MIT	p. 24 par. 2	"...the ICE [Diesel] engine fuel economy is as good as or better than any other potential automotive engine."
RICAR-DO	p.1-4 par. 1.	"The diesel powered vehicle will deliver up to 50% greater fuel economy than the equivalent gasoline powered vehicle, depending on the driving cycle."
	par. 2.	"...a diesel powered vehicle could not meet the secondary emissions target of 0.4 g/mile NO_x...."
	p.1-5 par. 8.	"The clear superiority of the diesel for such specialised applications as taxi cabs and light delivery vehicles indicates that a programme to demonstrate and encourage the conversion of these vehicles to diesel power should be instituted."
MIT	p. 86	"...the industry has quite reasonably chosen to concentrate its R & D efforts on other systems [than the diesel]."
	p. 89	"...a government program could help reduce both the technological and regulatory uncertainty regarding the diesel."

ROTARY

JPL	vol. II. p. 3-15 par. 2	"The advanced configuration...Otto engine is one that can be produced at some unspecified future date, given additional development and foreseeable extensions of today's technology."
	par. 3 & 4	"The rotary (Wankel) configuration offers several possible improvements, once projected far enough into the future to allow resolution of its current rotor-seal and housing distortion problems:....The advanced configuration is therefore taken to be a Wankel....Rotor(s) and a housing liner of ceramic material will provide improved dimensional stability and minimum heat losses."[No cooling system used.]
RAND	p. 7 par. 1 Ex.Sum.	"Our analysis indicates that the supercharged rotary engine with charge stratification dominates all other engine types, including the diesel. Compared with the conventional SIE, it yields about twice the fuel economy,..."
RAND	p. 38 par. 1	"...supercharged stratified rotary...fuel economy is improved 73 to 82 percent depending on auto size and driving cycle; ...."
NAS PANEL 1974	p. 99 par. 2	"Although the advanced stratified-charge rotary-engine concepts appear promising, it is doubtful whether they can be available until the 1980's."
EATON	p. 17	"Reciprocating piston engines will remain dominant well into the 1980's. The Wankel engine will receive increased use in passenger cars, possibly approaching a 25% penetration by the mid-1980's, but probably much less."

NAS PANEL 1974 p. 2

ROTARY

Emission Levels	Fuel Economy (relative to 1967)
0.41 - 3.4 - 2.0	5% - 10% Penalty
0.41 - 3.4 - 1.0	20% Penalty

STERN-LICHT	p. 22 par. 6	"The author does not believe that the Wankel, Rankine, or the gas turbine are likely to become automotive power plants with impact by the year 2000."
MIT	p. 23	"In terms of better meeting public policy goals, this alternative [rotary engine] has no advantages relative to the ICE."

RANKINE OR STEAM

JPL	vol. I. p. 78 3.	"...the Rankine powerplant delivers substantially lower fuel economy....It also has the highest production cost. While the Rankine engine does offer the same low emissions advantage and fuels adaptability as the Braytons and Stirling, these merits alone are insufficient to warrant its further development."
MORSE	p. 2 par. 3.	"Vehicles using external combustion engines for propulsion, such as the piston-type steam engine of advanced design, potentially offer a satisfactory alternative to the present automobile and should have very low pollution and noise characteristics."
STERN-LICHT	p. 22 par. 6	"The author does not believe that the Wankel, Rankine, or the gas turbine are likely to become automotive power plants with impact by the year 2000."
RAND	p. 40 3rd dot	"The Rankine engine appears to offer somewhat better fuel economy than the gas turbine...."
AYRES	p. 220 Tab. I	

	OC-Engine Case OC-70	OC(2)	Standard Turbine Engine Case RFT(4)	Standard Rankine Cycle Engin Case RCE(4)
Fuel economy (mpg)	11.4	9.1	12.4	12.2

OC-70 - Otto Cycle 1970

OC(2) - OC-70 plus Exhaust Gas Recirculator, plus Dual Catalytic Convertor and miscellaneous

RFT(4) - Regenerative Free Turbine with ceramic burner parts, with a stainless steel regenerator

RCE(4) - Rankine Cycle Engine, New valve by BICERI replacing TECO valve; no transmission

NAS PANEL 1973	p. 103	"In comparison with other heat engines that have better efficiency, lower cost, better integrability in automobiles, and better producibility, the Rankine engine is less suitable for use in low-emission cars."
BJERK-LIE	p. 13	"Efficiency of the Carter [steam] engine has been pushed to near the probable limit for simple steam engines.[26]"

[26] Jay Carter Enterprises

ELECTRIC

JPL	vol. I. p. 79 7.	"A major breakthrough in battery technology is required to make electric vehicles competitive with the heat-engined vehicles. Existing (lead-acid) battery technology results in vehicles with overall energy efficiencies about 10% better than those of comparable Otto-engined cars."
MORSE	p. 2 par. (a)	"The state of technology does not permit the current development of an economically feasible electric car except for special-purpose, limited-range use."
STERN-LICHT	p. 22 par. 4	"...the electric vehicle...will probably start making an impact in the late 1990s.... Hybrid (engine/electric) systems are also good candidates."
NAS PANEL 1973	p. 8	"Those candidates that appear to merit earliest consideration are as follows: Diesel.... Advanced diesel.... Advanced gas turbine.... Advanced Stirling.... Advanced battery...."

MISCELLANEOUS

Hybrid

JPL	vol. I. p. 79 8.	"The best heat engine/electric hybrid configuration (parallel, on-off) may achieve up to 20% higher fuel economy than a comparable-acceleration Otto-engine-powered vehicle....The hybrid's heat engine emissions are not sufficiently lower to significantly simplify its emission controls. The additional weight and cost of the energy storage system make the hybrids singularly unattractive....'
MIT	p. 31 par. 1	"Heat Engine Hybrid System...[is] complex and heavy, with disappointingly high emissions and fuel consumption."
STERN-LICHT	p. 22 par. 4	"...the electric vehicle...will probably start making an impact in the late 1990s.... Hybrid (engine/electric) systems are also good candidates."

Lean Burn

JOHN	p. 11 par. 2	"The somewhat sketchy amount of data currently available indicates the potential benefits of the lean burn approach both in decreased emissions and improved economy."

NAS PANEL 1974 — p. 2

LEAN BURN

Emission Levels	Fuel Economy (relative to 1967)	
0.41 - 3.4 - 2.0	5%	Penalty

Warren Engine

STERN-LICHT	p. 22 par. 5	"The Stirling engine is the most likely candidate, although the diesel or the Warren engine show considerable promise at this time."

LIST OF

ALTERNATIVE POWER PLANT STUDY REPORTS

SHOULD WE HAVE A NEW ENGINE? An Automobile Power Systems Evaluation, Volume I. Summary; Volume II. Technical Reports. Jet Propulsion Laboratory, California Institute of Technology, August 1975.

AN EVALUATION OF ALTERNATIVE ENERGY SOURCES FOR LOW EMISSION AUTOMOBILES, John W. Bjerklie, Elton J. Cairns, Charles W. Tobias and David Gordon Wilson (SAE PRE-PUBLICATION for October 1975).

LEAN BURN ENGINE CONCEPTS--EMISSIONS AND ECONOMY--James E. A. John (SAE PRE-PUBLICATION for October 1975)

A STUDY OF TECHNOLOGICAL IMPROVEMENTS IN AUTOMOBILE FUEL CONSUMPTION, Volume I: Executive Summary, prepared for Transportation Systems Center, Environmental Protection Agency, December 1974. Arthur D. Little, Incorporated, Report No. PB-238 693.

TECHNOLOGICAL IMPROVEMENTS TO AUTOMOBILE FUEL CONSUMPTION, prepared for U. S. Department of Transportation, Office of the Secretary, Office of the Assistant Secretary for Systems Development and Technology, and U. S. Environmental Protection Agency by C. W. Coon et al., December 1974. Final Report No. DOT-TSC-OST-74-39, Volumes I, IIA, and IIB. (Southwest Research Institute)

THE ROLE FOR FEDERAL R&D ON ALTERNATIVE AUTOMOTIVE POWER SYSTEMS prepared by John B. Heywood, Henry D. Jacoby, and Lawrence H. Linden with the assistance of Patricia D. Mooney and Joe M. Rife. Massachusetts Institute of Technology Energy Laboratory Report No. MIT-EL-74-013, November 1974.

WHICH AUTOMOTIVE ENGINES IN THE FUTURE? by Beno Sternlicht, Mechanical Technology, Inc., published in Mechanical Engineering, November 1974.

POTENTIAL FOR MOTOR VEHICLE FUEL ECONOMY IMPROVEMENT, REPORT TO THE CONGRESS, prepared by the U. S. Department of Transportation and the U. S. Environmental Protection Agency, 24 October 1974.

HOW TO SAVE GASOLINE: PUBLIC POLICY ALTERNATIVES FOR THE AUTOMOBILE prepared for the National Science Foundation by Sorrel Wildhorn, Burke K. Burright, John H. Enns and Thomas F. Kirkwood. Published by The Rand Corporation. R-1560-NSF, October 1974 and Executive Summary R-1560/1-NSF, October 1974.

LIST OF ALTERNATIVE POWER PLANT STUDY REPORTS continued...

EMISSIONS CONTROL OF ENGINE SYSTEMS, Consultant Report to the: Committee on Motor Vehicle Emissions, Commission on Sociotechnical Systems, National Research Council, prepared by James E. A. John et al., September 1974. (NAS PANEL 1974)

CURRENT STATUS OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS AND FUELS VOLUME II--ALTERNATIVE AUTOMOTIVE ENGINES, prepared by The Environmental Programs Group, The Aerospace Corporation, Contract No. 68-01-0417; prepared for the U. S. Environmental Protection Agency Office of Air and Waste Management, Alternative Automotive Power Systems Division, July 1974, EPA-460/3-74-013-b.

A STUDY OF THE DIESEL AS A LIGHT-DUTY POWER PLANT by M. L. Monaghan, C. C. J. French, and R. G. Freese, Ricardo and Company Engineers, Contract No. 68-03-0375, prepared for U. S. Environmental Protection Agency Office of Air and Waste Management, Office of Mobile Source Air Pollution Control, July 1974. EPA-460/3-74-011.

ECONOMIC IMPACT OF MASS PRODUCTION OF ALTERNATIVE LOW EMISSION AUTOMOTIVE POWER SYSTEMS by Robert U. Ayres, and Stedman B. Noble, International Research & Technology Corporation, printed in Journal of the Air Pollution Control Association, March 1974, Vol. 24, No. 3.

THE AUTOMOBILE--ENERGY AND THE ENVIRONMENT: A Technology Assessment of Advanced Automotive Propulsion Systems, by Douglas G. Harvey, and W. Robert Menchen. Work Sponsored by The RANN Program of the National Science Foundation, Contract No. NSF-C674, March 1974. Hittman Associates, Inc., Columbia, Maryland.

AUTOMOTIVE ENGINES FOR THE 1980's--Eaton's Worldwide Analysis of Future Automotive Power Plants by R. W. Richardson, Manager Technological Planning, Eaton Corporation (no date).

AN EVALUATION OF ALTERNATIVE POWER SOURCES FOR LOW-EMISSION AUTOMOBILES, Report of the Panel on Alternate Power Sources to the Committee on Motor Vehicle Emissions, National Academy of Sciences, April 1973. (NAS PANEL 1973)

AUTOMOTIVE GAS TURBINE ECONOMIC ANALYSIS, Final Report, December 1972, to Environmental Protection Agency, Advanced Automotive Power Systems Development Div., from Williams Research Corporation, Report No. WR-ER11.

LIST OF ALTERNATIVE POWER PLANT STUDY REPORTS continued...

AUTOMOTIVE GAS TURBINE OPTIMIZATION STUDY, Prepared by B. C. Riddle, R. C. Davis, and J. G. Castor, AiResearch Manufacturing Company of Arizona, Contract No. 68-04-0012, for U. S. Environmental Protection Agency, Office of Air and Water Programs, Office of Mobile Source Air Pollution Control, July 1972, No. APTD-1291.

FINAL REPORT, AUTOMOBILE GAS TURBINE--OPTIMUM CYCLE SELECTION STUDY, Environmental Protection Agency Contract No. 68-01-0406, Edited by R. J. Rossbach, June 1972, APTD-1343. General Electric Space Division No. GESP-725FS.

AUTOMOTIVE GAS TURBINE OPTIMUM CONFIGURATION STUDY, prepared by E. S. Wright, L. E. Greenwald, and R. R. Titus, United Aircraft Research Laboratories, Contract No. 68-04-0013, for the U. S. Environmental Protection Agency, Office Air and Water Programs, Office of Mobile Source Air Pollution Control, May 1972, APTD-1290.

THE AUTOMOBILE AND AIR POLLUTION: A Program for Progress, Report of the Panel on Electrically Powered Vehicles to the Commerce Technical Advisory Board, U. S. Department of Commerce, October 1967. (Morse Report)

Critique by

Ford Motor Company
Environmental and Safety Engineering Staff
Dearborn, MI 48121

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

2

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

June 29, 1977

RE: 34LPE-77-218-2

Mr. Herbert L. Misch, Vice-President
Environmental and Safety Engineering
Ford Motor Company
The American Road
Dearborn, Michigan 48121

Dear Mr. Misch:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

We were most pleased to receive your letter and the extensive evaluation attached. Our response at this time is in accord with our restructured heat engine work, now under the sponsorship of the Energy Research and Development Administration (ERDA). The background and status of our new program is summarized in the enclosure.

Ford Motor Company's 85-page critique of the subject report comprises a very thorough and detailed review of all the major subject areas of the study. It reflects a great deal of thoughtful analysis and a major commitment of time, and we are highly appreciative of the contribution this critique has made to our understanding of the technical state-of-the-art and of the technology assessment process.

JPL is gratified at Ford's evaluation of the report as "a very good piece of technical work and a valuable contribution to the literature on the subject". Despite some reservations and a number of detailed technical comments, Ford "agrees in a broad sense with the major findings" and endorses the principle of federal funding for high-risk, long-term basic research. These quotations are cited here to help other readers of this letter keep in mind that, while a lengthy critique will naturally emphasize the differences between author and reviewer, Ford does agree with the overall conclusions of the study. The Executive Summary of the critique raises several broad points of philosophy and approach, and poses 13 "open questions" pertaining to the methodology and conclusions. It concludes with a detailed commentary on each chapter of the report.

The breadth and detail of the critique preclude formulating a point-by-point response, which would have to be several times longer than the critique itself. Each of the specific technical topics and the systems-level assessments which tie the technical factors together would require either lengthy discussion or actual new work. The approach we have taken has been to generate a detailed outline of the critique in each major subject area. These outlines form a fundamental part of the work plan in the separate subject areas of the on-going ATSP Project (see attachment). The responses to this critique will then be implicit in the future work, rather than specifically set out.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Several major topics are mentioned in the Executive Summary which have a broader scope and can be briefly addressed here. Ford feels that more attention should have been paid to minimizing (and perhaps quantifying) the uncertainty in predicting technology, and to controlling the optimistic bias which assigns the highest technical expectations to the engines about which the least is known. The purpose of the study was to establish the potential of the alternate engines, and it is certainly out of place to try to establish a priori what kind of production compromises might be made in the end. The report describes specifically where each technology advance is required, and the performance predictions were realistically based on the stated predictions. The assumptions in the study about materials and configurations, which were not criticized as unfeasible, were duly considered in their performance and cost impacts on the engines.

Other comments centered on the high uncertainty in the cost projections, the financial resources required both for carrying out the recommended R&D programs and subsequent production conversion, and the effects of regulatory and non-technical real-world influences. These types of problems will receive increased emphasis in the ATSP Project.

A strong point was made that the ability for meeting near-term emissions standards with good fuel economy, using gasoline piston engines, was overstated in the study. An elaboration of JPL's technical assessment of catalyst-controlled Otto engines was given in the October 3, 1975 letter to Mr. Donald Jensen of Ford's Automotive Emissions Office (a copy will be included in the compendium). Events in the intervening time period have tended to support the APSES view that, given adequate development time, these standards can be met. Ford's concern about the "damage" that can be done through taking such statements out of context may be real enough; however, the statements in the study were very carefully phrased precisely because of this possibility. Surely the possibility of misquotation should not inhibit the undertaking and publication of studies altogether!

The above broad topics, and the 13 "open questions" in Ford's critique, together with the detailed technical comments on each chapter, form a major guideline for our continuing engine technology assessment work. We are indebted to Ford Motor Company for this painstaking and thoroughly constructive critique of the APSES study.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

JET PROPULSION LABORATORY California Institute of Technology · 4800 Oak Grove Drive, Pasadena, California 91103

October 3, 1975

Mr. Donald Jensen
Automotive Emissions Office
Ford Motor Company
World Headquarters
American Road
Dearborn, Mi 48121

Dear Don:

A question was raised in the afternoon session, following the September 9 APSES briefing, concerning our projection that a "Large" Mature UC Otto car could meet the statutory emission standards with some improvement in fuel economy over the best of MY75's. The following response is offered:

In all of our presentations, as well as in the report, we have carefully pointed out the distinction between the Present and Mature configurations of the heat engines - the former representing differing states of development at a fixed point in time (i.e. now), and the latter representing equal-footing fully-developed states at different time points in the future. We have emphasized (and you may feel that this point was not stressed adequately) that none of the Mature configurations - including the Mature UC Otto - is sufficiently developed that a decision to mass produce could be made now.

On the basis of data from a number of sources, including low-mileage data on 3-way converter efficiencies, we submit that it is indeed technically feasible, given adequate development, for Mature Otto-engined cars to be certified to the 0.41/3.4/0.4 emission standards with the fuel economies stated in the report. However, as noted on page 60 of Volume I, it will be difficult "...for larger cars using these powerplants to be certified to the 0.4 g/mi NOx standard and the 0.41 g/mi HC standard at the same time. This observation derives from the fact that large fractions of exhaust gas recirculation (EGR) and/or lean burning may be required to adequately suppress NOx formation, and this will tend to increase HC formation, possibly beyond the conversion capabilities of the oxidation converter."

One way to look at the issue is by resolving it into the three components of fuel consumption, feed-gas composition, and required simultaneous conversion efficiencies of the 3-way converter. The enclosed "maps" show the Mature "Large" (5000 lb curb weight) car in this perspective for HC and NO_x emittants.

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The expectation that the feed-gas requirements for all 3 pollutants will be met at the projected levels of fuel economy is based on experimental data. The simultaneous attainment of the required NO_x level in the feed-gas and the projected improvement in fuel economy results from optimum use of EGR in conjunction with near-MBT spark timing. It is recognized that in the past the increase in HC emissions accompanying the use of charge dilution has been ameliorated through retardation of the spark timing with a resulting loss of fuel economy. This problem should be addressed as part of the required development program.

Simultaneous catalytic conversion efficiencies well above those required have also been demonstrated under stoichiometric conditions, but here the data are admittedly sparse and mostly for low mileage. Our review of the available performance data indicates that simultaneous HC and NO_x conversion efficiencies at about 80% are reasonable development targets for end-of-life ($\gtrsim$ 25,000 miles).

While we have not assessed in detail the development time and funding required for the Mature UC Otto power system, it is our judgement, consonant with the discussion presented in Chapters 3 and 4 of Volume II, that the appropriate engine components and converter subsystem to meet this target performance are within reach of an intensive development program.

With regard to Chapter 3; I would like to call your attention to an erratum which slipped through the editorial process in the transition from an earlier version: Footnote "a" to Table 3-6 (p. 3-18) now reads "Average car at 50,000 miles;" it should read, "Well-maintained car at 50,000 miles."

I trust that this information will be helpful in understanding our treatment of the baseline UC Otto car. I am sorry for the delay in getting you this resonse, but with various briefings and other committments the team has had a hard time getting together to put together this letter.

Yours sincerely,

Rhoads Stephenson

R. Rhoads Stephenson
Principal Investigator
Automotive Power Systems
Evaluation Study

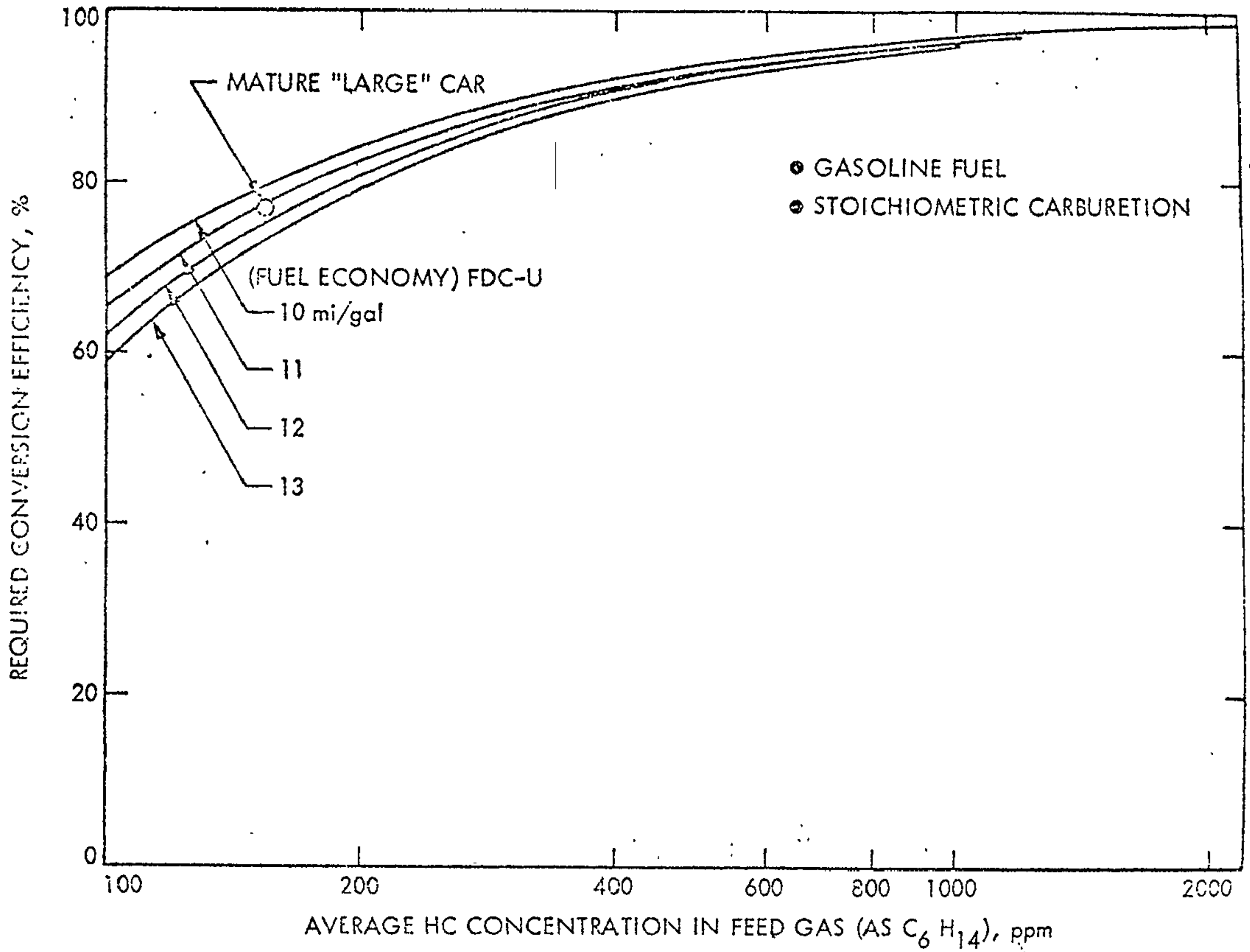
RRS:bl

Enclosures

cc: T. Barber, W. Edmiston, G. Klose, G. Meisenholder, N. Moore, G. Nunz

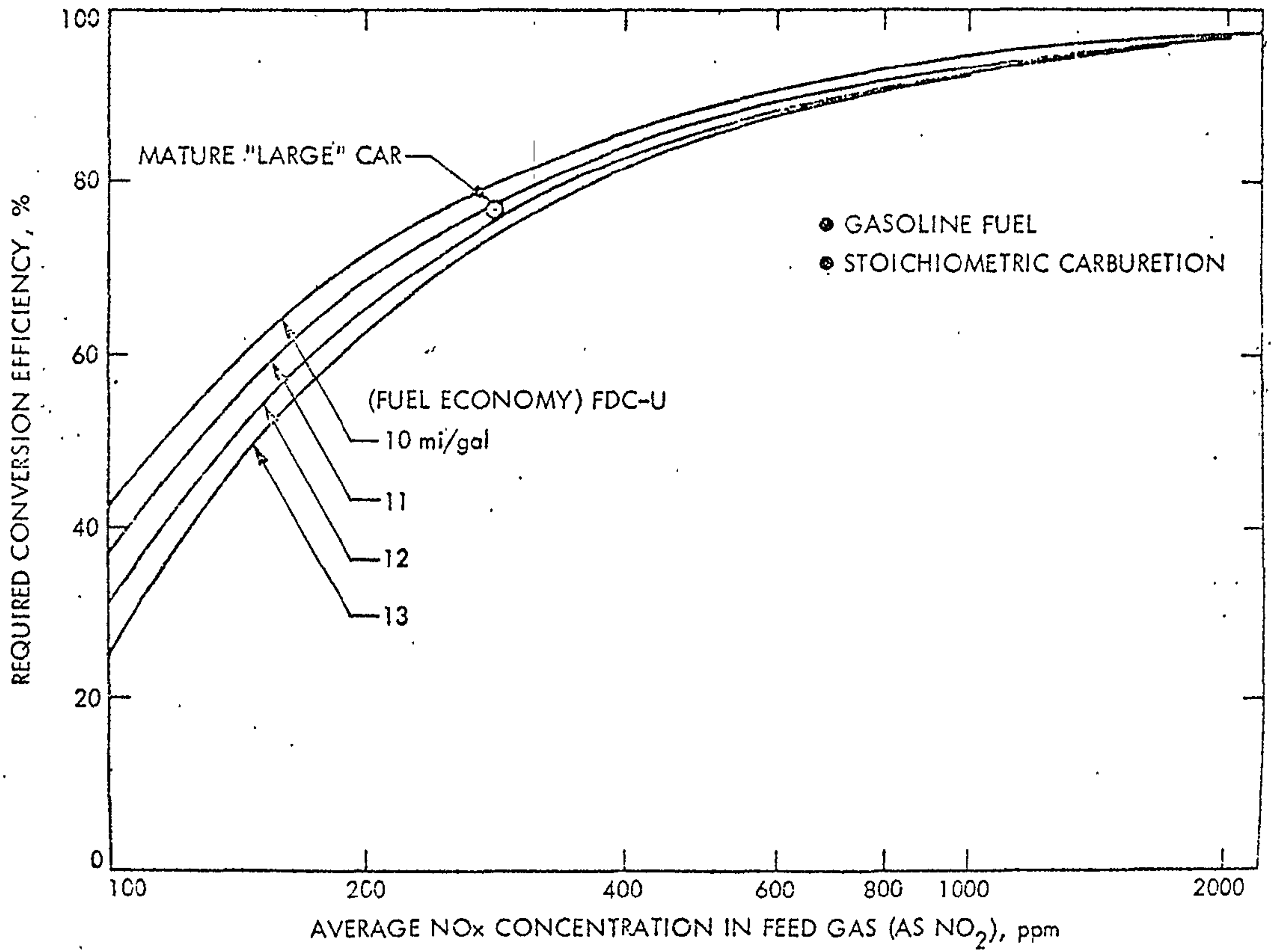
ORIGINAL PAGE IS
OF POOR QUALITY

END-OF-LIFE HC CONVERSION EFFICIENCY REQUIREMENT TO MEET 0.41 g/mi STANDARD



77-40

END-OF-LIFE NOx CONVERSION EFFICIENCY REQUIREMENT TO MEET 0.4 g/mi STANDARD



Herbert L. Misch
Vice President
Environmental and Safety Engineering Staff

Ford Motor Company
The American Road
Dearborn, Michigan 48121

October 20, 1975

Dr. Allan J. Grobecker
Assistant to the Manager of the
Task Force for Motor Vehicle Goals
Beyond 1980
Office of the Secretary
Department of Transportation
TST-8
400 Seventh Street, S.W.
Washington, D.C. 20590

Dear Dr. Grobecker:

Mr. Stoney's letter of September 26 requested a Ford critique of the Jet Propulsion Laboratory (JPL) report "Should We Have a New Engine?". As you know, this study was funded by Ford and touches deeply on issues of vital concern to us. Consequently we intend to be especially thorough in our evaluation. Our critique has been in progress from the day the report was issued, and the first management review is not expected for several weeks. Therefore I am unable to satisfy your request in time to meet your needs.

However, with the understanding that my failure to comment on a particular issue does not imply endorsement, I can share with you my general (and very tentative) reactions to the JPL study.

It is clear that this report represents a very competent piece of work and is a valuable contribution to the debate on alternative engines, but we disagree with the authors on many specifics. We particularly disagree with JPL's assessment of economic issues and with their assumption that statutory emission standards can be met in the near term with an Otto cycle engine more economical than those meeting 1975 standards. We are also apprehensive that -- as has happened with all major studies to date -- improperly qualified statements in the summary volume will be widely quoted and misused.

Despite these reservations, we agree in a broad sense with JPL's major findings:

1. Alternative engines, particularly the Stirling and Brayton, offer the hope of substantial improvements over the Otto cycle in both fuel economy and emissions.

2. Major technological advances must take place before these alternatives could be considered serious competitors to the Otto cycle engine. These advances can only be achieved through very large research and development expenditures over at least a five to ten year period.

3. When (if) the technology is finally proven, a lead time on the order of four years is required before production could begin. Total conversion of the industry would require at least eight to twelve more years, even at greatly increased levels of industry investment.

4. Even in mass production, most of the alternate power plants are projected to have significantly higher first cost.

These findings led the JPL team to endorse the industry's current strategy of refining the Otto cycle engine, reducing vehicle weight, improving aerodynamics, etc. They concluded -- as did we -- that there is no sensible alternative in the near term (i.e. for the next five to ten years).

JPL also recommended greatly increased funding of research and development on both the Stirling and Brayton cycle engines, by industry and by the federal government. Clearly, JPL did not, and perhaps cannot, appreciate the enormous strain placed on our capital resources by government regulations and the demands of the market. Nevertheless we intend to give this recommendation serious consideration, weighing the opportunities and risks of such a program against those of other programs competing for the same limited operating capital. Current levels of Company funding on these engines reflect our judgment that the most efficient approach in evaluating alternate power plants is to concentrate research on the one or two most important roadblocks.

We are therefore in agreement with JPL that the potential returns are too remote to warrant immediate expansion of our own programs to the levels recommended by the study. Because a major fraction of the benefits of alternate engines accrue to society at large rather than to the successful developer, we consider it proper for society to participate in the costs and risks. Accordingly, we endorse in principle the JPL recommendation for federally funded research programs. To that we would add the recommendation that such funding be restricted to basic technology characterized by high risk and long term payoffs. At this time both the Stirling and Brayton engines fit that description.

When our review has been completed, I will make sure that you receive copies. Meanwhile, I'd be happy to answer any specific questions you may have on the report.

Very truly yours,

H. L. Misch

FORD CRITIQUE OF THE JPL REPORT
"SHOULD WE HAVE A NEW ENGINE"

December 15, 1975

Edited by Wayne M. Brehob
Automotive Emissions Office
Ford Motor Company

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The JPL Report, "Should We Have a New Engine? -- An Automobile Power Systems Evaluation" is a very good piece of technical work and a valuable contribution to the literature on the subject. Its more significant contributions are in developing analysis techniques and terminology and in establishing an outline or structure for a complete technical and financial analysis of a vehicle system. However, the report should be considered as a first iteration of the analysis and the conclusions should be considered as tentative.

The report suffers from the bias of the authors; the bias is primarily due to optimism that assumes great things for the engines about which the least is known. This causes the Brayton (gas turbine) and Stirling engines to come out on top, and the Otto (spark ignition) engine and the Diesel engine to come out near the bottom. Much of the technical uncertainty associated with the new technology was assumed away by merely making the assumption that any outstanding problems would be solved before the engine was introduced.

The cost projections which serve as the basis for all the financial analysis are more uncertain than the technical projections. In combination, the uncertainties make it premature to accept the recommendation that the industry should spend about one billion dollars to research three alternate engines over the next seven or eight years, that the industry could afford to do so with minor changes in priorities, and that the profit potential justifies such an expenditure.

One conclusion of the report will undoubtedly be used and misused out of context to counter industry arguments about the trade-off between emission control and fuel economy. This conclusion creates the totally false impression that technology is at hand which will allow the current engine to meet the most stringent emission standards (.41/3.4/0.4 g/mi,HC/CO/NOx respectively) with no loss in engine efficiency (fuel economy) but rather with a slight improvement. The body of the report contains caveats which temper the conclusion, but not sufficiently to make it accurate. JPL was specifically asked to supply the quantitative rational for this conclusion but replied instead with a restatement of the caveats and a reaffirmation of their opinion that this was true.

This critique discusses the above points in more detail, points out other weak areas, and makes suggestions on how they can be improved. It also includes a list of questions for the JPL authors' consideration. Finally, it is recommended in this critique that a second iteration of the study is warranted in order to answer these questions and implement improvements in the techniques and to incorporate more recent data.

FORD CRITIQUE OF THE JPL REPORT "SHOULD WE HAVE A NEW ENGINE"

OVERVIEW

The JPL study set out to answer the question "Should our cars be powered by a new powerplant?" Their analysis intended to go beyond the technical question of what could be done by including societal considerations to decide what should be done.

Although the report is quite broad, there are limitations in scope that must be kept in mind when considering the conclusions. Special purpose vehicles such as taxi cabs, delivery vehicles, commuter cars, etc. are not considered; therefore, the fact that a powerplant is not recommended in this study does not mean that it might not have high potential in a special purpose vheicle. The report concentrates on what is termed an "Otto-Engine Equivalent" (OEE) vehicle, which, relative to a conventional Otto-engined counterpart has identical passenger and luggage accommodations, accessories, aerodynamics, and range; equivalent performance; and equally acceptable driveability, safety, durability, and noise level. Advantages were sought in fuel economy and emissions.

In order to compare power plants at equal levels of technology, three levels of technology were defined as follows:

Configuration	System Definition	Approx. time to production
"Present"	Powerplant performance currently demonstrated on an engine test stand or in a vehicle	0-2 yrs.

Configuration	System Definition	Approx. time to production
"Mature"	The level of powerplant performance achievable with known technology and with time to do necessary development	2 to 10 yrs.
"Advanced"	The level of powerplant performance achievable with major technological advances in materials and fabrication processes	beyond 10 yrs.

Although the report did not attach a specific time scale to these levels of technology, the times in years shown are approximately the time required to have the configuration in mass production. The engine related conclusions and recommendations were based on comparison of engines at the "mature" technology level.

The mature configurations assumed for the seven powerplants for which configurations were generated are shown below. Two powerplants, the pure electric and the hybrid, were ruled out before generating any configurations. The Brayton-cycle engine is carried in two options -- single-shaft and free-turbine. Several alternatives are listed for emission control of many of the powerplants.

Uniform Charge (UC) Otto (Baseline Engine)

Improved conventional spark-ignited piston engine; advanced carburetor (possibly sonic), 700 to 4500 rpm speed range, cast iron block and head, conventional valves and valve actuation.

Emission control alternatives

For emission standards of 0.41/3.4/0.4 -- exhaust treatment including a reducing catalyst, and oxidation in either a catalyst or thermal reactor (emphasized 3-way catalyst).

For standards of 0.41/3.4/1.0-2.0 -- exhaust oxidation treatment only, NOx control by dilute combustion (lean or EGR).

Stratified-Charge (SC) Otto

Open chamber, direct fuel injection, 11:1 compression ratio, reciprocating (slider-crank, 4-stroke), cast iron head and block, conventional valves and valve actuation

Emission control alternatives

For emission standards of 0.41/3.4/2.0 -- an oxidizing (HC/CO) catalyst and EGR.

For standards of 0.41/3.4/0.4 -- either an extra large HC/CO catalyst and EGR; or feedback control to maintain stoichiometry, and a 3-way catalyst

Brayton Cycle (Gas Turbine) -- Single Shaft (SS) Type

4:1 pressure ratio, 80% efficient compressor, 1900°F maximum turbine inlet temperature, superalloy turbine of radial type with 85% efficiency, premix prevaporizing (variable geometry) combustor, ceramic regenerator with 90% efficiency, and integrated hydromechanical controls.

Brayton Cycle (Gas Turbine) -- Free Turbine (FT) Type

Same specifications as single shaft; additional power turbine has same specifications as gasifier turbine except variable nozzles are used.

Stirling-Cycle Engine

Swashplate operation of double-acting stainless steel pistons, hydrogen working fluid with 1400°F maximum temperature and a maximum pressure of 200 atmospheres (approx. 3000 psi), a superalloy tube bundle or investment cast heater head, a ceramic air preheater, rollsock piston rod seals, and load control by variation of mean pressure level augmented with dead volume control

Rankine-Cycle Engine

A monotube steam generator, water working fluid; maximum outlet temperature and pressure of 1400°F and 2500 psi; a reciprocating expander with piston-actuated poppet valves; a shell-and-tube feedwater heater; and a positive displacement reciprocating, variable-flow feedwater pump

Diesel Engine

Reciprocating (slider-crank, 4-stroke), turbocharged to 10 psig, swirl chamber (Ricardo type), fixed 18 to 22:1 compression ratio, iron block and head, conventional valves and valve actuation

Criteria for Engine Selection

The main criteria for choice of an optimum powerplant were high fuel economy and low emission of gaseous pollutants from the OEE vehicle. According to the JPL analysis, the Stirling and both Brayton powerplants excelled in both economy and emissions; and -- since the choice was not refined to win, place, and show -- a tradeoff of the two criteria was not required. After the choices were made, analyses were developed to see if all selected powerplants meet the requirements of:

Powerplant safety

Manufacturability

Material availability

Fuel availability

Customer acceptance

Ownership cost

Reasonable introduction scenario

None of the prime alternatives were ruled out in this secondary analysis.

Related Studies

The report also considers subjects only loosely related to the choice of an automotive powerplant. These include:

Automobile design

Automobile use

Vehicle and Highway safety

Air Quality

Energy and Fuels

These studies were used to define the arena in which the alternate powerplants must compete. Little or no new analysis or insight is developed in these areas.

JPL CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of the report with brief comments where appropriate are listed below.

- The automobile will maintain its dominant role in personal transportation through the foreseeable future.

  Comment: None

- The production of over 10 million vehicles is a specialized undertaking that cannot accommodate "overnight" product changes.

  Comment: None

- The necessary materials of construction and fuel can be obtained for another generation of heat engines of any of the types considered, given adequate planning.

  Comment: None

- The financial resources required for conversion to vehicles with alternate engines would be readily available in our economy.

  Comment: This statement is incorrect because of the word "readily." Whereas the economy can support this type of effort, the decision of who pays, who does the work, and who reaps the rewards of any success are far from easy and were not adequately considered in this report.

- Automobile pollutant emissions and -- equally important -- emissions from other mobile and stationary sources, must be controlled more stringently than at present, and in a concerted manner, in order to meet the National Primary Air Quality Standards through the next decade.

Comment: This conclusion properly emphasizes the need for greater control on stationary sources. However, it is too general to be an answer to the real-world questions of how stringent and how soon. The air quality chapter is slightly more specific but still leaves more questions than answers.

Given some additional development, cars with catalytically controlled Otto engines do not have to give up fuel economy to comply with the strictest legislated emission standards. In fact, some improvement in the efficiency of such engines can be obtained without relaxation of those emission standards.

Comment: Without doubt, this is the most "damaging" conclusion, particularly when taken in context with the previous statement about the need to achieve lower emissions. An easy position to reach from these two statements is that since some reduction is needed, and the statutory standards can be met with some improvement in efficiency, these should be enforced. The caveats which go with this statement, and which are used by JPL in defending it, are not included in this statement and are only hinted at by the mild statement "given some additional development".

The additional development referred to is a catalytic exhaust treatment system - either three-way or dual bed - that is so efficient that the engine can run at nearly uncontrolled feedgas levels. Also, a system for controlling the air-fuel ratio as appropriate to obtain the required catalyst efficiency is needed. The body of the report states that they can't predict when such systems will be ready for production but they estimate 1978 to 1980. Although not explicitly stated, the general terminology uses introduction to mean one engine line; therefore, JPL is quessing that it might be as late as 1980 before one line of engines can meet the statutory standards and presumably a year or two after that before they all can. Obviously, the band of uncertainty in the JPL statement is much wider than an anti-industry reader will appreciate.

Also, the baseline from which an improvement is predicted is not stated in this conclusion. The body of the report gives it as 1975 model year, which of course, is not an acceptable objective from which to get "some improvement". The improvement is not qualified in the conclusion, but in the body of the report is predicted to be only 9 to 10%. The result is that their projected "improved" economy would be somewhat worse than 1976 actual.

A final objection to this conclusion is their statement on page 60 of the Summary that "It will be difficult, however, for larger cars using these powerplants to be certified to the 0.4 g/mi NOx standard and the 0.41 g/mi HC standard at the same time." Since the law requires that both standards be met, and the certification procedure introduces scatter that must be covered with a confidence allowance, it's questionable whether the report really predicts that the standards can even be met for large cars.

An example of how much different the conclusion could sound and still be in agreement with JPL's optimistic assumptions is shown by the following rewrite:

Even given continued concentrated effort, large cars using catalytically controlled Otto engines may not be able to comply with the strictest legislated standard for HC and NOx even if they are postponed until 1980 and even accepting a fuel economy loss relative to the cars that could be built without such stringent emission controls.

Based on JPL's conclusions, they recommend the following:

"Begin immediately the rapid implementation of design changes to the car itself which can significantly reduce fuel consumption, independent of the kind of engine used. Concurrently, accelerate and direct the development of two particularly promising alternative engines - the Brayton and Stirling engines - until one or both can be mass produced, with introduction in the improved cars targeted for 1985 or sooner. In the interim, press the development of the conventional Otto engine to its limits."

Comment: The direction stated in this recommendation is exactly that being taken by Ford Motor, so there is no reason to object to the statement. However, the implications behind it are not so agreeable. The financial commitment that JPL thinks we should make is excessive and the speed with which they expect results is unreasonable. JPL partly blunts the resource requirement by suggesting the work on stratified-charge Otto engines and on electric and hybrid vehicles should be de-emphasized, a very hazardous course of action.

JPL's willingness to effectively drop intermediate technology alternate engines and pursue the long range alternatives stem from their conclusion that the long range alternatives can be made practical in a relatively short time and will be better than all alternatives regardless of any reasonable perturbation of their analysis. In fact, the analysis is far from infallible - specifics will be covered in the detailed comments to follow - and the consequence of error is so extreme that the recommended course is very risky. JPL can treat this risk lightly because they don't have a financial stake in being right. The safer position is to avoid a commitment to any one or two systems at this time and to work on each hard enough to generate the hard data to reduce the risk of a future decision to an acceptable level.

UNCERTAINTY AND BIAS

Uncertainty in a study like this can be excused and is even expected because everyone agrees that projecting technology is extremely difficult. However, one could hope that the uncertainty would be minimized and quantified and that the study would be free from bias.

A few observations can be made to predict how any bias in conclusions of a study of this type are likely to be determined by what type group does the study. With the more explored technology, many of the features, that at first exposure would seem advantageous, have been tried and discarded. Therefore, the prognosticator is constrained to a rather narrow range of options. In fact, it's surprising how constrained the JPL study was in defining mature technology Otto and Diesel engines. For example they assumed an iron engine and conservative peaking speeds even though their analysis technique gave considerable advantage to low weight for the required output. In the group of less explored choices, engines were made differently: the Stirling engine, for example, assumed an aluminum block, a ceramic preheater, and an aluminum radiator. That is, for the engine which has never been mass produced and almost never been in an automobile, the investigators felt free to choose higher performance components, presumably because there was no body of knowledge implying that they weren't practical.

This illustrates how an optimistic prognosticator takes advantage of the wide uncertainty band of the newer engines to predict results near the best side of the rather wide uncertainty band. A pessimistic investigator presumably would do the opposite; but technical people, particularly research people, are most often optimists. That the JPL study was affected by this phenomenon is suggested by the fact that there is very good correlation between lack of knowledge about an engine and high expectation for the engine. The engine about which JPL was most optimistic was the SS Brayton (Gas Turbine), an engine which has never been built in a configuration that comes even close to the prediction JPL made for it. The worst or near worst was the UC Otto engine about which the most is known.

An optimistic bias is also reflected in the way many of the peripheral aspects of alternate engine performance were neglected or pushed off to impact on another attribute of the engine without the effect on the other attribute being accounted for. Examples are the assumption that maintenance cost and safety would be made at least as good as current cars as a requirement of introduction. However, neither performance, cost, or any other attribute were compromised to account for trade-offs that might be necessary to achieve the required safety and maintainability. That is, it is taken on faith that if problems are identified, they can and will be solved in a practical way that does not involve a trade-off.

There are two ways that could have been used to control the optimistic bias. The first, and most obvious, would have been to try to relate the projections to actual vehicle data where it exists and quantitatively account for and try to correct discrepancies. Although JPL may have done this to some extent, it is not documented in the published report. Rather, in the case of the UC Otto engined vehicles, where there is a great deal of vehicle data, the vehicle data were used for comparison to other engines, but computer projections were not presented for comparison. In the case of the alternates, where there was little vehicle data, the computer projections were used and the vehicle data were presented but not subject to detailed comparison. For example, the fuel economy for the current sixth generation Chrysler FT Brayton engined car was shown, and even though it is only about one half of that projected for the mature FT Brayton, the report gives almost no explanation of the difference. Neither does the report show a projection using the JPL vehicle model with appropriate input to describe the Chrysler vehicle to see if the JPL model would accurately predict the low fuel economy measured. This definitely should have been done.

A second approach to controlling optimistic bias would have been to carry a risk factor or confidence value with every major decision or assumption. For example, if a compressor efficiency of 90% were assumed, a confidence of this occurring in the time frame would also be assumed. By this means, ones enthusiasm to predict a high efficiency would be tempered by a desire to maintain a high confidence level. The confidence level for individual component assumptions could be used to arrive at an overall confidence level for the synthesized engine. A refinement of this technique would be to develop three sets of component assumptions matched to high-risk, medium-risk and low-risk confidence levels. This would tend to show the best the engine might be as well as the worst it might reasonably be expected to be. These extremes would help in making judgments about how much R&D effort would be justified.

Although the uncertainty in predicting technology is large, the uncertainty of predicting costs is much larger because it's another "dimension" removed from what is known. Technical considerations generate alternatives of configuration and material, but cost considerations must consider alternatives of fabrication and assembly methods for each of the technical alternatives. The cost estimates in the JPL report are probably the most uncertain and biased of the values that directly effect the conclusion of the report.

The JPL study stopped a step or two short of the analysis needed to give direction to an individual auto manufacturer. The individual manufacturer can't step off from a recommendation that the industry should pursue three alternate engines at the maximum effective funding level. An individual manufacturer could probably only pursue one (or at best two) of these; therefore, the question avoided by JPL, of which of the three is most likely to succeed, is critical. No manufacturer can afford to put the major part of his money into a second best alternative when competitors are working on the first best alternative.

Considering what might be involved in narrowing down the choices brings up the problem of regulatory and nontechnical influences which were largely neglected by JPL. For example, based on JPL predictions, the Stirling engine gets the best fuel economy, but, because of its higher cost, has a higher ownership cost and would be less attractive to the customer. Under the JPL assumption that decisions are made on logical technical and financial basis, the SS Brayton looks the best. However, if fuel economy standards are legislated, or if fuel is rationed, the Stirling engine could move into the number one slot. If a tight economy makes minimum initial cost more important than lifetime cost of ownership, the Otto engine might still be preferred - particularly for smaller cars. These regulatory and other nontechnical influences are outside of the technical and financial factors considered by JPL but are an important part of the real-world input to the corporate decision process.

The recommendations made were for the average, general purpose vehicle, but the advantages for the alternate engines did vary as functions of vehicle size or engine power. For example, the small vehicle receives much less advantage from the use of an alternate engine since the financial impact of an improvement in fuel efficiency is small when the base fuel consumption is low. Therefore, the recommendation to go all out for certain alternate engines is of questionable applicability to this segment of the market. The detail of engine models, integration of models, use in trucks, etc. was not covered by JPL but is very important in planning a future product/engine program.

OPEN QUESTIONS

The JPL report will increase in value if the analysis can continue to be developed and can be made responsive to new data and questions. What is needed is a living, maturing analysis of this very critical subject.

Some of the questions which should be answered are:

1. How are results changed if optimized engine torque curves and transmission characteristics are assumed?
2. How are the results changed by adding additional measures of vehicle performance such as 0-4 sec. distance, high speed passing, and hill climbing to be met?
3. How would the recommendations be affected by inclusion of possible legislative and other major nontechnical assumptions?
4. How would the availability of industry funds for alternative engines be affected by the need for funds to do the recommended work on vehicle design, transmissions, batteries, and emission treatment for Otto engines?
5. What are the specifics of the calibration for the Otto-engined system which JPL expects will meet the most stringent statutory emission standards and still give improved fuel economy? The most critical question is how the full-sized (large) car can reach HC emission levels low enough that certification can be predicted with reasonable confidence when using a non-lean calibration as required by the NO_x catalyst.

6. How would the relative positions of the lower-cost alternative engines be affected if they were modified to include higher cost, more advanced technology, such as variable valve timing?
7. What would be the overall probability of success for the prime alternate engines if confidence levels were assigned to every major component assumption?
8. Do JPL's projection techniques predict the performance of actual vehicles when the component characteristics of the real vehicles are used as input? The Chrysler gas turbine car is a case in point.
9. What would be the consequences for the total auto industry, an individual manufacturer, and the economy if the recommended action were taken and none of the alternatives were successful?
10. How are the total customer costs of the alternate-engined vehicles affected by inclusion of the research, development, and engineering costs in the cost calculation?
11. Once an alternate engine program is started, what criteria can be used to decide if it should be continued or stopped? What should the minimum efficiency and maximum cost objectives vs time be in order to continue the program?
12. How is the analysis changed by allowing for a vehicle population which is heterogeneous in a dimension other than size -- for example, if short-range (commuter cars) and long-range (general purpose cars) were assumed to coexist in near equal numbers?

13. What size vehicle should receive an alternate engine for the most benefit from a societal view? From the manufacturer's view?

CHAPTER DISCUSSIONS

The following discussion will consider each chapter of the report in turn in order to go into more detail and be more specific on areas of disagreement. The discussion of each chapter will start out with the apparent chapter objective, that is, what JPL wanted it to contribute to the overall report, then consider the important results and the Ford view of them. Further comments on some of the chapters are contained in the appendixes to this critique.

CHAPTER 1

Introduction only - no comments.

CHAPTER 2 - Fundamental Considerations of Heat Engines for Automotive Propulsion

This chapter deals with the basic thermodynamic relations which establish the efficiency potential of the various heat engines considered when temperature or compression ratio limits are assumed based on material or fuel limitations. Next they generate the expected brake efficiency based on inherent real-world limitations, data, and judgement. It turns out that only one half to three fourths of this "ideal" efficiency is assumed as brake efficiency for the various engines. This difference between the theoretical and the practical efficiency is dependent to a great extent on the mechanical configuration of the engine. Since the difference is large, the analysis is quite dependent on configuration assumptions which are arbitrary. Also the theoretical calculation is only for an optimum "design point". The fuel consumption of a vehicle is very much dependent on the fuel consumption at off-design conditions.

The biggest criticism is that the theoretical analysis may imply, to a greater extent that is so, that the final result is a function of irrefutable natural laws. The final vehicle fuel consumption is only rather loosely related to the theoretical considerations described in this chapter.

A few specific detailed comments are given in Appendix A of this critique.

CHAPTER 3 - "The UC (Uniform Charge) Otto Automotive Powerplant (Baseline)"

In this chapter, the current conventional engine was set up as the "titleholder" which all"challengers" must meet. The characteristics of the engine that establish its fuel economy and emission potential and its limited fuel acceptability were discussed. It seems this chapter both overestimates and underestimates the potential of this engine.

The near-term or mature technology as defined is overestimated in terms of fuel economy at low emission. As pointed out in an earlier section, JPL concluded that the engine can meet 0.41/3.4/0.4 emission standards and still give improved engine efficiency. This is a result of anticipating very rapid improvement in 3-way catalyst technology to 80% conversion for all three pollutants and crediting too much improvement to advanced induction and EGR systems, particularly when used near the stoichiometric A/F ratio required to make the catalyst work.

The large gain expected from improved induction systems is not supportable. Ford probably has more experience than any other group on the advantages of sonic carburetors, and this experience does not support the "up to 2" improvement in HC that JPL anticipates based on tests of vehicles which had more than just a carburetor change. Further, the main benefit -- extended lean operation -- will be much less important at the richer mixtures that must be used with NOx reducing catalysts. Ford data show that the fuel economy loss experienced when the mixture is enriched from maximum economy to stoichiometric is about 5 to 7%. This is a loss due to enrichment and not recoverable by carburetion.

The anticipated gain with optimum EGR control is also exaggerated. Ford mapping data show that even on a relatively small car (2.3L, 3000 lb., automatic) operated lean, there is a 3 percent economy loss associated with lowering the NOx down to a 2.0 g/mi feedgas to give a 0.4 tailpipe with an 80% efficient NOx catalyst. To provide reasonable confidence of certifying, by reducing the feedgas to 1.5 g/mi, increases the fuel economy penalty to 7%. Therefore, with the addition of a penalty for HC control, the fuel economy penalty from the uncontrolled economy is around 15% to 20%, for a small car using optimum calibration strategy and an 80% effective converter. Certainly by the late 1980 time period that JPL is considering as likely introduction for this system, a car at carry-over emission standards could be achieving near uncontrolled level fuel economy. In terms of the emission level trade-off with fuel economy, this is the important comparison rather than to the 1975 certification cars which were demonstrated to be far from optimum by the 1976 results.

JPL does not examine the loss in fuel economy penalty as a function of car size. Rather, they indicate a different emission capability for the various car sizes. Since the law is not written or administered this way, it would have been preferable to look at fuel economy at a constant emission objective, more stringent than the standard.

The JPL statement on near-term Otto-engine fuel economy will be interpreted by many as saying there is little or no fuel economy loss due to control to the 0.41/3.4/0.4 emission level. This is definitely untrue even for their mature system when the comparison is made to what cars could be. If their projection of 9 to 10% improvement relative to 1975 models were true, it would merely mean that at 1975 emission standards there would be potential for about a 25% improvement in fuel economy - most of which would not be available at the more stringent standards.

It is unfortunate that JPL did not start with a base 1975 vehicle and proceed step-by-step from that base to their mature system and identify and support the assumptions in each step. The semi-quantitative discussion that was used to support the conclusion was not done accurately. It went something like this: the 3-way catalyst cars tested give economy about equal to the best 1975 cars; a 5% improvement will be assumed for the improved induction, EGR and spark control systems for a total improvement of 9 to 10% from the average 1975 car. Evidently a 4 to 5% difference was assumed between the average and the best 1975's. Also, Figure 3-16 shows the fuel consumption of the 3-way systems to be about 5% inferior to the best '75's instead of equal. It is even possible that some of the 3-way data are hot-start data, for which fuel economy is about 5% higher than cold-start data (e.g. we know the Ford system listed in the referenced NAS report was tested by the hot-start procedure). Therefore, the "equal" statement is incorrect and should probably be 5 to 10% less. This wipes out most of the improvement projected. When asked specifically for this type of analysis after the report was published, JPL did not provide sufficient information to do a detailed critique.

In contrast to the optimism on near-term performance of the Otto engine is a pessimism relative to intermediate and long-range development. Engine changes such as variable valve timing, variable compression ratio, and ultra-dilute combustion were not considered even though, at the high funding level, their development is no less likely and variable cost would be no more than the alternate engine programs supported. This may partly be the fault of the auto industry for not having the vision to do more research in these areas.

Some more specific objections and comments on Chapter 3 are given in Appendix B.

CHAPTER 4 - The Intermittent-Combustion Alternate Automotive Power Systems

This long and involved chapter covers a very broad range of alternate engines; most notably, the lean-burn Otto engine, the

Stratified-Charge Otto engine, and the Diesel engine. Within the group of stratified-charge engines are the two Ford is working on the three valve prechamber (or CVCC) and the PROCO. Because of the wide range of alternatives covered, the discussion dealt mostly with the basics of pollutant formation in an intermittent-combustion engine and described the basic limitations rather well. The purpose was to choose and characterize a couple of engines in this category to represent the category in the engine comparison.

The prechamber diesel engine and the open-chamber direct-injected stratified-charge engines were picked as best candidates. It's widely recognized that without exhaust treatment these engines (and others in this family) cannot achieve the statutory standards for all three regulated gaseous pollutants without an extreme loss in fuel economy and power output.

The prechamber diesel engine is predicted by JPL to have the ability to meet the 0.41 HC standard, at least in vehicles up to about 3500 lbs. However, the lowest NOx standard that can be met at that vehicle weight is 1.5 to 2.0 g/mi. Somewhat lower NOx data has been reported, but JPL is correct in pointing out that this is not an OEE (Otto Equivalent Engine) and that the NOx emission might be higher with the turbocharger assumed for the mature configuration.

The stratified-charge (SC) Otto engines are projected to have higher HC and CO emissions and therefore require oxidation treatment to meet expected future standards. JPL correctly points out that "The use of a thermal reactor (as CVCC does) for control of HC evokes an increase in fuel consumption relative to the use of a catalytic converter to achieve the same HC control." JPL predicts 10 to 20% lower NOx emission than that from the diesel, but still not near low enough to meet the 0.4 standard. The 0.4 standard has been demonstrated at low mileage with the PROCO stratified-charge engine. However, this was accompanied by a large increase in HC and fuel consumption. JPL assumed the need for calibrations that would minimize these increases at the expense of poorer NOx control.

However, Ford Research has made some modificiations to the PROCO process, such as fast-rate injection, which promises a 15% improvement in fuel economy and a 50% reduction in NOx compared to the data used by JPL. This leads to a projection of 20 to 25% fuel economy improvement relative to a controlled uniform-charge Otto engine at the .41/3.4/.4 emission level rather than the 7% improvement projected by JPL. Possibly this more optimistic projection for the PROCO engine would have revised the JPL conclusion that this type engine "does not offer enough advantage over the improved conventional Otto engine, in vehicles of equivalent performance, to warrant their widespread introduction in general purpose automobiles".

Another reason for JPL's negative position on PROCO is probably because of fear that conversion to PROCO engines would cause a delay in eventual conversion to a Brayton or Stirling engine. In their words, "Also, conversion of the entire fleet to such an engine could further delay introduction of a Brayton or Stirling." Compared to even the "improved" PROCO, JPL would predict a fuel economy advantage of about 28% for the Stirling engine. The choice between intermediate and long-range technology depends on one's confidence that one of the prime long range alternates will "come home" at near the projected economy, cost, and emissions - regulated and unregulated.

One Ford reviewer stated that "We are not sufficiently clairvoyant to predict regulated pollutant limits or whether or not the pollutant of the period will be nitroamines, carbonyl sulfide, hydrogen sulfide, or a host of other chemical candidates to feel secure enough to recommend only one powerplant for the future". Additional detailed comments are included in Appendix C.

CHAPTER 5 - The Brayton Automotive Power System (Gas Turbine Engine)

This chapter discusses two of the three alternative powerplants which JPL feels should be given the major attention, namely, the two Brayton-cycle engines - the single shaft (SS), and the free turbine (FT).

The Ford turbine research group has also made projections on the SS turbine engine as a vehicle powerplant. Although the Ford projections were for a vehicle designed to somewhat different objectives, the results essentially support the JPL results with some minor differences as follows:

- JPL expects sizeable weight saving, whereas Ford feels the turbine engine will be as heavy as the piston engine it replaces.
- Ford projects slightly better 0-60 mph acceleration, but anticipates a problem with 0-4 sec. distance because of the response lag of the turbine. JPL did not calculate this measure of performance.
- Ford also projects 25% better fuel economy than JPL. The reasons for this includes higher projected component efficiency, low installed horsepower, and a larger and therefore more-efficient regenerator. The larger regenerator is partly responsible for the greater weight projected by Ford.
- Ford believes that the JPL projection of "approximately equal cost to a treated piston engine" is slightly low for a nearly all-metal-hot-part engine. Internal projections are that this lower cost level would require the use of ceramic stationary hot parts.
- Ford feels that start of production in 1985 is conservative for the metal mature-technology turbine.
- In Ford's opinion, the transmission to use with the SS turbine is a variable-stator torque converter ahead of a conventional three-speed automatic gear set. JPL seems unsure of what should be used and mentions six or more possibilities but do base their projection on the variable-stator torque converter type.

However, one must be cautioned against translating the relatively close agreement of the JPL and Ford studies into proof of accuracy. It merely means that both groups use similar or offsetting input assumptions and used a similar quasi-steady-state simulation of a dynamic driving cycle. A strong concern with both of these projects exists because -

- Even after six generations of the Chrysler FT turbine, it is below JPL's projected fuel economy for a FT type by a factor of about 2.
- The projections are based on component efficiencies of "handmade" parts and measured at steady state in the laboratory. Very little is known about how engine performance will be affected by:
  - Coupling losses, losses in efficiency due to non-ideal flow conditions in a tightly packaged engine.
  - Transient operation over a highly transient driving cycle like the EPA urban cycle. The temperature transients, particularly of the regenerator, could effect fuel economy significantly.
  - Production compromises in component design, for reasons of cost or durability of mass produced parts, may deteriorate performance. The GM truck turbine engine is known to have suffered severely in performance when turned over to Detroit Diesel for productionizing.

There is a general agreement that the SS Brayton is a better engine than the FT Brayton if the continuously variable transmission

(CVT) which it requires can be made to work. If the CVT is not reasonably sure, one has to question JPL's recommended level of expenditure on the intermediate SS Brayton; and, if the CVT is a sure thing, one must question JPL's recommendation to spend money on a parallel program on the FT Brayton.

The fairness of assuming use of a CVT with the SS Brayton while not giving the other powerplants benefit of an advanced transmission is questionable. It is argued that the CVT for the SS Brayton is state-of-the-art and CVT for other engines is not. However, some transmission improvements which are state-of-the-art such as four-speed automatics and five-speed manuals were not assumed even though they would have allowed smaller engines for the same performance and in other ways improved the fuel economy of the OEE vehicle. To compound the inequity, the development cost and retooling cost for the CVT transmission was not charged against the SS Brayton.

The long-standing question of initial response of the Brayton engine is still unresolved. Some experts think that the FT Brayton would be better than the SS Brayton and others hold the opposite view. There is some concern that the acceleration delay would be excessive if a metal radial-flow turbine were used; however, this is JPL's assumption for the mature engine. Also the question of fuel and combustor was left unresolved. Although the turbine's ability to use a wide range of fuels is expected to be an advantage, there is reason to believe that a highly volatile low-sulfur fuel such as gasoline will be needed to avoid excessive emission of sulfates and other small particulates.

Some more detailed comments are included in Appendix D.

CHAPTER 6 - The Stirling Automotive Power System

This chapter discusses the Stirling engine as an automotive powerplant and concludes that it, along with the two versions of the gas turbine, should be pursued at a top priority level. However, the state of knowledge for the Stirling engine as a powerplant for an automobile is very low; there has never been a near-OEE vehicle tested. Of course, Ford now has a prototype vehicle under development preparatory to testing. This lack of vehicle experience probably makes the vehicle projections on this engine the most risky.

This engine has the highest theoretical efficiency at the assumed operating conditions for a mature technology engine, but by only a very small margin over the Brayton engine. Because it is projected to be able to more nearly realize its theoretical efficiency than the Brayton, the mature engine efficiency is nearly 10% better than the mature Brayton. In advanced configuration, the higher temperature limit helps the Brayton more than the Stirling, so that an advantage of about 10% in vehicle fuel economy goes to the SS Brayton. Therefore, the honor for the most efficient engine depends on such nebulous things as the level of technology, even when both are at the same level, and on the practical efficiency loss, that is the loss from theoretical to actual.

The combustion process of the Stirling engine can be expected to be clean in terms of HC, CO, and NOx when EGR is employed. Bench testing of the burner confirms this expectation. There is still reason to be concerned about particulate emissions if droplet combustion of a diesel-type fuel is used. Droplet combustion may inherently produce emission of small particles and even the low conversion rate of fuel sulfur to sulfate may be excessive at the current sulfur level of diesel fuel. That is, the engine may not be pollution free the next time the emission regulations are rewritten.

The torque curve (vs. speed) of the engine is inherently very good - very much better than the unaided SS Brayton and therefore, it can be used with conventional transmissions. Noise is inherently low.

As might be expected, this impressive list of attributes is accompanied by some problems. The two major ones are power density and complexity. The complexity is partly the result of action taken to improve power density.

To achieve competitive power density without giving away efficiency, the engine uses a "barrel" design, a very high mean pressure, and hydrogen (H_2) as the working fluid. The barrel design uses swashplate actuation of the pistons and lends itself to a high ratio of swept volume to engine block volume, to the use of double acting pistons, and to a compact heater head. The high pressure and use of hydrogen add complexity to the problem of working fluid containment, particularly at sliding seals. In any configuration, the heat transfer surface required and the transient load control are complex.

The currently favored method of nearly eliminating leakage at sliding seals is the rollsock seal. This seal must be backed up by oil. This seal system alone is enough to discourage production application, particularly since a failure of a seal immobilizes the engine and requires a complete teardown for replacement. JPL recognizes that this problem by saying "The question of a production type rod seal has yet to be seriously addressed." Very recently, a near-zero-leakage sliding-type seal that should eliminate this complexity has been successfully tested.

There are five heat transfer interfaces in the Stirling engine. Two of these are basic to the operation of a Stirling engine and the other three are needed for reasons of efficiency or convenience. This extensive requirement for heat transfer surface with its attendant cost-volume-efficiency trade-off is a major disadvantage of the Stirling engine. The five interfaces are as follows:

1. From combustor exhaust gas to combustor inlet air. A ceramic rotating regenerator is assumed.
2. From combustion products to the working fluid in the heater head. A superalloy partially finned tube construction is assumed.
3. From hot working fluid to the internal regenerators for subsequent return to the working fluid during the next cycle. A porous metal monolith is assumed, but the current Philips engine uses a stack of stainless steel screen.
4. From the working fluid to the sink for rejected heat or more accurately to an intermediate heat transfer fluid. A bundle of cooler tubes surrounded by cooling water is assumed.

5. From the cooling water to the ambient air. This is the largest heat transfer surface because the Δ T between ambient air and cooling water must be kept low to maintain the efficiency and, since one side of the surface is a gas side, the heat transfer coefficient is low. Fifty-five pounds of aluminum alloy are assumed to be required for this component.

The final major system that stands out as complex is the load control system. Actually this could be further divided into the control of power output at a near-constant heater-head temperature and the control of fuel and air to the combustor to maintain a near-constant heater-head temperature. The later is fairly conventional combustor control based on the signal from four thermocouples in the heater head. Control of the engine output is more complicated and still in an early state of development. The most efficient way of controlling load is to vary the mean working pressure. However, this requires pumping working fluid either in or out of the engine from or to an external receiver; with a reasonable size pump, this process is too slow to follow vehicle transients. Therefore, this control must be augmented temporarily by either dead-volume control or bypass control or a combination of both. The JPL report assumes the use of dead-volume control, but the Ford/Philips (F/P) engine uses bypass control. Bypass control is very inefficient and therefore, the time it is used must be minimized. The F/P engine does this by a design that causes the first half of the load change to occur based on allowing equalization of a pre-existing pressure difference.

Because the mass of working fluid is held constant, the external receiver automatically takes on a pressure opposite in magnitude to the mean pressure of the engine. That is, when engine pressure is high the receiver pressure is low because nearly all the H_2 has been pumped out of it into the engine; conversely, when the engine pressure is low, the receiver pressure has to be high. Therefore, a high load (high engine pressure) condition can be dropped by letting H_2 escape from the engine to the receiver until the pressure balances and a low load condition (low engine pressure) can be picked up by letting H_2 flow from the receiver to the engine until the pressures equalize. Of course, once the pressure equalizes, pumping must begin to complete the load change. In the meantime, bypass or dead-volume control can be used to further decrease load; a further increase has to wait for the pumping process. The transfer of H_2 from the receiver to the engine must be timed to add the H_2 at the proper time in the working cycle of each of the four working volumes. Entry at the wrong time can temporarily decrease engine output.

The above discussion is intended to convey the degree of complexity and the number of new systems for which manufacturability must be established and that must be developed through successive generations to be durable, maintainable, low cost, etc. For this reason, even the better alternate engines must be thought of as "long shots" - deserving of continued development but not to be relied on at the exclusion of other alternatives.

CHAPTER 7 - The Rankine Automotive Power System

This chapter considered a range of Rankine or Steam engine types that have been proposed for vehicle use and chose a representative one for inclusion in the alternatives to be compared. JPL investigators conclude, as do most technical people other than those associated with a Rankine engine project, that this system would be a very poor choice for automotive use. It has the disadvantages of high cost, weight, and complexity without the compensating virtue of fuel economy. It does have virtues of good torque characteristics, potentially low noise, and low regulated exhaust emissions, but these are not too important without high fuel economy. Specifically JPL predicts that, at the mature level of technology, the Rankine engine would have the poorest fuel economy of the seven engines considered. At the advanced technology level, it would still be second from last. The poor theoretical efficiency is explained as being basic to the cycle so that only if the practical efficiency loss could be made very low, (actual efficiency very close to the theoretical efficiency) would this be an attractive engine. The steam engine proponents claim that new cycles using reheat, among other modifications, will overcome this efficiency problem. However, the additional complexity will further decrease its attractiveness from other standpoints.

The most important observation relative to this engine is to note how rapidly a "top contender" can become an "also ran" in the technical race to replace the Otto engine. Not more than three or four years ago, this engine was tops in the plans of EPA and receiving rave reviews in the popular press. Fortunately, this misplaced enthusiasm was not allowed to precipitate a massive commitment of industry funds to this engine or legislation requiring a commitment. A program funding level much below that recommended by JPL was enough to uncover the shortcomings of the engine. Similarily, a low profile on the current top, but unproven, alternatives may be the best course of action.

CHAPTER 8 - Electric Vehicles

This chapter on electric vehicles reached the conclusion that with current technology, even developed to a mature status, the electric vehicle could not compete with the liquid-fueled vehicle for general purpose, personal transportation. The single roadblock to effective competition is lack of a battery that fulfills all the requirements. This is a generally accepted position within Ford and the auto industry. The bulk of any research funds for electric vehicles must go toward development of the high-output batteries.

The concise statement of conclusions did not make it clear enough that electrics were not being ruled out, either in the very long term when liquid fuel may not be available or in the nearer term for special-purpose vehicles. There were strong objections to the relatively low quality of the technical discussion of electric vehicles even though the overall conclusion was not affected.

These specific objections are given in Appendix D.

CHAPTER 9 - Hybrid Vehicles

The objective of this chapter was to determine the potential of the hybrid vehicle concept to reduce fuel consumption at required emission and performance levels. A hybrid vehicle is defined in this report as one which has a reversible energy storage system on board. Technically, this includes the simple electric vehicle discussed. in the previous chapter. The total number of alternatives to consider within this general definition is enormous because of the multi-dimensional nature of the grid of alternatives. The major dimensions and some of the alternatives in each are as follows:

Prime power source

- Any of the alternate heat engines already discussed

Operating mode of power source

- Single point (on, off)
- Constant speed, variable load
- Constant load, variable speed
- Variable speed and load

Energy storage media

- Batteries
- Flywheel
- Compressed gas

Energy storage capacity

- All urban operation
- Acceleration augmentation

Basic drivetrain design

- Series
- Parallel

The large number of combinations as well as time constraints on the study may be responsible for some of the detail errors that appear in this chapter. A more general objection to this chapter is that the analysis deviated from the OEE concept of comparing OEE vehicles, which was developed and used for the heat engines and was not used for the hybrids. Neither were the EPA urban and highway cycles used as driving cycles for this evaluation.

Nevertheless, some very worthwhile insights were developed which allowed the hybrid vehicle to be put in broad perspective. JPL pointed out that improved fuel economy for hybrids generally comes from two areas: (1) improved heat engine load factor and (2) regenerative braking. The trick is to keep the lower than normal efficiency of the complicated "drivetrain" and the increased weight of the energy storage system from severely eroding these inherent gains. The bigger of the gains under all except extremely transient driving--the improved load factor--also can theoretically be achieved with continuously variable transmissions. The analysis suggests that if both alternatives existed (CVT and hybrid powertrain), the CVT would be best for highway driving and the hybrid best for severe urban driving. The crossover point cannot be quantified with current knowledge, but the EPA urban driving cycle is probably transient enough to give an advantage to a hybrid system.

Rated against the JPL mission of finding a powerplant for general purpose cars, hybrid was down-rated because the small heat engine would not give the vehicle sustained hill climbing ability. This would not be a problem in certain special applications such as a city delivery truck.

CHAPTER 10 - Vehicle Systems

One purpose of this chapter is to explain the vehicle simulation technique used by JPL to calculate performance of OEE vehicles and to use this model to show the importance of considering the vehicle as a complete system. Probably the most important point made is the obvious but frequently neglected one, that a fair comparison of alternate powerplants must be based on vehicles capable of performing their transportation function in a nearly identical way or at least so as to be equally satisfactory to the user. That is, they must be matched in accommodation space, mobility, performance, range, exhaust emissions, and comfort features.

Because fuel economy is of very high societal importance, the approach was to allow projected powertrain differences to show up as fuel economy differences after all other criteria had been equalized. A study <u>could</u> be made in which fuel economy is equalized for all the alternatives and one of the other criteria, such as performance, allowed to vary. It's worth noting that the relative position of the alternatives ranked according to the criteria allowed to float depends to some extent on the magnitude of the other criteria to which the alternatives are normalized. For example, had the comparison been made at a much lower performance level, the low-specific-output engines, such as the Diesel, would look more attractive, and the engines that scale down poorly, like the gas turbine, would look less attractive. JPL was realistic in assuming a performance level close to that of current cars.

The concept of the analysis is sound, and most of the constraints put on the vehicle were well chosen. However, the choice of 0-60 acceleration time and 0-10 sec. distance as the two measures of acceleration was unfortunate. These are typically too close together on the time-distance curve to define much of the performance function. It would have been better if a measure of initial response, such as distance in four seconds, had been included. Also, no accounting was made of high-speed passing, hill climbing ability or other sustained high-load operation. If more measures of performance had been considered, it would have been necessary to determine trade-off relations to equalize an importance-weighted performance index of some kind.

It's worth emphasizing that this approach is not intended to lead to comparison of vehicles at equal horsepower and equal weight, but rather vehicles with equal acceleration and equal passenger accommodations.

It appears that the fuel economy calculated for the alternatives can be rather sensitive to the power vs. vehicle speed curve used for each engine/transmission/shift-schedule/axle-ratio combination. A drivetrain with a "fat" power curve can achieve the standard acceleration rate with less installed horsepower than one with a less fat power curve. Lower horsepower means lower engine and lower total vehicle weight; this saves fuel. The smaller engine also operates at a higher load factor during the cruise modes and has a lower fuel consumption at idle - additional savings in fuel. The report did not explore this sensitivity in a comprehensive way.

If the sensitivity is as significant as expected, more attention should have been given to optimizing the drivetrain for each engine. Based on the report and conversation with JPL investigators, the calculations were done rather far from optimum for many of the engines. The shift speeds used were said to be 90% of maximum engine speed. Therefore, for the engines shown in Figure 10-1 to have their peak power at 100% speed, the maximum power is never used, and the shifts would drop the speed so low that power would be drastically reduced. What one calls 100% of speed is rather arbitrary. The power curves used (Figure 10-1) generally defined 100% speed as the peak power point except in the case of the FT Brayton where the 100% speed point is shown as more than 20% above the peak power point speed. Most reciprocating engines also reach peak power at a speed below the maximum safe operating speed by 10% at least. If the data for these engines had been plotted with peak power at 90% speed, this would give the effect of a fatter power curve and presumably improve the performance so as to allow a smaller engine. JPL defends their non-optimum analysis on the basis that it was the same for all engines and still gives an accurate relative comparison; however, the two gas turbine engines were not disadvantaged by the chosen power-speed curve. The correct technique would be to show the power curve to a 100% speed point equal to the maximum safe operating speed and then by iteration arrive at overall drive ratios and shift points to maximize fuel economy of the OEE vehicle.

Another drivetrain optimization decision which should have been handled better is choice of transmission. JPL's most obvious deviation from a uniform treatment was the assumption of a CVT of the variable starter torque converter (VSTC) type on the SS Brayton engine. Certainly other engines would have profited greatly by the assumption of a CVT. The reasons given for assuming a CVT in the one instance were that the SS turbine absolutely needs such a transmission to be practical and that the relatively simple VSTC type may be acceptable for this application whereas it is not acceptable for general application to the reciprocating engines. Nevertheless, one would think that some form of transmission optimization should have been considered for the other engines. In contrast, as indicated above, the other heat engines were attached to conventional four-speed manual or three-speed automatic transmissions without even optimization of power curve definition, intermediate gear ratios, or shift points. The advantage given the SS Brayton is somewhat compounded by the assumption that the VSTC transmission had the same efficiency as the conventional three-speed automatic. This is probably not true because of the high slip condition that exists over most of the operating conditions. This uneven treatment of the engines must be kept in mind when discussing the results.

The other main purpose of this chapter was to use the vehicle model to quantify the fuel saving possible with vehicle modification only. This was used to support JPL's recommendation that vehicle changes could be changed so as to significantly reduce the fuel consumption of Otto-engined vehicles until one of the more desirable alternate engines could be put into production. Therefore, this chapter really contains two distinct analyses. The first calculates how fuel consumption of current cars would vary when the engine only (engine and transmission in case of the SS turbine) was changed and the vehicle weight was adjusted to account for the difference in powertrain weight. The second leaves the UC Otto engine unchanged and calculates the fuel consumption reduction possible with certain vehicle design changes. The changes assumed were:

Weight reduction by

- exterior size reduction (maintaining passenger space)
- materials substitution
- V-6 engines
- front-wheel drive

Other changes

- 4-speed automatic with lock-up or CVT
- reduced acceleration capability
- lower aerodynamic drag
- improved accessories and accessory drives

The realism of some of the vehicle modifications projected is questioned. Nearly everything listed is being actively pursued, and some things are already incorporated in a first generation way. However, JPL has underestimated the difficulties involved in implementing the new programs, in terms of requirements for human and financial resources, effects on manufacturing facilities, and changeover of suppliers of finished parts and raw materials. The enormous costs of the changeover must be borne at the same time JPL would have the industry dramatically increase research expenditures on alternative powerplants. The two programs quite possibly are incompatible from a funding standpoint.

These changes must also be considered from the standpoint of marketability. For example, the increase in vehicle height that JPL recommends can only be implemented if people are willing to accept the less "sporty" profile. It's not true that, as JPL said, "the cars that get promoted get sold." It is a common notion outside the automobile industry that by some psychological advertising magic auto companies can manipulate customers' desires in new cars. In the long term, this is incorrect. (If it were correct, the auto industry would never have to drop car lines because of poor sales or ever have to switch production facilities from a model which isn't selling to one that is.) In reality, the cars that match consumers' perceived needs get sold, the ones that don't match, don't get sold, advertising notwithstanding. Advertising can inform customers of what you have to sell, what you believe are its strengths, and may temporarily result in sales benefits, but over the longer term it cannot make people buy what they don't want.

One must also account for the trade-off with other objectives--for example, achievement of a low aerodynamic drag coefficient (C_d) in terms of weight and package. Sloping wind shields reduce C_d

but add glass (weight) and can intrude on the passenger compartment.

For validation of the vehicle model to calculate, the fuel economy of the cars for which test data existed should have been calculated also for comparison. An extensive discussion is given about cold-start effects on economy and of the difference between fuel economy measured on the chassis dynamometer and actual road fuel economy. Yet the report is not clear, and possibly not consistent in what fuel economy measures are being used.

CHAPTER 11 - Manufacturability and Costs

Even though answers to the technical questions of what the alternate engines can do is known with only moderate accuraby, this is very much better than information on the cost. Technical questions can be answered with a single sample of an engine, the cost question for totally new components cannot be accurately answered until processes have been established, prototype machines have been designed, and prototype production has established machining speeds, scrap rates, etc. It would seem impossible to estimate costs on parts to be mass produced from material for which JPL had to estimate costs because the material is not yet mass produced.

More accurately, the cost question is how to optimize the trade-off between function and cost of manufacturing. Modern computer optimization design techniques assure that early cost-is-no-object prototypes will perform up to the potential of the engine; the risk is that function will have to be sacrificed when cost is reduced to an affordable level. This report uses the rather optimistic assumption that function will not be compromised in arriving at a manufacturable design. Therefore, when developing cost data, one must assume that the final parts bear considerable resemblance to the prototype parts; therefore, process costs are likely to be high.

Certainly JPL's almost total reliance on material cost without accounting for process costs cannot be used to give reliable cost estimates. The material costs do not reflect the process labor costs for special shapes such as tubing, castings and forgings. For this reason, all material costs reflected in Table 11-10 where JPL has multiplied the weight of the material by the pound requirements without regard to material processing costs, are unrealistically low; two glaring examples are:

(a) Superalloy (Stirling engine) usage is seven pounds times $3.70/pound which equals $26.00 (Table 11-10). This is assumed to be the tubing material for the heater head. In reality, adding the tubing processing cost to the basic material cost, seven (7) pounds of tubing would cost approximately $136.00.

(b) Ceramic (Stirling engine) usage is 15 pounds times $1.00/pound (average) equals $15.00 (per Table 11-8 for cost of cycle regenerator and cooler). There are no manufacturing costs added to make the ceramic regenerator; only the basic material costs were used.

In general, this type analysis was used throughout the study and all processed material costs are grossly understated.

In this chapter (Section 11.2), JPL states that to spread their cost estimates over a range of engine sizes, "material costs are scaled directly with horsepower. Labor costs vary with three factors: Foundry labor, assumed to vary directly with weight of material; assembly labor, a function of the number of pieces and held constant due to the assumption of design invariance with horsepower; and machining labor, a function of pieces," etc. This assumption is not necessarily valid because no consideration was given to complexity of manufacturing processes or assembly operations. The lack of a data base from which to develop cost data on the alternatives shows the need for manufacturing development programs to interact with the performance development programs.

In the next section, JPL states that variable costs are made up of fixed labor and material. They have failed to consider the variable overhead as part of variable costs. Further, in establishing the overall manufacturing costs, they state that it is 160% to 180% of the variable costs. This is extremely low and would not be a realistic plant burden rate for such a complicated and machine intensive manufacturing operation.

There are some additional cost related factors that are hard to quantify but should be considered when comparing the alternates to the current engine. Since the confidence of success with an alternate powerplant is less than 100% and there are other risks such as increased warranty costs, one would expect that the return on investment should be increased to compensate for the risk. Also, the analysis should be adjusted to account for existing Otto-engine facilities. The comparison is made as if all alternatives required totally new facilities. Possibly, the unrecovered value of any Otto-engine facilities that have to be scrapped should be added to the capital cost of the alternate engine in figuring the capital on which a return must be earned. The cost comparison was done only at the .41/3.4/.4 emission level; if the comparison were made at the higher NO_x level which the report states would be sufficient for most areas of the country, the cost of the Otto engine would be reduced in comparison to the Stirling and Brayton which have less to gain by relaxation of the emission requirements.

All the questionable cost data discussed above is summed to give total powerplant cost. This total cost, being no better than its parts, is not of sufficient accuracy in absolute terms and probably does not show the comparison between alternate engines with sufficient accuracy to be used to predict the commercial success of the recommended alternates.

CHAPTER 12 - Alternate Heat Engine Research and Development

The purpose of this chapter was to identify critical research and development tasks and estimate the time and money needed to attain the goals, or if there are any goals that are not likely to ever be achieved. The method used was the modified DELPHI technique which is an interactive estimation technique. Time did not permit full application of this technique to all of the R&D required.

The conclusions reached are that R&D to achieve a prototype, ready to be programmed for production, for either a mature Stirling or an advanced Brayton would have a variable cost of $130 million. Although the technical comparison was on the basis of a mature Brayton in this Chapter, JPL recommends that the advanced Brayton be researched because the experts consulted for R&D costs and timing predicted a prototype of the advanced version could be readied as soon as the mature version, and for very little more R&D money. This seems to be a weakness in the continuity of the report; it leaves one questioning whether the report is recommending the mature or the advanced Brayton for development. The Rankine R&D is shown as costing $260 million, but this is not recommended for pursuit. The above figures are based on pursuing research programs at the maximum useful expenditure rate to minimize the time (not the cost) to a preproduction prototype. None of these amounts include the production engineering, for which four years is assumed, needed prior to initial mass production.

Another cause for concern is that completion of a task is taken as the 75% confidence level; this seems overly optimistic to assume that such a low level of confidence is indicative of success. Exactly how this confidence level is calculated is not clear; conventional statistics would say that probability of a prototype engine would be the combined probability of its major components. However, if this calculation is performed for the mature Stirling engine using the probabilities shown in Figure 12-3 there is inconsistency between the combined component probabilities calculated as 55% and the total engine probability shown as 82%. The combined probability calculation is shown in Appendix F.

Based on these required amounts for alternate engine R&D and the industry's expenditure for powertrains as reported in Applications for Suspension of the 1976 Automobile Exhaust Emissions Standards, the study team concludes that "While it is beyond the scope of this chapter to say who should pay for the R&D, there seems to be little doubt that the industry itself can pay for it - in its entirety (which includes the necessary ceramics R&D)." This conclusion seems completely unrealistic because it ignores the large capital requirements for the vehicle and drivetrain improvements which the industry is already pursuing and which the

JPL report supports. An individual company cannot be expected to jeopardize its near-term competitiveness by falling behind relative to customer preference or, even worse, failing to meet government-mandated emission requirements and our voluntary commitment to a 40% fuel economy improvement by 1980. If anything, these near-term pressures would be expected to force a reduction of the longer range R&D - especially when success by the mid 1980's is only 75% assured.

CHAPTER 13 - Scenario Generation

This chapter discusses the input assumptions used to forecast total automotive fuel consumption and emissions in future years as a function of total vehicles, vehicle mix by age and size, and fuel economy for each class and age of vehicle. The modeling technique is nearly identical to the one that has been used at Ford for several years. The projected vehicle population input data is reasonable. The fuel consumption and emission assumptions that are used are developed elsewhere in the JPL report and will not be critiqued here.

CHAPTER 14 - Automobile Use

The main purpose of this chapter was to see if one should anticipate any radical changes in automobile use which would impact on the choice of a future automotive powerplant. The chapter also contains discussions, but no new or controversial insight, on such subjects as driving cycles, evaporative emissions, range requirements, and cold start effects.

CHAPTER 15 - Industry Practices

This chapter considers the process by which the industry might reach a decision to make an alternate powerplant and what factors might prevent them from making such a decision.

The principal conclusions of this chapter are as follows:

The automobile industry can generate sufficient capital to convert all Otto production facilities to any of the alternate engines recommended.

The industry can justify $200 million to over $1 billion in engine development programs on the free turbine, the SS Brayton and the Stirling between now and 1981 on the basis of potential increased profits. There are no barriers to conversion to alternate engines; and engine alternatives exist that can provide profit, fuel economy, low emissions, and protect the future of cars for use as private transportation.

Profitability calculations are based on the assumption that prices can be increased to the full extent of the total operating cost savings for a three-year period versus Otto-cycle engines equipped with 3-way catalysts. Incremental profit per unit equals the difference between the 3-year operating savings and incremental "manufacturing" costs.

These conclusions are based on several key assumptions which appear highly optimistic and, if erroneous to any significant extent, could result in a conclusion that replacement of Otto-cycle engines is uneconomic:

Car industry sales will increase at the same rate as the economy: This has not been the experience in the last two years and is difficult to visualize given the level of price increases envisioned in the study. Further, unit economic profits may fall substantially if mix shifts heavily to small cars.

Buyers are indifferent to price increases and will pay premiums for alternative engines if the differential pays out in 3 years (the JPL study assumes buyers will pay alternative-engine price premiums on top of the price increases associated with Otto-cycle engines equipped with 3-way catalysts): This assumption may be true over an extended period (possibly 20 to 25 years), but it's doubtful that an individual would have the price flexibility suggested during the period of transition to a new engine. The price increases associated with emissions and fuel economy programs for Otto-cycle engines probably would depress sales and severely limit additional price opportunity for alternative engines. Buyers could be expected to choose the lower priced Otto engine rather than higher priced alternative until all production facilities were converted. During the transition period, there would be major problems with competitive relationships, and there is a high probability that alternative engines would have to be discounted heavily. Further, price differentials always raise the question of trade-offs in the minds of potential buyers. It is likely that buyers considering the alternative engine also would consider down-sizing vehicle class or cutting back on option content, thereby depressing profitability.

Profit potential and mix: The profit projections are based on large car unit profit effects, and the analysis does not appear to include any small car mix. This overstates the profit potential considerable, and we suspect that on an average car basis the conclusions are invalid. If the market were to shift heavily to small cars, neither the FT Brayton nor the Stirling would appear to make technical sense relative to an Otto engine. The single-shaft turbine would still be profitable, however, holding all other assumptions constant.

Profit is calculated using the difference between retail price and manufacturing cost: This ignores the dealer margin and overstates the manufacturer's share accordingly. The JPL fixed expenditure estimate for one engine line (400,000 units) ranges from $430 to $870 million: The uncertainty surrounding costs reflects the state-of-the-art in Brayton and Stirling development and importantly affects decisions concerning the extent and timing of commitments to alternative engine programs. A more prudent approach may be to fund programs like Brayton and Stirling engines on a step-by-step basis with concentration on the critical technical issues. Funding can be increased at any time given cause.

The profit and investment uncertainties raise serious question as to the advisability of making commitments to alternative powerplants at the levels recommended. Ford generally agrees with JPL that "The dollar magnitude of the engine development program should be related to the profits that would result from a successful program outcome". Consideration of the risks leads to a conclusion that research should proceed at a more deliberate pace than JPL recommends. The industry justifiably requires a high confidence level in alternative engine designs prior to committing virtually all its resources to new engine types. If the assumption that Stirling or turbine engines can be feasible alternatives technically or from the manufacturing and cost standpoints by 1985 is optimistic, and assuming 1990 as the earliest practical date for production availability, the auto industry might have to implement UC Otto or SC Otto programs across the board in the early 1980's. Then the Stirling or turbine engines would become alternatives for the new engines.

Specific comments are detailed in Appendix G.

CHAPTER 16 - Vehicle and Highway Safety

This is another of the chapters whose purpose is to see if there is any peripheral reason why a particular alternate technology cannot or should not be introduced. In this case the question is whether there is any characteristic of any of the alternate powerplants or modified vehicles recommended that may adversely influence safety in normal use by increasing the accident rate or the consequence of an accident. The conclusion reached is that none of the actions recommended constitutes a major safety problem.

The major safety questions considered were the effect of a reduction in vehicle weight and size, the hazard of the Stirling engine with its highly flammable hydrogen working fluid, and the advantage of engines that could use a less volatile fuel than gasoline.

There seems to be some conflict between the recommendation in this chapter that "the industry should emphasize the building of large but light weight cars", and in chapter 10 where "exterior size reduction" is recommended as a way to reduce weight.

On the positive side, there are some worthwhile observations made in this chapter on the importance of avoiding regulations which severely compromise one objective while trying to achieve another. The adverse effect on fuel economy of the weight increase to meet damageability standards was mentioned as an example.

Since this chapter is not used to affect the relative ranking of any of the powerplants or vehicle modifications, it will not be critiqued further here. Some detailed comments are given in Appendix H.

CHAPTER 17 - Energy and Fuels

The primary purpose of this chapter is to predict energy and fuel aspects of the arena in which alternate powerplants will be competing in the future. In particular, answers were sought to questions about how extreme the pressure for conservation of fuel would be and what types of fuel would be in short or long supply.

The major premises in this chapter have been taken from two references (17-6 and 17-7) which predate the Arab oil embargo of the 1973-74 Fall and Winter. Although the JPL Report acknowledges the embargo and the probable efforts of the U.S. to achieve energy independence, the analysis is deficient. The inclusion of timely political and economic data and projections (available during the analysis preparation time period) would have produced a more balanced report encompassing both optimistic and pessimistic scenarios. A balanced analysis would have greatly reduced the strength of the case for rushing a new engine.

For example, Project Independence (available in November, 1974) projects a more optimistic view than the JPL Report. This report describes a 1985 future and beyond in which it is possible through accelerated domestic crude production, increased nuclear capacity, and conservation measures to achieve zero dependence on foreign crudes without developing a new engine. It is evident that the JPL authors were aware of Project Independence because Figures 3 and 4 of Volume II of the JPL Report contain data points from it.

There are six major explicit conclusions in this chapter that should be discussed. First, JPL concludes that fuels for automobiles through the 1980's and 90's will be liquids derived from petroleum crudes or coal. This is the current belief of nearly every source. The market and distribution networks are based on liquids, and the lead time for change-over is much greater than the period under consideration. The technology of converting coal reserves, tar sands, and shale to liquids is known or under rapid development awaiting a favorable economic climate for introduction. Therefore, this conclusion appears sound.

Next, JPL concludes that conservation measures and modifications in the use and energy consumption characteristics in the U.S. could eliminate the need for imported oil by 1990. This is consistent with other reports even without the requirement of the introduction of the Stirling or Brayton engines. There are many unknowns in the complicated effort to extricate ourselves from dependence on foreign crudes. For example, the impact of $11 per barrel crude on the number of wells drilled per year, rate of leasing of government lands, tax charges, price controls, voluntary and mandated conservation, and environmental regulations is still indeterminate. Increases in the price of imported crude should accelerate our efforts to achieve independence.

Also JPL concludes that process energy and dollars could be reduced if more diesel fuel were produced relative to gasoline. This assessment is consistent with that of others. This conclusion must not be confused with the energy impact of total conversion to diesels. The savings to be expected by total conversion to diesels decreases because the normal gasoline fraction is no longer effectively utilized.

JPL states that methanol-gasoline blends appear to offer no distinct advantage over gasoline. The use of methanol-gasoline blends will occur not because they offer a distinct advantage over gasoline but because gasoline will be in short supply or its expense can be reduced with the use of a less expensive extender. Ethanol is used in Brazil as a gasoline extender because of its availability. The JPL statement that "gasoline and methanol are not miscible to any great extent" is false and creates an incorrect negative impression about the feasibility of its usage. The aromatic content of gasolines is the controlling solubility factor. Gasoline with aromatic contents less than 15% (which are unknown in today's gasolines) may reject 35-40% methanol additions (it is unlikely that the methanol content will be this high) at temperatures below 70°F. Dry blends of typical gasolines containing 35-40% methanol do not separate at temperatures above +10°F. The phase separation of methanol-gasoline blends is a poor argument against its use because commercial alcohol-gasoline systems already exist in Brazil and Scandanavian countries. The removal of butanes and pentanes from gasoline to accommodate methanol would not result in the loss of these substances from the total energy picture since they can be alkylated to higher molecular weight products. On the whole, the basis for this conclusion was poorly developed and incorrectly biased.

JPL also concludes that engines that do not impose specific chemical requirements on their fuel will generate fewer energy availability problems than those which do. It is obvious that the more versatile the powerplant in terms of fuel, the more easily it is to satisfy.

A final JPL conclusion is that the capacity for electric power generation will not constrain the rate of introduction of electric vehicles. Since there appears to be no prognostication which predicts a significant number of electrical vehicles by 1985 or even 1995, this conclusion is probably valid.

As in several previous chapters, the overall conclusion of importance to the basic question of the JPL study is the lack of influence this consideration has on the choice of an alternate engine.

CHAPTER 18 - Material Resource Requirements and Supply

The object of this chapter is to evaluate the material resources (not cost) required to produce the alternate-engined vehicles in order to make sure the requirements do not exceed the supply, which can reasonably be expected to be made available. The key conclusion is that the required materials do exist in the ground in sufficient quantities for the next several decades and that proper planning and commitment can make them available.

The planning is made more difficult by the fact that several of the important materials (nickel, chromium, and cobalt) are not currently produced domestically in large quantities, but must be imported. The commitment is required because the increased demand would exceed the historical growth rate and the metal producers would not put the extra capacity in place without a firm long-term commitment.

Although not a cost chapter, the main importance of this chapter is how the material supply commitment might affect the total cost of the material when risk factors are included. For example, if a 10-year commitment must be made several years before production of an alternate engine,there is the risk that engine production may be delayed or aborted due to some technical or regulatory hitch, or that the material need may go away because of the introduction of yet a different powerplant or because of material substitution, such as ceramic for metal. The high risk associated with early commitment should be factored into the material costs in the cost chapter.

CHAPTER 19 - Air Quality Impact Study

This chapter only served to determine if JPL could support the need for some gross changes in the emission standards that would affect the choice of emission objectives for automobiles. JPL calculated reductions required using the rollback technique. The result was biased to give the highest possible rollback factor because JPL started with the highest observed concentration and failed to account for the expected change in spatial distribution with time. The statutory emission standards 0.41/3.4/0.4 (g/mi of HC/CO/NOx) seemed to be accepted by JPL as status quo to be deviated from only if they fell outside of the range of uncertainty.

The only deviation from the "unposition" that the statutory standards might as well be used is for NOx. Here JPL considers that, because of the large contribution of stationary sources, there is little advantage in going below 2 g/mi NOx for most regions of the country, but that in a few regions such as Los Angeles, the 0.4 NOx standard is necessary. The 0.4 NOx standard is assumed even though in the calculation based on a 1.0 NOx standard, the contribution of light-duty vehicles drops to only less than 1/3 of the total.

JPL generally failed to use cost effectiveness analysis or judgement to determine how each of the pollution sources should share in the allowable emissions of each pollutant in a particular region. JPL concludes for example, that a .41 HC standard is appropriate for the New York study area even though no reduction in total mass emission of HC from stationary sources is assumed, so that by 1990, light-duty vehicle emission of HC becomes only about 1/4 of the HC emission from stationary sources.

If JPL was not prepared to do a more definitive analysis of required air quality, it might have been better to merely use the legislated standards as objectives rather than give the appearance that an independent derivation was made supporting them.

Additional specific comments on this chapter are included as Appendix I.

CHAPTER 20 - Ownership Costs and Economic Impact

The purpose of this chapter is to determine the relative attractiveness to the customer based on engine alternatives as affected by total cost of ownership, and to estimate what effect a switch to one of the prime alternatives would have on economic growth rate, employment, and profitability of the auto and related industries.

The impact on the national economy was quickly dismissed by the claim that "the growth and stability of national output and employment is controlled by the government. Impact on the national economy due to changes in industry is usually limited in size and temporary in duration, compared with the effects of normal variations in government policy". This is probably not a universal truth. It seems unlikely that, in the long term, national economy would not be affected favorably or unfavorably, by a massive commitment to an alternate technology that proved to be either better or worse than that adopted by the vehicle industry of other countries. Also, neglect of near-term vehicle improvements for long-range improvements could have a serious effect on car sales and the economy in the near term. The attention that some foreign governments give to their auto industry implies that they don't see government monetary policies as the only factor in economic well being.

The cost of private automobile ownership is treated in more concrete terms. The ownership cost factors which are assumed to vary as a function of the engine are: original purchase price, maintenance (including expendable fluid except fuel), fuel cost, and resale value. The conclusion reached is that with either the SS Brayton or the Stirling engine, the generally somewhat higher initial cost would be recovered in reduced fuel cost (discounted back to current value) in from 0 to about 40,000 miles (for the mean or unperturbed case) depending on vehicle size and whether a Brayton or Stirling engine is used. Larger vehicles are projected to have a shorter payoff time; and, in spite of its poorer fuel economy relative to the Stirling, the SS Brayton is projected to have a shorter payoff time because of its lower initial cost. In fact, the SS Brayton-engined car is projected to have $30 lower selling price than the equivalent Otto-engined car; in which case the customer is financially ahead before he leaves the showroom. For a compact vehicle the cost is equal and in the small car, the SS Brayton is projected to cost $50 more than the Otto-engined car. The higher initial cost of the Stirling over the SS Brayton is never made up by its better fuel-economy during the projected life of the vehicle -- even when projected out beyond 11 years.

The main problem with the results of this chapter do not originate in this chapter but originate in Chapter 11 from which the prime cost input for this chapter comes. For some obscure reason, the cost data were reorganized using different formats and labels for the pieces of the total cost when moved from Chapter 11 to Chapter 20. The costs which were omitted from Chapter 11 computation, namely the distributed R & D cost, the contingency "profit" to cover the added risk, and the lost value of existing Otto engine tooling are still neglected here. When added to the possibly hundreds of dollars underestimation of the variable cost, the retail price differential could be many hundres of dollars higher than that shown by JPL in Table 20-2.

Since the possibility exists of severe underestimation of the cost of alternate-engined vehicles, the sensitivity study should have considered a much wider upside swing in initial purchase price than the $100 considered. Even using only this nominal increase above estimated price, the payoff period for compact Stirling engined cars exceeds 40,000 miles, and the small car payoff increases to nearly 60,000 miles. With such long payoff periods, there is serious question whether the average customer would not choose the lower initial cost Otto-engined vehicle.

The sensitivity study also seems lacking in that it did not consider perturbations on more than one of the parameters and did not consider the more important combined perturbations. For example, JPL did not consider how the cost to the customer would stack up if a higher than JPL anticipated initial cost were combined with a lower than anticipated improvement in fuel economy?

Some specific comments on the chapter are contained in Appendix J.

SPECIFIC COMMENTS ON CHAPTER 2: "FUNDAMENTAL CONSIDERATIONS OF HEAT ENGINES FOR AUTOMOTIVE PROPULSION"

In Section 2.2.3, the definition of indicated efficiency should be in the form of

$$\frac{\left(\begin{array}{c}\text{Work available at the output shaft}\\ \text{were no mechanical losses present}\end{array}\right)}{\text{Energy supplied in the fuel}}$$

Energy added to the working fluid should not be equated to the energy of the fuel for external combustion devices

Equation (3) in Section 2.4.1 is valid only for open systems. For closed systems, equation (3) should be in terms of Cv instead of Cp.

In Section 2.4.2, Cs is not the energy transport rate but rather the heat capacity transport rate and has units of Btu/hr/^{o}F, not Btu/hr.

The Emission Index used in Section 2.4.3 is a strong function of speed and load. Therefore, PPM estimates based on an average value may be misleading for detailed analysis.

SPECIFIC COMMENTS ON CHAPTER 3: "THE UC OTTO AUTOMOTIVE POWER SYSTEM (BASELINE)

The JPL investigators apparently misunderstand the sonic carburetor mechanism -- the discussion on page 3-9 suggests that the nozzle bar moves up and down, while actually the jaw slides back and forth. The report speaks of a durability problem with the sonic carburetor due to its sonic operating conditions. Ford has not found this to be a significant problem. The report expresses concern about cold-start transient operation when the sonic carburetor is operated at subsonic velocities. Actually, a sonic carburetor should function at least as well as conventional carburetors under these conditions. The report seems overoptimistic on the potential of ultrasonic atomization, possibly because of erroneous data. Table 3-1 of the report lists Thatcher & McCarter's ultrasonic carburetor as emitting only 0.89 gm/mi CO without exhaust treatment. This apparently was taken from the March, 1973 issue of Popular Science. This is probably a decimal point error and should probably read 8.9 gm/mi. Even completely vaporized mixtures do not give CO as low as 0.89 gm/mi.

SPECIFIC COMMENTS ON CHAPTER 4: "THE INTERMITTENT-COMBUSTION ALTERNATE AUTOMOTIVE POWER SYSTEMS

The fuel economy projection for the Mature PROCO engine is based on dynamometer data taken during 1974 at 16:1 A/F ratio and 12% EGR. No improvement in economy and emissions is projected as the engine reaches the "Mature" state of development. In contrast, the gas turbine is projected to achieve a 93% improvement in CVS-C/H economy from the sixth generation Chrysler turbine to the Mature (non-ceramic) turbine and the Mature Otto engine is credited with a 5% improvement relative to the "best" of '75 vehicles in addition to a significant reduction in feedgas emission levels.

At its present state of development, the fuel economy of the PROCO engine at the 1250 RPM 100 ft. lbs. point is 15% better than the 1974 data considered by JPL to represent the Mature-configuration PROCO. The feedgas emission level with the present configuration shows an identical HC level and 50% lower NOx.

So far as the HC emissions are concerned, advances in catalyst technology and fuel cleanliness which assure 77% in HC and NOx efficiency in 3-way operation can be projected to give 80% HC efficiency on the PROCO engine where excess O_2 is perfectly mixed in the exhaust and the HC concentration is inversely proportional with the mass flow rate.

Based on this latest data, and put in the context of the JPL study, the fuel economy gain of a .41/3.4/.4 level Mature PROCO engine in medium and large passenger cars is projected to be 20% against the Mature 3-way catalyst Otto vehicle and 25% against a Mature dual-bed catalyst system. Whether or not this projected gain justifies full development and volume production introduction depends among other things on the confidence level attached to the Brayton and Stirling projections of the JPL study.

SPECIFIC COMMENTS ON CHAPTER 8: "ELECTRIC VEHICLES"

The study reports a number of data on electric vehicles quoted from the literature completely out of context. Therefore, the reader would have no way of finding out that, for instance, in many cases the maximum speed listed is attainable only when the batteries are new and fully charged, and that the statements about range are in many cases meaningless and in general are not comparable to each other. Some of the ranges are given for steady speed, others are given for specific driving cycles, and still others are given for unspecified driving modes. The report does not mention that, while in the case of the Comuta, for instance, the range was fairly realistic, since it was defined as the range at which one could still attain the specified design performance; in other cases, the vehicle performance was quite inadequate at the end of the range. It appears that the report mixes actual experimental data with projections. For instance, it lists a Ford Comet powered with 1086 pounds of Sodium-sulfur battery which has never been built. Such a non-critical listing is certainly misleading.

In discussing specific batteries, the report is equally non-critical. For instance, JPL reports on the zinc-chlorine battery on the basis of a paper presented at the Third International Electric Vehicle Symposium and gives the impression that a fully functional, rechargeable battery was installed and operated satisfactorily in a vehicle. The fact that the battery was not (and possibly never will be) rechargeable is hidden in the easily overlooked phrase "A mechanically rechargeable system (was) used for vehicle tests . . ."

Much of the JPL discussion is based on obsolete information. For instance, it appears that all of the discussion on the Sodium-sulfur battery was based on an old 1972 paper. In the case of the Argonne lithium-sulfur battery, JPL is very bullish, apparently oblivious of the fact that Argonne has abandoned development of that battery, presumably as a hopeless task, and have redirected their efforts to lithium-iron sulfide battery.

The report makes general statements without documentation. For instance, they state "The lead acid battery ... does possess adequate power and cost characteristics for the electric vehicle." They base this simply on a TRW report, ignoring extensive other literature which indicates that the adequate power feature deteriorates during discharge and that, while the initial cost may be acceptable in some cases, the replacement cost is quite unacceptable because of the short cycle life of high-power lead-acid batteries. Most of the literature indicates that the cycle life of lead-acid batteries is so short that their overall replacement cost will be between 20 and 30 cents per kilowatt-hour delivered. Even neglecting the cost of the electricity used for recharging, this would amount to about three times the cost of gasoline, even at the current low efficiencies of internal-combustion engines.

In short, it appears that the authors of this chapter relied too heavily on 34 selected publications without any consideration as to how authoritative or current they were, and extracted information from these rather uncritically.

SPECIFIC COMMENTS ON CHAPTER 9: "HYBRID VEHICLES"

The discussion of batteries for the hybrid suffers from the same deficiencies as the battery discussion in Chapter 8, that is, it is insufficiently critical of reported work. For instance, JPL claims adequacy for the lead-acid battery in this application on the basis of a TRW-Gould report, neglecting the fact that the batteries which Gould supplied to TRW did not provide adequate power, and therefore TRW had to use, for their tests, twice the weight of batteries which they considered practical for vehicle use (Neal Reichardson, TRW, Inc., priv. comm.). They quote the long life of the BTL lead-acid batteries without mentioning their high cost and implying, quite incorrectly, that their power is reduced only as a result of the geometrically disadvantageous cell configuration. Actually, these are low-power batteries, designed for a low-power application, and no known published data is available to suggest that they could ever approach the high power indicated as a need for hybrid vehicles elsewhere in the Chapter.

It is disappointing that promising new concepts such as those of Bosch and IKA were discounted so quickly. These organizations have built hybrid vehicles which achieved good fuel economies even though the main thrust of their design was emission control.

Specific objections to the treatment of hybrid follow:

Comparisons were made on the basis of an operating cycle not representative of CVS - one which penalized hybrid operation unfairly.

- Only very light vehicles were considered, while it is well known that hybrids are promising for vehicles with low battery-to-vehicle weight ratios.
- The comparisons show idle fuel usage for hybrids with fuel shut-off capability - with the amounts actually exceeding that of the ICEs. During discussions with several of the authors, they acknowledged this error and that the idle fuel calculations for parallel hybrids (lines A, R, and S in columns E and F of Table 9-3) should be eliminated, and that the fuel calculations of line P should be the final predicted fuel economy for parallel hybrids.
- The report claims a concurrence by TRW in the low fuel economy improvement potential stated in the report. In fact, this is incorrect. The referenced TRW article actually projects a 49% improvement potential.

SPECIFIC COMMENTS ON CHAPTER 12:
"ALTERNATE HEAT ENGINE RESEARCH AND DEVELOPMENT"

The probability of success projected for total engine systems does not agree with the probabilities of success for the system components, at least in one specific case: The following probabilities of success were read off the curves of Figure 12.3 for the Stirling engine using mean curves at 1985:

Component	Probability of accomplishment by 1985 (using mean level of optimism)
Preheater	86%
Metallic heater head	87%
Cycle regenerator	94%
Cycle cooler	94%
Control system	91%
Improved seal	91%
Prototype_Mature Engine	82%

If the chances for success of each component are independent of the others (which seems to be a reasonable assumption in this case), the product of the component probabilities should equal the system probability of 82%. If the above component probabilities are multiplied together, however, the result is not 82%, but 55%.

SPECIFIC COMMENTS ON CHAPTER 15: "INDUSTRY PRACTICES"

The research and development phases shown in Section 15.2, and the timing and costs as they pertain to Otto-cycle experience, appear to be reasonable. The assumption that alternate engines will conform to similar patterns is not known, and if they do, it will probably be on a third or fourth generation engine rather than the first attempt.

The statement in section 15.3.1 that changeover from cast iron to aluminum casting can be accomplished at no cost is not true and is a major understatement of potential cost to convert to new engines.

In table 15.4, the period 1964-1973 was used as a benchmark to determine the ability of industry to fund a changeover to new engines. This was a unique growth and profit period for the industry. It is risky to count on these conditions in the late 1970's and 1980's.

The following quotation in section 15.4 is worth considering: "There are mistakes to be made; they will be expensive, and the automobile industry must be prepared for setbacks in these programs similar to the experiences of the past."

If the turbine experience were scaled up to the program recommended by JPL, the auto industry would have been a disaster. The JPL statement underlines the importance of avoiding commitments to programs prior to completion of advanced engineering work.

The cost and price data shown throughout Chapter 15 does not tie with data in other chapters. A sit down review would be required to understand fully the analysis.

Specifically, required information would include

- Development of the manufacturing cost increments which are applied to Table 15-10 to arrive at Table 15-11, "Profit Increase."
- Reconciliation of the estimates from Chapter 11 to those in Table 20-2.
- Table 15-3 detailed the development of the "Lower Bound" and "Realistic" changeover cost estimates. How does this relate to Table 11-12, "Alternate Engine Facility Costs?" How are the tooling costs developed?

In section 15.3.2, the funds for maintenance of the Otto engine facilities during the change-over period is handled by adding in half the current amount, based on the assumption of a linear transition. This approach does not make adequate provision for the first years when nearly all of the Otto-cycle engine facilities are still in place. Also, it seems some extra provision should be allowed for more maintenance and more rapid replacement of the first generations of alternate engine tooling. Certainly one would expect rapid advancement, but this will require replacement of earlier outdated tooling.

SPECIFIC COMMENTS ON CHAPTER 16:
"VEHICLE AND HIGHWAY SAFETY"

In Section 16.1, it is stated that "research on highway safety problems can yield improvements in the future, but there are presently known methods capable of greatly reducing the high cost of human accidents, which lack only meaningful application and vigorous enforcement." This would appear to be an over-simplification in view of the complexity of the problem. Later in the chapter, some comment is made relative to the reduction which could be accomplished through the elimination of the alcohol problem. However, no viable program is outlined to accomplish this.

In Section 16.2.2, no discussion is made of the possibility of explosion of the working fluid (hydrogen) in the Stirling engine in the event of a severe collision.

In Section 16.2.3 where electric power plants are discussed, the indication is that "electric prime movers and their controllers present no special safety problems beyond the normal design considerations implicit in their use in any commercial application." Considering the high voltage present in electric power plant application and the extremely high current, it would appear that the problem of servicing such equipment would present a major problem.

In Section 16.3, mention is made of the design of the vehicle structure arranged to deflect the engine under the car instead of allowing it to be displaced straight back towards the occupants. Attempts to deflect the engine under the car in Otto-cycle engines have been unsuccessful thus far. Adequate roof crush strength is mentioned as an important factor in accidents involving roll-over. Studies by Huelke of the Highway Safety Research Institute, University of Michigan, indicate that some roof crush is not detrimental.

SPECIFIC COMMENTS ON CHAPTER 19: "AIR QUALITY IMPACT STUDY"

The JPL report suggests that their approach and conclusions are consistent with those of the NAS study (National Academy of Sciences, "The Relationship of Emissions to Ambient Air Quality, Volume 3 of Air Quality and Automobile Emission Control," Washington, D. C. August, 1974). This implication is at best misleading, but is, in fact, incorrect. The NAS study discussed at great length the limitations of the simple rollback methodology and reached quite different and less pessimistic conclusions about the VES required to meet the AQS for CO and NOx. This matter has been discussed in some detail also by the NAS Panel report ("A Critique of the 1975 Federal Automotive Emission Standard for Carbon Monoxide," National Academy of Sciences, May 22, 1973) and in a number of publications from our laboratory.

As an illustration, the JPL report states:

> "Since carbon monoxide is a relatively stable gas in the atmosphere we can assume its concentration will be directly proportional to CO emissions (Ref. 19-23)."

Ref. 19-23 is the NAS report.

The JPL report has incorrectly represented the NAS report's position on this question. The NAS report (p. 95) states in part:

> "5.4.2.1 Linear Rollback. For a pollutant which is essentially non-reactive (such as CO) or one which decays through a first order chemical reaction (such as SO_2, in some instances), the equation describing its concentration is linear. Because the basic

governing equation is linear, if emission levels are reduced or increased uniformly, with little alteration in the distribution of emissions in time and space, then the resulting change in ambient pollution levels will be directly proportional to changes in emission levels."

There is the important caveat underlined in the NAS report that appears not to be understood by the JPL authors. The NAS (p. 96) states further:

"However, for situations where distinct changes in emissions occur in space and time, the proportional approximations may be grossly in error ... Regardless, maximum concentrations measured in the central city would not be reduced in proportion to total emission reductions."

There is general agreement that the "growth" of CO emissions with time will result in a marked change in spatial distribution. This is because of the saturation effect in the center city where the CO concentrations are measured. The expected growth is in the suburban and exurban areas.

Similar considerations apply to their NO_2 analysis. The JPL report states:

"Maximum nitrogen dioxide (NO_2) concentrations also appear to be proportional to oxides of nitrogen (NOx) emissions in the smog chamber or in the atmosphere."

This statement is reasonable for smog chamber studies, but has little basis for the atmosphere. In Los Angeles, for example, the NOx emissions from power plants are physically separated from vehicular NOx. The power plants have tall stacks and their NOx emissions go into the inversion layer, where they are transported some distance before affecting ground concentrations. In addition, NOx is emitted largely as NO and not as NO_2. The conversion of NO to NO_2 will be markedly reduced in rate because of HC reductions. The result will be that the NO will be much more diluted by atmospheric dispersion before it reaches its peak NO_2 concentration. Again, the simplistic assumption used by JPL should have been qualified by them if we are again to accept their conclusions as at all derived in a critical way.

The JPL report uses a new smog diagram attributed to Schuck and Papetti as well as the Barth diagram in relating HC concentrations to oxidant. The use of these diagrams is quite controversial. In fact, the Barth diagram is repudiated in the NAS report. A critical analysis of the Schuck-Papetti diagram is not possible because it is unpublished. One obvious flaw in the diagram (Fig. 19-7) is that the extrapolation should be made to 0.05 ppm oxidant, the background level, and not to zero. This would make the JPL predictions about HC control even more severe.

The use of Larsen's statistical treatment of atmospheric data[8] is often referred to in the JPL report. Larsen's point in using the statistical treatment is to give less reliance to the highest observed values because of the possibilities of errors. Thus, he states:

> "One alternative is to select a frequency close to the actual maximum, but far enough away to compensate for the possibility of inaccuracy in higher observations.

> The 0.1 percent frequency has been selected for this purpose. It represents the ninth highest value in the year, if data are available for 100 percent of the hours."

The JPL report does not follow this advice. They only use the highest value observed. Their frequent reference to the Larsen approach is really the inverse of what he did.

SPECIFIC COMMENTS ON CHAPTER 20:
"OWNERSHIP COSTS AND ECONOMIC IMPACT"

The calculation of (average) cost of ownerhsip neglected the financial loss when vehicles are lost from the population early in their life due to catastrophic causes. This financial loss increases as the initial cost increases and should be spread over the population by adding an increase in insurance costs to the cost of ownership. Table 13-1, mean survival propability by age, could be used to develop an appropriate cost increment to add to the ownership cost.

The use of fuel pump price in calculating ownership costs may not be appropriate when the scenario assumes essentially the entire vehicle population changes to a lower fuel consumption alternative.

The part of the fuel tax which is used to build and maintain roads, etc., is <u>really</u> a cost of ownership that is independent of the engine in the vehicle. If this cost is not met because fuel consumption per vehicle mile drops significantly, either the tax per gallon will have to be increased or an alternate source of highway funds will be required. Therefore, it would seem more accurate to treat the current fuel tax as a fixed ownership cost and credit alternate engines with savings in only the non-tax price of the fuel.

Critique by

Chrysler Corporation
Public Responsibility and
Consumer Affairs Staff
Detroit, MI 48231

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

3

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-222-3

June 29, 1977

Mr. S. L. Terry, Vice President
Public Relations and Consumer Affairs
Chrysler Corporation
P.O. Box 1118
Detroit, Michigan 48231

Dear Mr. Terry:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We are in receipt of your letter of October 16, 1975 to Bill Stoney of DOT wherein you provided comments on the subject report for use by the Federal Interagency Task Force on Motor Vehicle Goals Beyond 1980. JPL was pleased to learn of Chrysler's interest in the JPL report as evidenced by the preparation of the critique, and of Chrysler's conclusion that they "have been uniformly impressed with both the thoroughness and objectivity reflected in the overall effort. The report contains good information on not only the technical aspects of future power plant alternatives, but also on the economic and societal factors facing our Nation and the world in the 1980's and beyond".

The Chrysler comments were summarized under five headings which are responded to below in order of their presentation in your letter. The first comment in the Chrysler Summary concerns financial costs. Chrysler is correct in stating that JPL did not include the costs to redesign the vehicle to take maximum advantage of an alternate engine. The implicit assumption was that JPL recognized specific costs of alternate engines in addition to "business-as-usual" costs. It was the JPL assumption that redesign of the vehicle would be done at periodic three to five-year major model change points on an incremental basis, and thus be more properly classified as a business-as-usual cost rather than a specific cost chargeable to the engine. It is also true that the JPL costs implicitly assume a "success path" type of development. However, to the extent that there might be major setbacks of technical, or other nature, cost overruns could develop. We recognize this as a normal business risk.

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The second comment concerns our estimates of a 10-year product development cycle leading to possible introduction in 1985. Assuming success, of course, this means work seriously started in 1975, the year of publication of the report. Obviously, if one delays commencing the recommended development, the completion date will slip commensurately.

The third Chrysler Summary comment regarding the development effort justified for the longer-term alternatives, namely the Brayton and Stirling engines, relative to the near-term options, appears to be a matter of emphasis and degree. JPL's position has never been that work on stratified-charge engines and lower polluting diesel engines should be stopped. We did, however, find that Brayton and Stirling engines offer sufficiently high potential that substantial development effort appears warranted.

Chrysler and JPL are in full agreement on the fourth Summary comment pertaining to the less attractive alternatives.

The fifth Summary comment concerns first-cost versus life-cycle costs. JPL agrees that this is a controversial and complex area in which knowledge of consumer behavior is important but relatively sparse. It also appears to us that as the price of fuel increases there will be greater opportunities for creative merchandising aimed at developing consumer awareness of life-cycle costing.

Regarding the detailed technical discussion section of the Chrysler critique, there are many comments that cannot be adequately addressed here. The responses to these points will be implicitly incorporated in the appropriate Technical Task Summaries as explained in the enclosure.

Regarding the final comment that "Chrysler encourages any further efforts to update and refine the data provided in the JPL report", we are endeavoring to do just this in our on-going ERDA-sponsored work. We look forward to further opportunities for dialogue.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:tm

Enclosure

CHRYSLER CORPORATION

S. L. TERRY
VICE PRESIDENT
PUBLIC RESPONSIBILITY
AND CONSUMER AFFAIRS

October 16, 1975

Mr. W. E. Stoney
Acting Assistant Secretary for
Systems Development and Technology
Office of the Secretary of Transportation
400 Seventh Street, S. W.
Washington, D. C. 20590

Dear Mr. Stoney:

In reply to your letter of September 24, attached is a critique by Chrysler Corporation's Research Department on the report published by the California Institute of Technology, Jet Propulsion Laboratory (JPL report), "Should We Have a New Engine? An Automobile Power Systems Evaluation," JPL SP 43-17, August 1975.

In general, the attached critique follows the outline and conclusions reached in the JPL report. However, it is appropriate to note that no alternate power plant will be introduced for automobiles unless its overall cost can be justified by the manufacturer as a worthwhile investment. The cost of tooling any alternate power plant for automobiles runs into hundreds of millions of dollars. To take the risk inherent in making such an investment, a manufacturer must be certain of at least five years to ten years of volume production of the engine in order to compete cost-wise and price-wise with competitive engines of the then current design. Thus, when considering the timetable involved in getting alternate engines into production, at least several years must be added to cover the time necessary to develop the manufacturing processes and tooling required to produce the engine in volume. For both the Stirling and the Brayton-cycle engine the problems involved in reaching efficient low-cost volume production appear to be very substantial.

I hope that the critique and the foregoing comments will provide useful information for the Interagency Task Force in preparing their report on Motor Vehicle Goals Beyond 1980.

Sincerely yours,

SLT:rh
Attachment

CHRYSLER CORPORATION COMMENTS ON THE J. P. L. EVALUATION OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS

Introduction

The following report is a critique of the Jet Propulsion Laboratory's Evaluation of Alternative Automotive Power Systems for the 1980's. In our review of the J. P. L. report we have been uniformly impressed with both the thoroughness and objectivity reflected in the overall effort. The report contains good information on not only the technical aspects of future power plant alternatives, but also on the economic and societal factors facing our nation and the world in the '80's and beyond. Chrysler Corporation does, however, question some of the recommendations contained in the report and the conclusions that can be assumed from them.

We agree that the minimum time frame for developing and tooling a new power plant is ten years. We also agree that the time to start the clock running for the ten year period is at the time that adequate funding is applied to the project. Thus the J. P. L. report should not be construed to mean that a new power plant will be in production by 1985, because clearly funding of the magnitude the report recognizes to be required for an endeavor of this size has not been applied, nor does it seem likely that it will be in the near future. Even assuming the ten year time frame for the development of an all new engine, we do not agree that the new power plant will or can compete with the internal combustion engine on all counts of fuel economy, reliability, performance and even exhaust emission quality.

Some alternate power plants have theoretical advantages over the internal combustion engine. These theoretical advantages have caused Chrysler and many other industrial firms to spend tens of millions of research dollars investigating them over the years. But as any engineer or scientist knows, there is a great deal of effort required to turn a theoretical idea into a reality. A lot of hard work and money remain to be spent to prove that a new power plant will or can be more efficient for vehicles of the 1980's and beyond. The internal combustion engine has become the proven workhorse for vehicular propulsion for over seven decades and a great deal of effort and money is going to be required to develop a successor that can match or exceed its capabilities, particularly in the light of probable future improvements. In this regard we agree that given adequate time for development, cars equipped with Otto engines can be improved to meet J. P. L's assumptions for emissions requirements and also provide improvements in fuel economy. (J. P. L. 's emission requirement assumptions are 0. 4, 3. 4, 2. 0 nationally and 0. 4, 3. 4, 0. 4 for the L. A. basin only)

The following discussion summarizes Chrysler's specific comments on the J. P. L. report:

Summary

1. The findings and recommendations of the report appear reasonable on the surface. We are concerned, however, that because the subject is so involved and complex, it can be easily misinterpreted, resulting in improper conclusions. This is particularly true in regard to the financial assumptions and supporting development capabilities. For example, the report concludes there is "ready availability of resources for conversion to vehicles with alternate engines". This conclusion is apparently based only on the cost and research required for the engine changeover itself, and does not include that required for the total vehicle redesign to take full advantage of the new concept. Additionally, the cost of developing the advocated engines apparently does not include the cost of supporting existing vehicles and power plants during the phase-out period or of pursuing additonal alternatives. Experience has shown that a plan of action, funding requirements, and anticipated results defined on a "theoretical" basis are rarely accurate predictions of an "actual" long range R&D effort.

2. Throughout the J.P.L. report, "on or before 1985" is repeatedly stated as the time frame in which any of the Mature alternates could be brought to initial production. However, in the verbal briefing to Chrysler, J.P.L. cautioned that this should be interpreted as 10 years from time zero. Only when firm programs are established by industry and/or government will time zero be established. It is therefore emphasized that the 1985 date is of itself irrelevant.

3. In their summary, J.P.L. is very specific in recommending that development efforts should be concentrated on the Brayton and Stirling engines and that one or both should be introduced as soon as their benefits (fuel economy and emissions) can be realized in economically mass productible hardware. However, in the body of the report, J.P.L. does not rule out either the diesel or the stratified charge engines; a point that is lost in light of the strong conclusions and recommendations regarding the Brayton and Stirling engines. Chrysler studies indicate that equal priority should be given to the Diesel and Stratified Charge engines; the Continuously Variable Transmission; and the present Otto engine until a clearer choice is apparent. Specifically, this differs from the J.P.L. recommendation because:

   a) We disagree with J.P.L.'s premise that a CVT will benefit all engines equally. Our studies indicate that it will benefit the Otto, Diesel, and Stratified Charge engines significantly more than the Brayton and Stirling.

b) We disagree with J.P.L.'s premise regarding sizing the various engines to provide the same acceleration from a standing start. Our automotive experience indicates that this criteria alone is insufficient to provide a common performance basis for comparison. Other performance factors, such as 50-70 passing ability should be included, which result in different engine sizes and therefore differences in fuel economy predictions.

c) The results of our own efforts on Diesel and Stratified Charge engines indicate that these engines have development potential for low emissions as well as good fuel economy and that they cannot be ruled out as potential alternatives at this time.

Our conclusions therefore, are that the superiority of the Brayton and Stirling engines have not yet been sufficiently established, and that the other alternatives merit continued development. This additional devopment effort invalidates J.P.L.'s conclusions regarding both funding availability and time required.

4. We agree with J.P.L.'s conclusion that the Rankine, Electric and Hybrid engines are not viable alternative concepts for the 80's. Our studies concur that on a comparable basis the steam Rankine engine is inherently deficient in fuel economy and high in cost. Our studies on hybrid engines concur that overall system complexity, cost and weight (engine, electric motor, battery transmission, etc.) are excessive with no significant advantage in fuel economy or emissions.

5. Our experience indicates that J.P.L.'s direct balancing of higher first cost against reduced operating expense is overly simplistic. Granted, it might apply to commercial sales, but experience tells us that first cost is by far the major consideration in a highly competitive consumer market.

Discussion

The following is a more detailed discussion of the major technical conclusions made in the J. P.L. report:

1. Use of a Continuously Variable Transmission (CVT)

The J.P.L. report states that the use of the CVT will improve the fuel economy of all engine concepts equally. We disagree. (This transmission concept matches engine speed to vehicle speed in such a way as to approach the ratio desired for maximum fuel economy.)

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Chrysler studies support J. P. L.'s conclusions that the fuel economy of the standard Otto engine, the diesel or the stratified charge will improve by approximately 15% with the use of this transmission. However, our studies indicate that because of the flat specific fuel consumption characteristics of the Stirling and free turbine engines the use of the CVT results in much less improvement. We further believe that within the ten year time frame, the CVT is a more likely development than any of the new engine alternatives. If developed, the CVT would improve the relative fuel economy position of the conventional Otto engine, diesel and stratified charge, versus the Stirling and free turbine concept.

2. Engine Size for Comparable Performance

The J.P.L. report uses an Otto-Engine-Equivalent (OEE) vehicle concept to establish the alternate engine size and vehicle weight. It takes into account the differences in torque-speed characteristics, specific power (HP/LE) and the packaging of alternative power plants. These power plant effects then dictate corresponding structural weight changes in the rest of the vehicle. This approach is critical to their study and affects weight, performance, fuel economy, emissions, cost, etc.

JPL chose to size the various engines by using equivalent 0 to 60 acceleration rates for all cars. By doing this other performance such as the 50-70 mph passing ability was allowed to vary. The magnitude of this variation is summarized in the following table:

Concept	Time* 0-60	HP*	Curb* Wt.	Power to* Weight with 300# Test	Reference Passing Time 50-70 mph
US Otto	13.5	125	3100	.037	6.9
Brayton F.T.	13.5	89	2710	.030	8.6
Stirling	13.5	99	3050	.030	8.6
Diesel	13.5	131	3340	.039	6.6

*OEE Concept

The chart shows significant differences in passing time results. To provide more equivalent performance, balancing acceleration ability and passing ability, the Brayton F.T., for example would have to be up sized to approximately 107 hp. This would increase its size by 20% and reduce its fuel economy by about 10%. Thus, while a concentrated effort was made to evaluate the alternates on a common performance basis, we do not agree with the criteria chosen.

3. Reference Engine, - The Uniform Charged Otto

The J.P.L. report refers to the standard spark ignition engine as the U.C. Otto. Their Mature version of this engine is presumed to be of a reciprocating configuration, either 4 cylinder in line, V6 or V8 depending on engine size, J.P.L. assumes that this engine will be capable of 5% lower BSFC than the best of the 1975 engines through improvements in the induction system, and moreover capable of meeting the .4g/mile NOx level using only a 3-way catalyst regardless of vehicle size.

Based upon Chrysler's experience to date, this latter assumption is overly presumptive and could lead to erroneous conclusions regarding future developments because at this time we know of no system, including the 3-way catalyst that is capable of meeting these standards. We agree that the low emissions target will eventually be met, but the exact nature of the system and the time to develop it are still unknown.

For their Advanced U.C. Otto concept (circa 1990) J.P.L. assumed that an additional 15% in fuel economy could be achieved through development of materials and seals for a ceramic rotor Wankel. We question this selection until the effect of heat loss on fuel economy has been determined. The surface of volume ratio of the Wankel combustion chamber is over double that of a reciprocating engine, a factor intrinsically detrimental to fuel economy.

4. Diesel Engine

J.P.L.'s analysis indicates an approximate overall cost advantage of only $50 for owning and operating a diesel powered vehicle for 3 years. They conclude that this is insufficient to warrant its wide-spread use in passenger cars. This judgment stems essentially from their choice of the turbo-charged pre-chamber engine to represent the diesel class. We suggest instead that:

1) The specific power deficit of diesel engines compared to U.C. Otto engines is not so large as to warrant the use of turbo-charging for

passenger car application. Increased displacement (10 to 20%) can be a more cost-effective means of achieving the desired performance level in a given vehicle without significant depreciating fuel economy (being an unthrottled engine).

2) The open-chamber diesel has significant efficiency advantages over the pre-chamber engine. Additionally, there are recent indications that its emissions, peak-pressure and noise problems can be solved.

The result of the above changes to the input format of the analysis would improve both the initial and operating costs of the diesel powered vehicle, and thus the lifetime savings over a U.C. Otto vehicle. We suggest, therefore, that the Mature diesel engine may well play an important role in the transition from today's engine to that of the next generation of power plants.

5. Stratified Charge Otto Engine

At J.P.L.'s 2g/mi reference NOx level, our experience has indicated a 20 to 30% fuel economy advantage for the TCCS Stratified Charge engine over the U.C. Otto. Published data presented to EPA by Ford Motor Co. have indicated similar advantages for PROCO. This conflicts with the J.P.L. finding that S.C. Otto fuel economy is only slightly higher than the corresponding Mature U.C. Otto power system.

We do not accept the suggestion that the potential for lower NOx emissions of a Stratified Charge does not represent a major long-term advantage.

Finally, we do not accept the proposal of a rotary engine for the advanced configuration for the reasons stated earlier.

In the light of these potentials, it is our opinion that the Stratified Charge engine can not be ruled out as an interim or long range possible candidate.

6. Brayton Engine

The J.P.L.'s report considered two distinct arrangements of gas turbine engines: (1) a single shaft engine requiring the use of a CVT and (2) a free turbine. Details of their Mature free turbine concept closely parallels the design we are currently working on under an E.R.D.A. contract. We are scheduled to have our first engine running in April of 1976. A comparison of predicted BSFC values is as follows:

% Power	BSFC	
	JPL Mature	Chrysler/ERDA
20	.55	.60
50	.44	.46
100	.44	.44

As shown, there is excellent agreement at high power level. The disagreement at low power level is principally due to our selecting a more conservative part load temperature schedule than did J.P.L.

J.P.L. concludes that an Upgraded engine concept such as the Chrysler/ERDA is a potential production candidate. We consider it to be marginal at this time. Our reason for this, as discussed earlier, is that the turbine should be judged with respect to a CVT equipped Otto engine, and at a size adjusted upward to avoid an excessive penalty in vehicle passing time. Taking these factors into account, the Mature Brayton engine would project little or no fuel economy advantage over the Otto engine. However, its low emissions, use of broad cut fuels, and reliability might still make it a desirable choice. As material technology advances, allowing turbine operation at higher temperatures, significant improvements in fuel economy might be expected.

J.P.L. predicts, and we would agree, that a single shaft engine could be made to operate more efficiently than a free turbine. However, response time is more of a problem with the single shaft design. Our analysis indicates that until a ceramic turbine wheel is available the single shaft design is not practical.

For the Advanced Brayton engine, J.P.L. anticipates increasing cycle temperature from the 1900°F level of the Mature engine to 2500°F. This, of course, is predicated on the use of ceramic or other high temperature material which permits the use of the simpler single shaft arrangement. We predict a 30% improvement in fuel economy for the Advanced single shaft engine over the Mature free turbine. This is less than predicted by J.P.L., but significant enough to make the Advanced concept an attractive long term candidate. Parallel development of the required CVT is, of course, again presumed.

7. Stirling Engine

Current Stirling engine concepts utilize hydrogen gas at 3000 psi as a working fluid. The development of adequate sealing of this gas, especially in a mass production application, will be a monumental engineering challenge. Maintaining satisfactory engine response by controlling the amount of dead

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volume within the engine or by varying the pressure level of the working fluid will similarly be a major challenge. However, because of the engine potential: excellent fuel consumption, especially at light load; quietness; and use of clean burning continuous combustion with broad cut fuels, we believe that it is an excellent candidate for alternate engine development.

Final Comment

As noted above Chrysler disagrees with several of the conclusions in the J.P.L. report. Nevertheless we want to reemphasize that we consider the report to be an excellent effort which has provided extremely useful information. It has provided us with a detailed reference against which we are able to review and reexamine our stated position on the various alternative engines.

Finally, Chrysler encourages any further efforts to update and refine the data provided in this report.

Critique by

Ricardo and Company Engineers, Ltd
Bridge Works Shoreham-by-Sea
Sussex BN4 5FG, England

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

4

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

RE: 34LPE-77-221-4

June 29, 1977

Mr. D. Downs, Director
Ricardo & Co. Engineers (1927) Ltd.
Bridge Works, Shoreham-by-Sea
West Sussex BN45FG
England

Dear Mr. Downs:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We are responding at this time in accordance with our restructured heat engine program as summarized in the enclosure. The Ricardo and Co. critique of the subject report is a thorough and detailed review of the technical areas of the study. We appreciate your sharing the results of this intensive analysis, which reflects Ricardo's long experience in heat engine development.

The scope of the Ricardo review is so broad that responding to all of your specific points is not feasible within the constraints of this response. These specifics are being integrated into our current work plan while the main thrust is discussed here. Thus, our responses to the critique will be incorporated in our ERDA funded (see enclosure) work, rather than addressed in this letter.

The general thrust of your review is that JPL's Otto cycle and Diesel engine assessments assume too little improvement in the future, while the Stirling and Brayton engines are evaluated too optimistically. Our judgement was based on the long development history of the Otto-cycle and Diesel engines, and on the fact that intermittent-combustion engines are largely limited by thermodynamic considerations. The Brayton and Stirling (continuous-combustion) engines, on the other hand, appear more responsive to improvements in temperature capability of materials and in component efficiencies.

Telephone 354-4321 Twx 910-588-3269 Twx 910-588-3294

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Mr. D. Downs -2- June 29, 1977

Again, these broad judgements are not addressed here, although our Brayton engine projections were supported in a letter from J. D. Collins of the Ford Motor Company to Ricardo, dated 3 February 1976 (copy attached). We intend in our on-going work to give special emphasis to the overall status and future prospects for each of the alternate engine types.

Again, we would like to thank Ricardo for furnishing us with their comprehenvise review and critique, and appreciate your continued interest in our program.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:tm

Enclosures (2)

J. D. Collins
Executive Director
Powertrain and Systems Research
Engineering and Research Staff

Ford Motor Company
20000 Rotunda Drive
Dearborn, Michigan 48121

February 3, 1976

Ricardo & Co. Engineer (1927) Ltd.
Bridge Works, Shoreham-by-Sea
Sussex DN4 5FG ENGLAND

Gentlemen,

We have read, with interest, your review (D.P. 20583) of 24th November, 1975 of the J.P.L. (Jet Propulsion Laboratory) report on alternative engines and would like to comment in particular on your views concerning the gas turbine.

We would agree that 1985 may be too early to expect production of the ceramic gas turbine.

On page 11 of your review, you indicate that J.P.L. estimates of fuel economy may be 10% optimistic for a mature 36HP design and 15% optimistic for the advance 86HP design due to potential losses in turbine wheel efficiency. We believe that the efficiencies assumed by J.P.L. are reasonable for the following reasons.

Recent work by NASA reported in ASME publication 72-GT-42 shows results from a family of wheel designs of 5" diameter in which efficiencies of 92 to 93% were demonstrated at pressure ratio of approximately 2:1. We believe that is an appropriate size for a 100HP mature engine and the level of pressure ratio is in the range that we design for in order to attain peak efficiency under road load operating conditions. If this wheel were scaled down to a 36HP range, we would expect a 40% reduction in wheel diameter and Reynolds number. Based on this NASA work and the work of Ricardo & Co., Mr. G. F. Hiett's paper 13 in 1964, published by the Institute of Mechanical Engineers, we would not expect a loss of more than 3 points of efficiency for this change of Reynolds number. Further, based on the NASA work and Mr. Hiett's work, we would expect that any adverse effects due to operating clearances resulting from scaling would be negligible. Since J.P.L. had assumed 85% efficiency total-to-total, we believe they have been conservative.

Turning to the assumptions for the advanced 2500°F engine, we have been using a design analysis method developed by NASA for obtaining maximum efficiency and off design predictions reported in their notes TN D-4384 and TN D-8063, respectively. While somewhat limited in attaining optimum specific speed by currently available material properties of ceramics, we project that 88% efficiency will be reasonably attainable with a wheel of 4" to 5" diameter, which is the approximate size needed for the higher tip speeds of a 100HP high temperature engine. With potential improvements of material properties of new ceramics, which we are currently working on, we believe that wheel efficiency can eventually be pushed to significantly higher values.

Incidentally, the NASA design method does correlate with the results from a 5" diameter wheel that we designed several years ago with which we demonstrated 90% efficiency at 4:1 pressure ratio.

You had postulated that ceramic wheels could not be made to the same level of accuracy as metal wheels, but this we do not find to be the case. Although all of our fabrication development has been done on axial type wheels, we are now able to fabricate ceramics both by injection molding and slip casting with accuracy equal to investment cast wheels, and have obtained trailing edge thicknesses also equal to metal wheel practice. We, therefore, believe that the turbine efficiency of 88% assumed by J.P.L. is reasonable.

We would agree that mass produced components will show variations from the experimental parts on which the case is built. However, we have found in our limited production of turbine engines that the adverse effects of these variations are due more to mismatch of compressors and turbines rather than inherent loss of component efficiency. We believe that in high volume production, we will have a better opportunity to overcome this problem by selective fit of components.

On the subject of combustor performance, we find that our experience does not support your concerns. In order to meet the most stringent requirements for NOx and stay within the window between high NOx and high CO, it is necessary to stay within a fairly narrow range of flame temperature or fuel/air ratios in the combustion zone. HC concentrations are not a problem. In order to accomplish this control throughout the operating range, it is necessary to vary the ratio of air provided to the primary or combustion zone and that provided to the dilution zone. This requires the use of variable geometry and, in addition, prevaporization of the fuel and premixing with the air is required to prevent droplet burning and consequent local stoichiometric combustion which produces high NOx. Prevaporization of the fuel is aided by the high combustor inlet temperature of a regenerative engine. By this method, we are also able to control combustion temperatures during transient operation if the change of variable geometry position is accurately timed to the change of fuel flow; this we have also demonstrated.

With this type of combustor, it will be possible to attain emission levels well below the .41/3.4/.40 gm/mile future requirement of our government even in the 2500°F advanced engine. General Motors has demonstrated in a vehicle this level of emissions with their low temperature metal engine. With very low HC and CO emissions, combustion efficiency is by definition very close to 100%.

You had expressed concern about the fuel volatility limits of the turbine combustor. We find that our low emission combustor works equally well with diesel fuel or gasoline, and the leading oil companies tell us that if turbine vehicles become plentiful, the best energy conservation use of a barrel of crude oil would yield a broad cut fuel with boiling point limits essentially between these two extremes.

You had questioned the need for a torque converter with the two shaft or free turbine type and suggested that its elimination would improve the free turbine fuel economy. There are several reasons for use of the torque converter. We have built free turbine passenger cars without the torque converter, and find it difficult to maintain acceptable shift smoothness in the automatic transmission without the torque converter and, in addition, we find that the exhaust noise tends to be unacceptable with a stalled power turbine. Chrysler, on the other hand, has included the torque converter for other reasons. By driving accessories from the power turbine they can eliminate the cost of a second reduction gear for accessories and can significantly reduce engine starting power requirements and battery size. The starter is directly connected to the gasifier shaft by a rubber belt. Secondly, by removing the accessory load from the gasifier shaft, engine response and idle fuel consumption should be improved. The latter is important to overall fuel consumption on any driving schedule that includes a significant amount of idle time. For these reasons, we do not believe that the torque converter should be eliminated from the free turbine nor that so doing would significantly improve overall fuel consumption.

In summary, we would agree that 1985 may be too early to expect the advanced ceramic turbine as there is a great deal of work yet to be done. We believe that J.P.L. assumptions for component efficiency are in general reasonable, but in particular we feel that the turbine wheel efficiency for the mature engine is conservative. We do not believe that their projections of fuel economy are unrealistic because of turbine efficiency or because of transient operation of the combustor. We believe that the fuel volatility tolerance range of the turbine is sufficiently broad and that the optimal turbine fuel of the future will have no adverse affect on combustion efficiency, flexibility or emissions. We do not believe that the free turbine should be used without a torque converter nor do we believe that so doing would significantly improve overall fuel consumption. While the CVT transmission efficiencies assumed by J.P.L. are modest, they do correspond to those we have attained in use with a single shaft turbine. If a more efficient CVT is developed in the future, we believe that the single shaft and free turbine will benefit approximately equally.

I hope that these thoughts on our part will help you in your thinking about the turbine engine.

Very truly yours,

J. D. Collins

BTH/md

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30th July 1976

Mr. G.J. Nunz,
Manager,
Surface Transportation Studies,
Jet Propulsion Laboratory,
California Institute of Technology,
4800 Oak Grove Drive,
Pasadena, California 91103,
USA.

Dear Mr. Nunz,

Thank you for your letter of the 8th June, only recently received.

We should be pleased to give you permission to publish pages 4 to 16 of our critique, as requested in your letter.

Yours sincerely,

D. Downs

3. RICARDO COMMENTS

To enable the Ricardo comments to be related to the report the Chapter numbers used will be quoted for reference.

3.1 Presentation of the Report

The scope of the survey is impressive as it not only encompassed the problems of the various powerplants, but also the effects of each on safety, U.S. fuel requirements, material resource requirements and the impact on air quality.

3.2 Chapter 2 - Fundamental Considerations of Heat Engines for Automotive Propulsion

Ricardo agree with the fundamental analysis of the various powerplants.

3.3 Chapter 3 - The U.C. Otto Automotive Power System (Baseline) (uniform charge spark ignition engines)

Ricardo agreed in general with the assessment of the present configuration, but queried those of the mature and advanced configurations. The mature engine was to be similar to the present engines with the exception of some form of sonic carburettor and a more complex after treatment of the exhaust. This assumes that engine design has or will stagnate in the next 10 years. Ricardo consider that much attention will be focused on the basic engine to investigate fully various factors such as:-

a) compression ratio; the compression ratio has a significant effect on the fuel consumption especially at low powers, the condition at which the majority of engines operate during normal vehicle operation.

b) bore/stroke ratio; Ricardo are at present investigating this using the Ricardo Hydra single cylinder engine, covering a range of bore stroke ratio from 0.84 to 1.3.

c) friction losses; it is known that a wide range of values can be obtained from current automotive gasoline engines. Investigation is required to find out the reason for the differences such as piston ring pack design, bore/stroke ratio, number of bearings, etc.

d) combustion chamber design; this is an area where further work is required to quantify the possible advantages, e.g. the 4 valve cylinder head. These could include;

improved fuel consumption due to reduced heat transfer to the cylinder head;

lower HC emissions due to the reduced surface/volume ratio and a larger portion of the chamber not directly in contact with the coolant with bore/stroke ratios of less than 1;

a small reduction in pumping losses due to the improved valve area/time diagram;

reduced CO and NO_x emissions as a result of an extended lean mixture misfire limit.

All of these factors interact and require a detailed investigation, which is not considered in the J.P.L. report.

The use of separate reducing and oxidising catalysts to achieve the low NO_x emission levels is generally not favoured, for reasons of poor fuel economy and catalyst durability and most catalyst manufacturers have concentrated their effort on the 3 way catalyst. At present this system has not proved its ability to maintain 0.4 g/mile NO_x emission for prolonged periods, but extensive development of both the catalyst and the oxygen sensor is being conducted by several companies. The problems with catalyst poisoning are misleading as reported by J.P.L. Sulphur only has a deleterious effect on non-noble metal reducing catalysts. Although phosphorus is not a fuel refinery problem, significant amounts can reach the catalyst from the lubricating oil. S.A.E. 750447 concludes that phosphorus originating from ZDDP or from a combination of ZDDP and ashless anti-oxidant is mildly toxic. However phosphorus originating from an ashless anti-oxidant can de-activate a platinum oxidising catalyst in the absence of calcium or zinc.

The J.P.L. statement that the 1975 model year vehicles have a superior fuel consumption in relation to previous years emission controlled models is true, but the 1975 model year vehicles fuel consumption is still inferior when compared with an optimised non-emission controlled engine.

The comments regarding an improvement in fuel consumption when using EGR is also considered confusing as Ricardo experience would not support this claim.

The J.P.L. advanced configuration of a twin rotor 10,000 rpm ceramic Rotary engine is considered to be unrealistic. Although the compact nature of the design allows a claimed 55% reduction in weight this is not sufficient to offset the many problems with the engine. The efficiency of the rotary engine would have to be considerably improved compared with current designs to compete with the Ricardo envisaged 'mature' engine. The tip seal performance and durability have been a problem and J.P.L. admit that adaption of ceramic technology will require a major research and development effort, possibly as a spin-off from that applied to the Brayton cycle units. Ricardo consider this extremely optimistic as is the use of the ceramics for both the rotor and housing. If ceramic coated housings are used differential expansion problems will occur. Alternatively if an uncooled all ceramic housing is used there are doubts regarding its mechanical strength. Lubrication between ceramic seals and housings will present problems due to the high temperatures. The temperatures likely to be experienced within the ceramic combustion chamber are estimated by Ricardo's to be between 700 and 1000°C. This could create problems which may be insurmountable with pre-mixed charge engines due to pre-ignition or detonation. Ricardo tests on metallic rotary engines have shown that pre-ignition commenced when the spark plug electrode temperature reached 850°C.

The future of the Otto cycle engine is played down but the proposed mature and advanced configurations do not indicate a full awareness of the engine developments at present being considered for the reciprocating engine or the inherent problems of the rotary engine. The use of ceramics is considered by J.P.L. to be the panacea for the current rotary engine problems with very little factual support for the optimism.

3.4 Chapter 4 - The Lean-Burning Otto Engine, Stratified Charge Otto Engine and the Diesel Engine

The lean burning engine is only briefly considered, and most of the examples given could well have been included in the comparison of induction systems in Chapter 3, table 3-1. No mention is made of the Chrysler, Ethyl or Yamaha lean burn systems in this chapter. The present Ricardo opinion of the lean burn engine is that it does not show any significant advantage except lower NO_x levels. At air/fuel ratios leaner than 17:1 the thermal efficiency (and therefore fuel economy) is worsening rapidly and unless air/fuel ratios of 19-20:1 are considered the reductions in NO_x are insufficient. In addition driveability problems are likely to occur in practice as the engine will be more sensitive to deterioration of the ignition or mixture preparation system than the conventional engine.

Hydrogen augmentation to extend the lean misfire limit is reported in some detail, but only the J.P.L. work, with no details given of the Siemens or I.M.C. (International Materials Corporation) systems.

The stratified charge engine has been typified by the Ford Proco, as representing the best current example a decision with which Ricardo would agree, as stated in their Survey of such engines on behalf of the U.S. Federal E.P.A. As a result of this Survey, Ricardo would however consider the CVCC system a close second. As a significant advantage of the continuous combustion engines quoted by J.P.L. is their ability to accept wide cut fuels, their review of stratified charge engines should have taken more account of the Texaco TCCS and MAN-FM systems which have, unlike Proco, a multi-fuel capability. The mature configuration of stratified charge assumes no development in the next 10 years as the specification given is of current technology (this being due to the choice of system). The claim in the J.P.L. report that the fuel economy of the S.C. engine can never exceed that of the Ford Proco system is based on the Blumberg prediction, with which Ricardo do not agree. Blumberg incorporated certain restrictive assumptions within his model, which whilst applying to the Ford Proco process do not necessarily apply to S.C. engines in general. By using the same degree of thermodynamic calculations that are applied to the Brayton cycle engines an improvement of 10-20% in fuel consumption of the S.C. engine can be shown.

The suggestion of the use of a 3 way catalyst on a stratified charge engine reveals a lack of understanding of the stratified charge process. The exhaust from the S.C. engine does not contain a constant level of 0_2, a requirement for the efficient operation of the 3 way catalyst. Attempts to achieve a constant level of 0_2 result in restricting the mixture strength range over which the engine can operate, therefore losing the potential advantage of the S.C. engine.

The choice of the ceramic rotary engine for the advanced configuration is considered unproven, the Ricardo comments being similar to those on Chapter 3 relating to U.C. Otto engines, and based on Ricardo's detailed study of the only direct injection S.C. rotary engine, the Curtiss-Wright, in their E.P.A. Survey. The Ford Proco combustion process cannot be applied to a rotary engine, due to the modulation of the fuel injection timing required. The only type of system that could be used is one in which the injection is always close to T.D.C., such as the Texaco or Curtiss-Wright systems.

The diesel "mature engine" configuration assumes no developments in the next ten years as with the exception of the turbocharger the suggestion is typical of current practice. Development of combustion systems and advanced fuel injection systems have not been considered, neither has the structures approach to reduce engine weight and noise. The combination of fuel injection and air swirl characteristics of the indirect or divided chamber systems offers the best compromise that can be achieved, with current technology, between thermal efficiency, wide speed range performance, gaseous emissions, noise, etc. However, on the basis of experience with larger truck size diesel engines, the best compromise between fuel economy and gaseous emissions lies in the more quiescent form of open chamber where mixing is predominantly fuel injection controlled. The application of this approach to the wide speed range light duty engine is inhibited by the limitations of current jerk injection systems, and active development is being undertaken at this time in this area.

It is predicted that an open chamber combustion system would result in 10% reduction in current light duty engine fuel consumption over the entire load and speed range. Clearly there is scope for further development on these lines. Gaseous emissions and noise may well increase compared with the indirect systems but should also respond to better control of the combustion through the medium of the fuel injection system. Table 1 summarises the Ricardo assessment of future combustion system developments.

Table 1 - Asssessment of Combustion Systems for Light Duty Diesels

	Indirect or divided	Swirling Direct	Quiescent
Attributes	Wide speed range operation due to high mixing rate also resulting in low NO_x emissions and noise by retard of injection.	Reduced heat rejection giving 10% reduction in fuel cons., better cold starting.	Minimum heat rejection. Therefore best economy and starting.
Limitations	High heat rejection due to high gas velocities. Also poor cold start ability.	Moderate speed range, limited by poor fuel injection/air motion matching. Advanced timings give high NO_x and noise.	Very narrow speed range with conventional jerk pump fuel system.
Innovations required	Reduced heat losses to give better economy, starting and reduced radiator size.	Better fuel injection/air motion matching over speed range, scope in both fuel injection and swirl generation.	Fuel injection system giving rapid but controlled mixing thus allowing wide speed range operation with retard of timing for low NO_x.

The use of ceramics again is proposed by J.P.L., but with very little evidence of either its successful application or ultimate advantage. The effect of increased internal surface temperatures on volumetric efficiency or lubrication problems have not been fully considered.

The suggestion of a rotary configuration as a solution to the likely practical problems of ceramic cylinder heads fitted with poppet valves ignores the more basic problem of achieving good combustion and an adequate compression ratio, at least in Wankel type engines, without having to resort to two stage compression and expansion. The compression ratio of 15:1 for the advanced configuration engine is considered too low for satisfactory starting even with the use of ceramics to reduce heat losses.

The conclusion that the widespread introduction of the diesel or the stratified charge engines could delay the introduction of the Brayton or Stirling Engines is based on the optimistic production date for these engines and their rapid widespread acceptance. Both of these factors are assumptions and therefore the stratified charge and diesel engine should not be abandoned until the Brayton and Stirling engines indicate their ability to achieve the J.P.L. target dates. The J.P.L. report does admit that the diesel engine should be adopted for specialised applications such as taxicabs. Ricardo completely agree with this point as the high mileage market is the area in which the greatest benefits from dieselization will be obtained, and quantified them in a paper to the Institution of Mechanical Engineers, entitled 'The High Speed Diesel Engine for Passenger Cars'. It is interesting to compare the correlation of the J.P.L. and Ricardo estimates for the future gasoline, diesel and stratified charge engines, shown in the following tables.

Table 2

Compact vehicle, 3 speed auto. transmission

CVS fuel economy

	J.P.L. mature engine			Ricardo		
Engine	Power HP	Test Weight lb	Fuel Economy mpg	Power HP	Test Weight lb	Fuel Economy mpg
Gasoline	125	3100	17.4-18.3	128	3500	16-17.4
Stratified Charge (Proco)	127	3150	20.0	128	3500	18.7
Diesel*	131	3340	20.7 (23)	128	3500	19.6 (22)

*J.P.L. - turbocharged.
Ricardo - naturally aspirated.

The diesel engine in the J.P.L. report was turbocharged while the Ricardo engine was naturally aspirated. The diesel fuel economy is quoted in the equivalent for gasoline fuel, and the true mpg is given in brackets.

Table 3*

CVS Emissions	J.P.L. (50,000 miles)	R & Co. (low mileage)
Engine	HC/CO/NO_x g/mile	HC/CO/NO_x g/mile
Gasoline	0.34/2.8/1.5 (catalyst + EGR)	0.2/1.0/1.3 (catalyst + EGR)
Stratified Charge	0.29/1.1/1.0 (catalyst + EGR)	0.15/1.0/1.4 (catalyst + EGR)
Diesel	0.32/1.3/1.1	0.46/1.0/1.3

Table 4

Engine Weight (excluding cooling system)

	J.P.L. (150 BHP)	R & Co. (128 BHP)
	Weight lb	Weight lb
Gasoline	591	540
Stratified Charge	620	580
Diesel	720	700

Table 5

Engine Cost Comparison (actual values not stated in J.P.L.)

	J.P.L.	R & Co.	
	$	$	$
Gasoline	0	595	0
Stratified Charge	+80	700 (avg)	+105
Diesel	+200	701	+106

The additional cost of the J.P.L. diesel is due to turbocharging and the inclusion of a wastegate.

3.5 Chapter 5 - The Brayton Power System, Gas Turbine Engine

The mature configuration proposed is a metallic turbine with a ceramic regenerator, a system already tried in truck engines and, with metallic regenerators, by Chrysler in passenger cars and therefore fairly well understood. The advanced configuration employs ceramics in the power and gasifier turbines and combustor as well as the regenerator and this may well not be achieved within the time scale. Because of the current knowledge of metallic turbines and intensive development of ceramic regenerators the introduction of the mature gas turbine by 1985 is considered feasible, but Ricardo optimism does not extend to the advanced gas turbine in the same year.

Much of the reported data is based on an AiResearch study which included a single shaft engine using a CVT (continuously variable transmission) with modest efficiencies. The maximum required power output is low because of the torque characteristic of the engine but whether the efficiencies predicted for low power engines can be achieved is doubted. The fuel consumption values given in J.P.L. table 5-9 (below) are considered to be up to 10% optimistic for the mature mini and small vehicles and 15% optimistic for the advanced compact vehicles. The reason for this is that in the case of the low power engines, component efficiencies are based on those of 100 hp units and it is known that as the component size is reduced so is the efficiency; J.P.L. have only allowed for changes in compressor efficiency. For the advanced turbine the higher inlet temperature of 2500°F as opposed to 1900°F will result in a significant increase in specific output and the component sizes will be further reduced for a given power requirement. It is also unlikely that the accuracy of the ceramic component shapes will be as good as the metallic type, resulting in further efficiency losses. Therefore the expected increase in compressor and gasifier turbine efficiencies are unlikely to improve relative to the mature engine and the values will probably be inferior. The mature engine component efficiencies are based on prototype units and it is unlikely that these values can be maintained when the components are mass produced.

J.P.L. Table 5-9 - SS Brayton vehicle fuel economy projections in mpg (gasoline)

			Mature configuration		Advanced configuration	
			Driving cycle			
OEE auto. class	Curb weight lb	Design maximum power, hp	FDC-U	FDC-U	FDC-U	FDC-U
Mini	1500	36	32.2	48.7		
Small	1880	49	28.9	42.7		
Subcompact	2270	66	25.5	37.3		
Compact	2660	86	22.9	33.4	32	46
Full-Size	3400	118	18.9	27.8		

Fuel consumptions based on steady state results are over optimistic as some of the latest published results show. This is because the continuous combustor can be optimised for steady state operation, but to achieve transient conditions a significant degree of enrichment is required. This causes excess HC levels and a poor fuel consumption. The increase in combustion temperature resulting from the enrichment raises the NO_x levels and any attempt to reduce this affect results in an undriveable vehicle.

Although a high efficiency, low emission, continuous combustor is able to accept wide-boiling range fuels, the fuel must still be within certain volatility and density limits. Any fuel outside these limits would effect the emission levels and fuel economy as well as the reliability of the total system, as components such as the regenerators are prone to chemical attack.

The single shaft gas turbine predictions assume the use of a CVT whereas the free turbine is coupled to a torque converter and conventional automatic transmission. Ricardo consider that the torque converter is unnecessary with a free turbine and the removal of this would increase overall efficiency and reduce the brake efficiency advantage of the single shaft type.

3.6 Chapter 6 - The Stirling Automotive Power System

The weight/hp of the mature Stirling is claimed to be comparable with that of the mature U.C. Otto power plant, the J.P.L. figures being deduced as 4.66 lb/hp and 4.3 lb/hp respectively. As shown previously in this note Ricardo agree with the weight of the mature Otto engine provided that the V8 configuration is retained. The mature Stirling engine weight however shows significant reduction compared with the present designs, again (it is thought) somewhat optimistically.

The problem of sealing is vital and neither the rollsock or multiple gland solution appear to be the complete answer. As the result of a rollsock seal failure is potentially catastrophic the J.P.L. statement that the seals must have a "graceful" failure mode seems to be an understatement. The durability of the current seals has been shown on rig tests, but has not been confirmed in vehicle road tests with components manufactured under mass production conditions.

Another area of vital importance is the heater head; difficulties with porosity of metallic heater heads have been reported. The use of ceramics for this component should be treated with extreme caution, because most candidate ceramics are porous and their tensile strength is doubtful at conditions such as 200 atmos. pressure at 2000^{o}F temperature.

The combustor is required to operate at atmospheric pressure and although variable geometry is quoted as being required for low NO_x, Ricardo consider it will also be necessary for control of combustion, over the very wide range up to the exceptionally high intensity required at full power. Similar comments to those made for gas turbine apply to Stirling engine combustor. The fuel acceptance is restricted within certain limits if the low emission levels are to be achieved. All the currently quoted fuel consumption figures are based on steady state tests and the excess richness required under accelerating conditions will have a detrimental effect on both emissions and fuel consumption.

The power output control of the Stirling engine is also very difficult as the various methods of altering the working fluid pressure, directly and indirectly, while admirable at steady states, would have significant response time problems during cycled operation. The parasitic losses of the compressor required for pressure modulation would need to be considered during the prediction of cycled results. The alternative method of altering the swash plate angle is favoured, but the difficulties in doing this have not been fully considered. This section is generally considered to be far too optimistic.

3.7 Chapter 7 - The Rankine Automotive Power System

Ricardo agree with the J.P.L. findings regarding this type of power unit, as in its mature configuration it offers no advantage over the mature U.C. Otto engine in fuel consumption although emissions are improved. In its advanced configuration fuel consumption is only improved due to extreme optimism over the operating temperatures requiring the extensive use of ceramics in both the vapour generator and expander.

3.8 Chapter 8 - Electric Vehicles

This is a reasonable review of electric vehicles, and Ricardo agree with the conclusions. It is considered that the electric vehicle will make some further penetration, beyond milk floats and invalid vehicles, for urban use. The great defect of batteries, frequently not underlined by those writing on the subject, is the low specific power level (i.e. W/lb) both when discharging and charging, and the poor efficiency and life if the specific power is forced up.

The attempt in Chapter 8 to bracket the flywheel with the battery is not realistic, the one thing the flywheel does not suffer from is low specific power. Its specific energy however may not be as great as a lead acid battery and therefore a pure flywheel vehicle suffers from short range.

3.9 Chapter 9 - Hybrid Vehicles

This seems to be an uncritical literature review. Ricardo do not disagree in general with the assessment of the electric hybrid vehicle, but the view of the flywheel hybrid is dominated by the Lockheed/E.P.A. study. Ricardo consider that the Lockheed conclusions were pessimistic for the following reasons:-

1. The use of a hydrostatic transmission gave low efficiencies at light loads where the vehicle spends much of its time, in spite of a split power type box.

2. The use of a rather large flywheel resulted in relatively high parasitic losses.

3. The use of the engine in a continuous mode instead of an intermittent mode, made it impossible to run the engine at best specific economy at all times.

Even so it is difficult to make a case for the flywheel hybrid on fuel economy or emissions alone.

3.10 Chapter 10 - Vehicle Systems

This chapter contains some useful figures concerning weight reduction but does not take the question of transmissions very far, apart from pointing out that a manual change gearbox is more efficient than current automatic boxes and that an overdrive ratio is helpful, especially on a 3-speed box.

The use of the CVT on the U.C. Otto engined vehicle is important as the improvements in fuel consumption being claimed in J.P.L. Table 10-10 are significant compared with the 9% improvement claimed for mature Otto engine alone. This line of development appears more worthwhile than that of the ceramic advanced configuration rotary engine.

Ricardo agree that large overall improvements in vehicle fuel consumption could be obtained from the use of superior transmissions. The normal vehicle road load power requirement curve indicates that the engine is operating at high specific fuel consumptions for the majority of the time. Increasing the overall gear ratio can shift the road load curve towards lower fuel consumption conditions but the high gear ratios can only be used at steady cruising conditions: therefore a continuously variable transmission is required to provide adequate acceleration with optimum cruising consumption.

These comments also apply to the stratified charge and diesel engines as the relationship between the fuel consumption map and the road load curve is similar.

The optimistic fuel consumptions for the single shaft Brayton cycle engine relied on the use of a CVT, so the development of the two items are inter-related. Therefore the CVT could equally well be applied to other engine configurations and, provided a reasonable degree of optimism is applied, the fuel consumption advantage of the Brayton cycle engines could be considerably reduced.

J.P.L. Table 10-10 - Composite fuel consumption reductions from vehicle improvements (%)

Source of reduction	Vehicle class			
	Small	Subcompact	Compact	Large
1. "Intermediate" weight reduction	6	10	15	18
2. 4-speed automatic transmission with lockup	3	6	7	8
3. Reduced acceleration*	2	2	5	10
4. Lower aerodynamic drag	3	3	3	2
5. Improved accessories and drive	1	1	2	3
Overall effective of intermediate improvements	14	20	29	35
6. Longer-term weight reduction (replaces item 1)	12	21	23	25
7. Continuously variable transmission (CVT) (replaces item 2)	10	13	14	15
Overall effect of long-term improvements	26	35	40	45

* Assumes an increase in 0.60-mph acceleration time ranging from 1 second for the Small car class, to 3 seconds for the Large car class.

3.11 Chapter 12 - Alternate Heat Engine Research and Development

The assessment of the Stirling Engine is considered even more over optimistic than that of the Brayton cycle. The suggested date for start of production of mature Stirling engines given in J.P.L. table 12-5, is 1983. Currently the Stirling engines have barely reached the prototype stage for present engines. This date of 1983 appears quite unrealistic in comparison with the figure of 1985 for the start of mature gas turbine production as this technology already exists and, Ricardo agree, could be in production by then. Additionally the development costs are felt to be under estimated, by a factor of the order of 10.

J.P.L. Table 12-5 - Estimated time and costs comparisons for prototype alternative heat engine development

Alternate engine	Year prototype development complete	Maximum (minimum) effective expenditure rate, $ million/year	Total direct cost to develop, $ million
Mature stirling	1983	16 (9)	130
Mature gas turbine*	1985	14 (6)	95
Advanced gas turbine	1985	14 (5)	130
Mature rankine	1990	15 (3)	260

*With ceramic regenerator

3.12 Chapter 17 - Energy and Fuels

The multi-fuel capability of the Brayton and Stirling cycle engines has been one reason for considering them so optimistically for the future. By predictions of the various scenarios it has been shown that the U.S.A. could become independent of imported oil supplies. The assessment of future power plants appears to have been biased towards achieving this aim as the predictions assume extensive market penetration by these alternate engines. The conclusion that refinery costs and process energy consumption could be reduced if more diesel fuel were to be produced is accepted. However no account was taken of this when considering the stratified charge engines, some variants of which, not discussed in this report, will operate satisfactorily on diesel fuel. In addition the more extensive use of diesel engines would also be encouraged, a factor which would provide a considerable energy saving, as this is possible almost immediately, whilst the optimistic introduction dates for Stirling and Brayton cycle engines must be conjectural, particularly for the former.

5

Critique by

Department of Transportation
Automotive Energy Efficiency Project
Washington, DC 20590

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-226-5

June 29, 1977

Dr. Richard L. Strombotne
Department of Transportation
400 7th Street, SW
Washington, DC 20590

Dear Dr. Strombotne:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

In your capacity as Chairman, Automotive Design Panel (ADP) of The Federal Interagency Task Force on Motor Vehicle Goals Beyond 1980, you accumulated on behalf of yourself and Dr. Alan Grobecker various comments on the pertinence of the subject report to the Task Force on Motor Vehicle Goals (MVG) Study. Included in the material we received are comments by Messrs. Robert A. Husted, Robert Nutter, Carmen Difiglio, and W. D. Eberle. JPL wishes to thank you and the members of the MVG study team for your interest in the JPL report as evidenced by these commentaries.

The detailed technical comments of Mr. Robert A. Husted have been responded to by JPL on a point-by-point basis in our letter dated November 5, 1975 signed by R. Rhoads Stephenson. This letter will be included in a Compendium of Critiques to be published. The critique response plan and a description of our restructured automotive studies are presented in the enclosure.

Regarding the brief observations by Mr. Robert Nutter, we are in basic agreement. While JPL would disagree that its study was one-dimensional, it is true that our attention centered on technical issues whereas the MVG study embraced a broader scope. Mr. Nutter's letter simply pointed this out without specific detailed comments since the MVG study was not completed at the time of the letter.

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Dr. Richard L. Strombotne -2- June 29, 1977

The comments of Mr. Carmen Difiglio pertain to the difference between the MVG Marketing and Mobility Panel's approach to automotive use and JPL's Chapter 14. We agree that the MVG study approach is more elegant; however, it is not clear that there is any significant real-world differences in the results of the two techniques. When the MVG integrated behavioral model becomes available, JPL would be pleased to employ it in future work, if it can be expected to show improvements of practical importance. As a final observation, it is correct that JPL did not consider in detail all possible exogenous policy variables of a non-propulsion origin. To the extent that non-propulsion system changes affect automobile usage, the effect of these variables could probably be retained with improved engines.

We greatly appreciate the consideration given the subject report by the MVG Task Force and for your interest in our work.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Tefhnology Status and
Projections

HEC:tm

Enclosure

DEPARTMENT OF TRANSPORTATION

automotive energy efficiency project

October 9, 1975

INTERNAL MEMO

SUBJECT: Comments on JPL Report from Automotive Design Panel

TO: Distribution

FROM: Chairman, Automotive Design Panel

Attached is R. Husted's summary of comments on the JPL report on automobile power systems which he has discussed with several members of the Automotive Design Panel and which he considers a fair representation of their views. Separate members may take exception to part or all of his comments.

Richard L. Strombotne

Richard L. Strombotne

Form DOT F 1320.1 (1-67)

UNITED STATES GOVERNMENT

Memorandum

DEPARTMENT OF TRANSPORTATION
OFFICE OF THE SECRETARY

DATE: OCT 8 1975

In reply refer to:

SUBJECT: Comments on JPL Report "Should We Have a New Engine?"

FROM : Robert A. Husted

TO : Richard L. Strombotne

I have discussed the following comments with members of the Automotive Design Panel from other agencies and believe they are a fair representation of their opinions, exclusive of JPL. Individual members may take exception to any of these comments, of course.

The ADP considers the report to be an excellent and well written one in documenting the present understanding and status of automobile power plant development and manufacturing technology. It will be an excellent reference on these subjects for some time.

The ADP generally agrees with the report's conclusions regarding the projected potential for fuel economy improvement of vehicle-related design changes and Otto engine improvements. It also agrees with JPL's findings concerning electric vehicles. The panel does not agree with the assessment of the potential for fuel economy of the alternative engine options considered for mass production in the mid-eighties. The report seems to underestimate the potential fuel economy of the Diesel engine and overestimate that of the Stirling and Brayton engines. The ADP supports the need for more R&D on these alternative engines.

Comments on the major findings expressed in the JPL report summary (pages 9 through 11 of Vol. 1) are given below. Each finding is quoted with the ADP's comments following. These comments have been discussed by telephone with JPL, TSC, EPA, and ERDA panel members.

"(1) Comparatively simple vehicle design changes--primarily weight-saving, essentially independent of engine type and functionally acceptable to the buyer--can reduce the conventional automobile's fuel consumption by 14 to 35% of present usage. Such changes can be incrementally introduced and all be in production by 1981. Other modifications, requiring some additional development, can further reduce fuel usage. All of the vehicle improvements can and should be incorporated by 1985, since their benefits would largely be retained when an alternate engine is introduced. A modest shift in market preference toward smaller cars would also yield a short-term payoff in fuel saving."

ADP Comments:

We agree. The potential fuel economy improvement and need for continued development of the continuously variable transmission (CVT) should be emphasized. Note, however, that the resultant fuel economy improvement of the CVT is not "essentially independent of engine type." Rather, the relative advantages of the CVT are expected to depend significantly upon the type of engine.

"(2) Vehicles powered by Brayton or Stirling engines can reduce national automotive fuel consumption by about one-third from that of equivalent cars with conventional engines (for the same usage) and with emissions below the strictest presently legislated standards. Introduction of either of these alternate engines can be accomplished without significant adverse impact on the nation's economy. One or both should be introduced as soon as these benefits can be realized in economically mass-producible hardware."

ADP Comments:

We disagree with the report's specific conclusions concerning potential fuel economy improvements of alternative production engines in the mid-eighties ("mature engines"), and agree or do not challenge the potential fuel economy improvements of engines for the early nineties ("advanced engines"). The report indicates a potential of 43 percent fuel economy improvements for the mature Stirling over the mature Otto engine (30 vs. 21 mpg for the compact vehicle--see table 5, page 57). The report's baseline mature Otto projection is within the range of our projections (21 to 22 mpg for this case); however, the ADP considers 20 percent to be more representative of an optimistic relative fuel economy difference for Stirling. Specifically, the OEE mature Stirling engine car is projected to have 23 to 27 mpg potential, rather than 30 mpg potential. Most of the discrepancy is related to the report's assertion that OEE Stirling engines may be designed with nominally 25 percent less rated net horsepower than Otto engines. BSFC engine map comparisons of a comparably-sized Best-75 Otto engine (the OLD's 350 CID V-8), with the projected Stirling engine map in the JPL study, do not support this assertion. ADP majority opinion, supported by this map analysis, is that the horsepower to weight ratio of OEE vehicles must be comparable for equal acceleration performance of Otto and Stirling engine cars.

Concerning alternative engine candidates for mid-eighties mass-production, the ADP opinion supports the position of the ERDA headquarters members that a reasonable assumption for the projected fuel economy is the fuel economy expected for current (or soon-to-be-demonstrated) advanced development models. This is because the projected lead-time to mass-production (300K units per year) is 10 years, starting from an acceptable advanced development model. The major task in that time interval is to make a given design cost competitive in mass-production with the existing engines and to develop and demonstrate its required durability.

The report assumes that the energy efficiency of the Stirling engine can be increased 13 percent over that represented by an engine map which was measured in engine dynamometer tests of the engine soon to be demonstrated. The ERDA headquarters members do not consider this improvement likely for the mature (1985) version. If the assumed improvement in efficiency cannot be obtained, the fuel economy potential advantage of the mature Stirling over the mature Otto engine would drop from about 20 percent to about 7 percent.

To represent the Brayton engine, the current two shaft engine development program by Chrysler is deemed appropriate. The current demonstration objectives for this engine are not competitive with the projected mature Otto engine potential. If ceramic turbine technology is developed, however, we agree with the report that the improvement potential is very significant in the 1990 time period.

Further, the ERDA headquarters members consider it a very high risk, or improbable projection, for a competitive, mass-producible OEE single shaft turbine design to be available in the mid-eighties. The variable-geometry transmission, required to provide the competitive fuel economy for this engine, has not yet been developed.

"(3) The present development status of the Brayton and Stirling engines does not, at this time, permit a decision to begin mass production; hence their introduction cannot be forced by an abrupt change in emission standards or legislation of a fuel economy standard over the next few years. Rather, a more aggressive development program, involving at least a five-fold increase over the present rate of spending, must be pursued. Such a program requires a firm commitment on the part of industry, supported by government funding or incentives. An introduction target date of 1985 (earlier, if possible) should be incorporated in the development schedule."

ADP Comments:

We agree with the first sentence, generally support the second sentence if the development scope is broadened to include all relevant alternative engine technology, and support the third sentence.

"(4) While the Brayton/Stirling development is proceeding, about 9% reduction in fuel consumption from that of the average 1975 conventional Otto engine can be obtained, without giving ground on emissions control, through improved induction systems and exhaust converters. The combination of such upgraded Otto engines with the improved vehicles discussed in finding (1) constitutes not only a good stopgap automobile configuration, but also a very acceptable "fallback" position if intractable difficulties arise in both alternate engine developments."

This finding is at the conservative end of the range of potential projected by the ADP. With sufficient development, ADP considers the potential of 5 to 10 percent reduction in fuel consumption to exist with respect to representative Best-1975 Otto engines. These consume about 8 percent less than average 1975 engines. The ADP emphasizes the need for substantial continued development, particularly with regard to catalytic emission controls and engine controls.

"(5) Intermittent-combustion alternate engines--the Stratified-Charge Otto and the Diesel--do not offer enough advantage over the improving conventional Otto engine, in vehicles of equivalent performance, to warrant their widespread introduction in general-purpose automobiles. Also, conversion of the entire fleet to such an engine could further delay introduction of a Brayton or Stirling."

ADP Comments:

We disagree that these engines do not offer enough potential to warrant wider spread introduction in general purpose automobiles. The report indicates a fuel economy advantage of only 10 percent for the mature Diesel over the mature Otto. The ADP supports the recent Volkswagen projections for a mature Diesel, which, we believe, represents a potential of 15 percent improvement over the mature Otto engine car (in gasoline-equivalent mpg). In other words, the Diesel fuel economy improvement is in the range of the mature Stirling for the mid-eighties time period.

Further, ADP majority opinion supports Volkswagen's posture that their current demonstration model could be mass-produced by 1980. They have been demonstrating about 13 percent improved gasoline-equivalent fuel economy with respect to Best-75 Otto engines. We note, however, that the Volkswagen data was not available to the JPL study team at the time of their study, and that Volkswagen's current engine and their projections seems to represent somewhat lighter weight Diesel technology than heretofore considered available in these time periods.

Robert A. Husted

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MVG Panel Chairmen
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JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

November 5, 1975

Richard L. Strombotne
Department of Transportation
400 7th Street, S.W.
Washington, D.C. 20590

Dear Dick:

This letter is in response to your memo of October 9 relative to the ADP's position on the JPL report. We thank you for the statement that this report is "an excellent and well written one in documenting the present understanding and status of automobile powerplant development and manufacturing technology." This, however, was only our starting point — we went on to project future potential at consistent levels of technology ("Mature" and "Advanced"). We defined these in technical terms, not in terms of the date available, since the date obviously depends on what we do between now and then. Many of the comments in Bob Husted's memo reflect a feeling that it will take longer than we say. That's an easy point of view to take — if we do nothing, it will take forever. More important is the question, what would we have to do to make it a reality by 1985 (or sooner)?

Our response to your comments on our five major findings is given below. To save space, I have not repeated our finding and the ADP comment, but a copy of Bob's memo is attached for easy reference.

JPL RESPONSE TO ADP COMMENT ON JPL FINDING (1):

In total, the benefits are essentially independent of engine type. We agree that the transmission improvements will have different payoffs on different engines but all will benefit. The rank order is not expected to change either, eg., the Otto with CVT won't surpass the Diesel with CVT. Further work is urgently needed to resolve the CVT issue on the Otto as well as with the other engines.

JPL RESPONSE TO ADP COMMENT ON JPL FINDING (2):

(1) It is silly to put much credence in the "Advanced" engines and especially to associate a calendar date with them ("early 90's") since they all require a research breakthrough in materials which cannot be scheduled. They could come in the mid-80's and essentially leapfrog the "Mature" (metal) configuration, or perhaps never happen.

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(2) Regarding the horsepower differences between the Brayton and Stirling engines and that of the U.C. Otto. These sizings were done on an absolute basis (not on a HP/WT ratio basis) and were determined by computer simulation. The recent 350 CID engine map provided us by Bob Husted does have a better torque-speed characteristic than our Mature U.C. Otto engine. Our torque-speed curve is similar to that of three engines: 1973 350 CID Chevy, 1974 Toyota four cylinder, and a pre-emissions controlled 305 Chevy. We are in the process of synthesizing an OEE vehicle powered by the GM engine in order to determine HP, fuel economy, and vehicle weight. Note, however, that the effect will be a lowering of the required Otto engine HP.

(3) You disagree with our "fuel economy improvements of alternative production engines in the mid-80's (Mature engines)." This confuses two points: (a) the performance of the "Mature" configuration engines, and (b) the date at which they will be available.

Our configurations (pressures, temperatures, component efficiencies, parts breakdown, etc.,) are defined in detail in each engine chapter in Volume II. If you disagree, it is only meaningful to talk at a technical level based on the referenced reports and/or test data and thermodynamic calculations. (Since it is always possible to do worse than the best possible, it is easy to find references to lower performance - can you show fault with the performance which will be achieved after an intensive development program?).

If you disagree on the date the Mature technology will be ready for production, that is easy to understand since it's strongly a policy variable (eg., in the control of man). Obviously, if nothing is done, the Mature engines may never be achieved. We contend that with immediate funding at the levels we suggest, and with a government/industry commitment to success, that the 1985 date is a meaningful target.

The statement that "current (or soon-to-be demonstrated) advanced development" models are the only ones that could be in production in 1985 is very conservative - more so than the industry's posture.

(4) It is stated that the ERDA members do not consider the 13% Stirling efficiency improvement "likely" for the mature (1985) version. We did not consider the likelihood since that is mainly a policy variable — obviously if everyone says it can't be done, it won't be. We made an estimate of what could be done as the result of a high-level development program.

(5) Relative to the Single-Shaft version of the Brayton, we agree that there is uncertainty about the required CVT — otherwise it would be such a clear winner that the free turbine would be dropped. Two points: (1) The CVT for the SS Brayton can be of a different kind, and is thought to be a simpler problem, than a CVT for the Otto (or other) engines; (2) Ford has run a VSTC (Variable Stator Torque Converter) type transmission with a SS engine in a car and considers that existing problems will yield to a development program.

JPL RESPONSE TO ADP COMMENT ON JPL FINDING (3):

You agree with us here, with the proviso that the scope be broadened to include "all relevant alternative engine technology." If there were an infinite amount of money — maybe so. The danger, of course, is a dilution of limited resources to such a low level that little gets accomplished (the problem to date). We tried to pick the most promising to focus the effort, while not putting all the eggs in one basket.

JPL RESPONSE TO ADP COMMENT ON JPL FINDING (4):

We agree with the need for "substantial continued development, particularly in regard to catalytic emission controls and engine controls" to allow the UC Otto to achieve better fuel economy while simultaneously meeting the Statutory Emission Standards. If this is not achieved, the widely publicized fuel economy loss will, in fact, happen and the Brayton and Stirlings will look even better by comparison.

JPL RESPONSE TO ADP COMMENT ON JPL FINDING (5):

The great trust put in the "projections" and "posture" of VW relative to their Diesel is amazing compared to the distrust usually accorded statements by U.S. manufacturers.

It is true that the VW Diesel Rabbit EPA test data was not available to us at the time we did the study. Very little has been said about the technical details of the engine itself, but no breakthrough in design or combustion efficiency has been claimed. There is no reason to expect any significant BSFC improvement over other divided chamber engines.

As can be seen from Attachment A, our diesel fuel economy projections are not very different from those of the panel (6% lower on a sales-weighted average). We have the greatest discrepancy at the smaller sizes. In retrospect, our Mature diesel engine weights for the smaller sizes are probably too high (because we kept a constant BHP/CID rather than let it increase) and for the "Full-size" and "Large" sizes our weights may be too low. In any case our Mature diesel weights are considerably lower than current diesel engines.

The frequently quoted statement that the VW Diesel Rabbit weighs only 50 pounds more than its gasoline counterpart is irrelevant since these are not OEE vehicles. If you resize the gasoline engine (and account for weight propagation) the equivalent gasoline-powered Rabbit would be about 150 pounds lighter - generally consistent with our weight differences. Diesel engines are heavier because they have higher stresses. If VW does it with little weight (and/or cost) increase, they either have a lower durability engine or the baseline gasoline engine is greatly overdesigned.

We feel that the known environmental problems of particulates, odor, and Nox higher than the statutory limits must be resolved before widespread introduction of the Diesel. There may be fundamental limitations in these areas. The availability of fuel may also limit the scope of applicability.

The statement that the VW Diesel should be 15% better than the panel's improved Otto engine ignores the effect of performance level. The Diesel should look relatively better in high performance cars than in low performance because the Otto suffers most from throttling losses on high performance engines. See Item (4) below for quantitative data.

We have had several reactions to the effect that our Diesel numbers look low. Before jumping to conclusions, we suggest considering four reasons why our numbers are smaller than those commonly quoted:

(1) Comparisons are made on a gasoline equivalent (BTU/mi) basis.

(2) Our base point is the Mature UC Otto which is 5% better than the best 75's and 10% better than the average 75's (on a sales-weighted basis). Both of these basepoints are much better than the 1973 or 1974 basepoints frequently used.

(3) Our vehicles are compared on an Otto-Engine-Equivalent (OEE) vehicle basis. The HP has been adjusted to yield the same acceleration (including engine weight changes and vehicle weight propagation).

- Such comparisons are rarely made.

- Current vehicles which are sold with either Otto or Diesel engines (Mercedes, Peugeot, Opel, and, perhaps in the future, the "Magic Rabbit") are definitely NOT OEE vehicles.

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

(4) Our fuel economy comparisons in Volume I are sales-weighted averages on the composite cycle. A comparison of Tables 3-5 and 4-10 shows that the Mature Diesel has a 17% advantage for the high performance (Large) cars and only a 6% advantage for the low performance (Small) cars (on the composite cycle). The sales-weighted difference (composite cycle) is 13.4% as shown in Volume I. It should also be noted that the Diesel is relatively better on the urban cycle (plus 19%, sales-weighted, present market) than the highway cycle (5%, sales-weighted, present market).

In summary, Dick, I'd like to point out that the entire ADP critique was based on an "opinion poll" of the (non-JPL) members. I contend that this method is appropriate for policy variables or consumer preferences but not for resolving a technical question such as how many MPG a Brayton-powered car of given characteristics will have.

Throughout the critique a philosophical difference emerges. The members seem to be interested in "being right" in the sense of accurately predicting the future. Statements about what's "likely" or what the industry will or will not do are of this type. A more important question, especially for a government study, is what can the government do to accelerate progress to lead to significant improvements in our energy and environmental problems. It is no challenge to predict less will be accomplished or that it will take longer. Since the outcome is at least partially in the hands of the government, your pessimistic estimates may turn out to be a self-fulfilling prophecy. You get to be right and only the nation loses.

Please take this in a friendly vein — we all have similar goals. Let's get on with it!

Sincerely yours,

R. Rhoads Stephenson

R. Rhoads Stephenson
Systems Analsys Section Manager

RRS:bl

Enclosure

Distribution:

R. A. Husted
W. Stoney, TST-1
A. Grobecker, TST-8
C. Frasier, TSC-400
R. John, TSC-610
H. Miller, TSC-404
L. Roberts, TSC-600
S. Powell, TSC-612
Motor Vehicle Goals Panel Chairman
Automobile Design Panel Members
APSES Team Members

ATTACHMENT A

DIESEL FUEL ECONOMY COMPARISONS

(Composite Cycle, Gasoline Equivalent)

SIZE CLASS	CURB WT	HP	(1) JPL MATURE DIESEL (MPG)	(3) ADP 1975 PROTOTYPE DIESEL (MPG)	(4) ADP IMPROVED (TURBO) DIESEL (MPG)
MINI	1790	53	37.0	39.9	43.9
SMALL	2310	74	32.2	32.0	35.2
SUB.	2830	101	27.4	26.4	29.0
COMP.	3340	131	23.3	22.4	24.7
FULL	4220	182	18.8	18.0	19.9
LARGE	5160	238	15.5	15.0	16.5
SALES-WEIGHTED[(2)]			19.5	18.8 (-4%)	20.7 (+6%)

(1) From JPL Table 4-10, Vol. II.

(2) Based on "Present" market mix, Table 3, Vol. I.

(3) Configuration D, Table 6.17, Oct. 22nd Draft of chapter 6, using JPL HP/WT Ratio, divided by 1.11 for gasoline equivalence.

(4) Configuration E, same as Footnote 3.

Form DOT F 1320.1 (1-67)

UNITED STATES GOVERNMENT

DEPARTMENT OF TRANSPORTATION

Memorandum

OFFICE OF THE SECRETARY

ORIGINAL PAGE IS OF POOR QUALITY

DATE: October 9, 1975

In reply refer to: TPI-50

SUBJECT: Comment on the JPL study

FROM: Robert Nutter RDN.

TO: Alan Grobecker

As compared to the MVG study, the JPL study objective was essentially one-dimensional. The stated aim was to investigate an engine to maximize fuel economy given the emissions statutes. No consideration of safety was included and no systematic analysis of the total costs or beneficial impacts appear to have been made. Given this same limited objective and assuming that the JPL technological work is not grossly wrong, the MVG study would reach the same conclusion. However, because the MVG study objective covers a broader range of costs and benefits as well as a wider scope of technological alternatives and strategies, it is not necessarily true that the suboptimization of the JPL study will also be the global optimum that MVG seeks.

The JPL study does highlight one important consideration that the MVG study is encountering - near term versus longer term alternatives. The EDC designs show promise of being able to very nearly meet emissions, fuel economy and safety goals simultaneously at a reasonable price if the Stirling engine and Mini-car construction technique both pan out. However, the CTE designs appear to be still divergent along the various vectors. Thus in the 1980-85 period, some compromise is likely to be necessary. Furthermore, the most fuel efficient CTE engine, the diesel, could be superceded in 1985 by the Stirling so that investments in diesel production facilities and superstructure could be short lived and expensive. Near term investments in the best CTE could inhibit growth to the best EDC. The EDC Stirling engine development involves a risk so that it would be possible to trade off the best CTE in expectation of a better EDC and then have that expectation not realized.

The JPL study faced this near term - far term problem on a one-dimensional basis. The MVG must face the same problem on a multi-dimensional basis.

FEDERAL ENERGY ADMINISTRATION
WASHINGTON, D.C. 20461

October 14, 1975

Dr. A. Grobecker
TST/TST
Nassif Building
Department of Transportation
Washington, D. C. 20594

Dear Al,

The JPL Report extends the implications of alternative engine designs through to the calculation of gasoline consumption using the methodology of Chapter 14, "Automobile Use." In this respect, the procedures used in Chapter 14 are parallel in function to procedures developed by the Marketing and Mobility Panel in support of the MVG Task Force. However, the approach used in each study are substantially different. The JPL Report uses a chain of assumed events regarding diversion from auto travel, vehicle miles traveled per vehicle, future fleet size, and scrappage. Auto sales are a residual of the assumptions regarding fleet size and scrappage. The Marketing and Mobility Panel, in contrast, has developed a integrated behavioral model which places the greatest emphasis on auto sales and market mix. The remaining variables, fleet size, vehicle miles traveled and scrappage are also estimated in a consistent equation system in concert with auto sales and market mix. The difference between each approach can not be overestimated. In the JPL approach, there is no opportunity for any of the different characteristics of alternative designs or government policy options to affect auto demand, market mix or travel behavior. In the Marketing and Mobility Panel's approach, the alternative vehicle costs, fuel and operating efficiencies and government-induced price alternations in the auto or fuel markets are the instruments (exogenous policy variables) which drive the model to produce new estimates of the output variables. While this difference between the two approaches is reasonable given the technology-oriented emphasis of the JPL Report, the JPL travel and auto forecasts are not well based. All variables are forecasted into future periods based entirely on past trends and pure assumption. Realistically, this may turn out to produce as reasonable, or even more reasonable, forecasts as would be produced from an econometric approach, but it is inconsistent with the level of effort exhibited in other sections of the JPL Report.

The JPL Report does pay attention to "specific urban basins" (14.1.3) in the context of an air quality analysis. Since the Air Quality Panel is responsible for this area I will not comment on that section of Chapter 14.

I hope these comments are sufficient for your purpose. If not, let me know.

Sincerely,

Carmen Difiglio
Economist

NEW YORK
366 MADISON AVENUE

DETROIT
320 NEW CENTER BUILDING

MOTOR VEHICLE MANUFACTURERS ASSOCIATION
of the United States, Inc.
1909 K STREET, N.W. SUITE 300 • WASHINGTON, D.C. 20006 • AREA 202-872-9339

October 24, 1975

Dr. Allan J. Grobecker
Program Manager
Climatic Impact Assessment
Office of the Secretary
Department of Transportation
Washington, D.C. 20590

Dear Dr. Grobecker:

On September 26, 1975, Mr. William E. Stoney wrote the four domestic light duty vehicle manufacturers and the Motor Vehicle Manufacturers Association (MVMA) requesting a critique of the JPL report entitled, "Should We Have a New Engine?"

Because individual manufacturer analyses would be more specific and responsive to your purpose than an MVMA staff report can possibly be, we have encouraged our members to respond directly to you. I understand that at least three of the four manufacturers are preparing substantive replies, based on their individual experiences, to assist in an evaluation of the JPL report as a possible reference in the Task Force report.

Although MVMA staff will therefore refrain from submitting a critique, please call on us if we can assist the Task Force in any other way.

Sincerely,

W.D. Eberle

Critique by

Energy Research and Development Administration
Office of Highway Vehicle Systems
Heat Engine Systems Branch
Transportation Energy Conservation
Washington, DC 20545

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-225-6

June 29, 1977

Mr. George Thur, Assistant Director
Office of Highway Vehicles
Division of Transportation Energy Conservation
Energy Research & Development Administration
20 Massachusetts Ave.
Washington, DC 20545

Dear ~~Mr. Thur:~~ George

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

This letter is in response to comments, originating within ERDA, about the methodology and conclusions of the subject report. Aggregating and responding to these critiques is being carried out under the ATSP Project as summarized in the enclosure.

In a memorandum from R. A. Mercure to T. Sebestyen (formerly of ERDA/TEC) there is a summary of the initial critiques by American Motors, Ford, and Chrysler. These critiques and the JPL responses will be contained in the Compendium of Critiques in Sections 7, 2, and 3, respectively. Copies of three JPL responses are attached. R. Mercure also refers to a critique by Gregory Flynn, Jr., which mostly concerns overall conclusions about the Stirling and Brayton engines, and discusses some of the policy judgments expressed in the subject study.

Comments by R. Mercure center on forecasts of major near-term technological developments. He points out the historically slow pace of automotive innovation. It is important to note that the subject study looked not at what is likely to happen in a business-as-usual world, but rather at what can be made to happen as a result of a comprehensive success-oriented development program. This would require changes in incentives and funding levels, and it would seem that ERDA/TEC can play a significant role.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

A letter by Graham L. Hagey (ERDA) expresses his concern about future fuels availability and elaborates on the trade-offs between electric and heat-engined automobiles. These matters interest us greatly, and we hope that they may be treated in our future work.

Our general approach to these major critiques, instead of attempting to reply point-by-point in a letter, is to reflect these comments in structuring our ATSP work. Our responses to many of the critiques will thus be implicit in our future work.

We would like to thank the several ERDA staff menbers who contributed their comments, and to express our appreciation for the opportunity ERDA has afforded JPL in making this work possible.

Sincerely yours,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:tm

Enclosures: (4)

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C.
JAN 5 1976

Thomas Sebestyen, Acting Chief
Heat Engine Systems Branch
Transportation Energy Conservation

SUMMARY OF AGREEMENTS AND DISAGREEMENTS TO JPL'S (JET PROPULSION LABORATORY) REPORT "SHOULD WE HAVE A NEW ENGINE?"

Based on critiques received to date, including my own, the general consensus of appraisals is that the JPL report is a useful and comprehensive study. A majority of the comments are complimentary on the report's attempted objectivity displayed in comparing alternative power systems against conventionally powered passenger cars. There is a uniformity in agreement with in-house company programs by industry and experience or self-interest by individuals.

Responses on the JPL report were obtained from Dr. Allen J. Grobecker of DOT. They include American Motors who does not have the manpower to critique the report, Ford who promised a more detailed follow-up to an initial critique submitted, and Chrysler. Dr. Grobecker, in a memorandum to Dr. Richard Strombotne, also of DOT, recommended that these contributions should be reflected in the panel reports of the Automotive Design and Automotive Manufacturing Panels.

In addition, a critique prepared by Gregory Flynn, Jr., a former General Motors staff engineer associated with their Stirling engine program for many years, is also included. The critique was prepared for Continental Motors - Muskegon and was released to ERDA.

The agreements and disagreements with JPL's major finds and/or assumptions are therefore listed as follows:

FORD

Agreements

1. The Brayton and Stirling engines offer the greatest potential in reducing fuel consumption and emissions.
2. Major technological advances must occur before the Brayton and Stirling engines could become serious competitors to the Otto engine.
3. Lead time of at least 4 years is required to begin production after the needed technology is finally proven.
4. Both alternative engines would be significantly more costly in first cost.

Disagreements

1. JPL's assessment of economic issues.
2. Statutory emission standards can be met in the near term with an Otto engine more economically than those meeting 1975 standards

CHRYSLER

Agreements

1. The Brayton and Stirling engines--that one or both should be introduced as soon as their benefits (economy and emissions) can be economically realized in mass production hardware, but that equal priority should be given the Diesel, Stratified Charge and Otto Engines as well as the Continuously Variable Transmission.
2. The low emission target of 0.4 g/mile NOx will eventually be met, but the exact nature of the system and the time to develop it including the 3-way catalyst are still unknown in regard to the Uniform Charged Otto.
3. Minimum time to develop and tool a new engine is 10 years.
4. Rankine, Electric and Hybrid engines are not viable alternative concepts for the 1980's.

Disagreements

1. CVT's will benefit all engines equally.
2. JPL's assumed "Otto Engine Equivalent" of 0 to 60 mph acceleration time--does not represent equivalency in the 50 to 70 mph acceleration time.
3. JPL's balancing higher first cost against reduced operating cost--Chryslers experience is that first cost is far more important to the customer in the competitive auto market.
4. JPL's conclusion that an overall cost savings of $50 results in owning and operating a Diesel powered car over 3 years. Also with JPL's choice of turbo-charged pre-chamber engine--that they should have considered an open chamber Diesel engine.
5. The potential for lower NOx emissions of a Stratified Charge does not represent a major long term advantage.
6. JPL's Advanced U.C. Otto concept (1990) assumed a 15% increase in fuel economy could be achieved in a Wankel with the use of a ceramic rotor and further developments in seals.

GREGORY FLYNN, JR.

Agreements

1. Stirling engine may possibly be an excellent alternative engine for automobiles.

Disagreements

1. Accuracy of the adjusted data used.
2. Cost studies.
3. Brayton engine as an alternative engine.
4. Widespread introduction of the Stratified Charge Otto or Diesel engines would inhibit the introduction of the Brayton and Stirling engines.

No attempt is made here to reference articles or editorials published by automotive writers who unanimously appraised the JPL report as,

1. optimistic in predicting the introduction of the Brayton and Stirling engines based on unresolved problems in component performance, durability and cost, and
2. a paper study that recommends what should be done without specifying how to do it.

COMMENTS BY R. A. MERCURE

I summarized my general comments and recommendations in my memo to you on November 6, 1975. Since then, there have been some questions raised on the predicted fuel economy of the Stirling engine. Bob Husted's memo of October 8, 1975 to Dick Strombotne summarizing the Automotive Design Panel member's comments disagreed with the 43% improvement in mpg for the Stirling engine over the Mature Otto as shown in the JPL report for the compact vehicle. We now have some data obtained from Ford through Bob Schulz. Accordingly, Ford's estimated contract goal was for a 25% increase in the Stirling powered Torino over a conventionally powered Torino. Based on projections of engine dynamometer tests, Ford has revised its estimate upwards by 10%, claiming a total 35% improvement for the Metro-Highway driving cycle. Actual vehicle testing is planned and is considered the only valid indication which may still not be representative of a mass produced engine.

In regard to the critiques, further qualification as to their validity not only appears necessary, but is recommended. Initial reactions tend to display personal prejudices which we all have. After re-examining my own critique, I find issues I might now like to modify. It will, however, take a considerable amount of digging into the report itself, and in particular the report's references, to do justice here.

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Insofar as the recommendations of the JPL report are concerned, I have strong reservations, not so much in regard to what should be done, but more on how and when it can be done. In this respect, it might be worthwhile looking back at the history of developments that have taken place in the aircraft gas turbine as well as the automotive industries over the past 30 years.

Modern turbojets employ the use of axial flow compressors exclusively. Their flow field is, incidentally, considerably less complex and more efficient than that of the centrifugal compressor which is a mandatory requirement for a low cost application such as the automobile and for pressure ratios exceeding 4:1. Turbojet designers certainly have had the incentives to increase efficiency and stage loading in terms of the resulting payoffs such as higher thrust-to-weight ratios, lower fuel consumption and simpler mechanical design. Yet most of the gains here have been relatively minor. The progress that has been made was accomplished with the application of a given technology and not with any breakthroughs in aerodynamics. Higher Mach numbers and lower Reynolds numbers, a result of optimizing on the employment of higher turbine inlet temperatures, mean higher losses.

In regard to materials, an examination of history here will demonstrate that the gains in stress rupture properties particularly in low alloy materials has been small. Most of the increases in turbine inlet operating temperatures have been achieved through developments in heat transfer and not in material advancements. Manufacturing innovations were largely responsible in implementing the heat transfer developments made here. Also, it can be stated that ceramic technology is in its infancy if the concentrated efforts by NASA (NACA) to develop non-strategic alternatives to nickel based turbine blades is completely ignored. The difficulty in designing components with brittle materials and in matching low expansion materials with high expansion materials has been extensively explored and the problems have not yet been resolved.

An examination into the history of developments that have taken place over the years in arriving at today's automatic transmissions will reveal that alternatives including CVT's are certainly not new to the automotive industry. Patent searches would make this obvious. The modern 3 speed automatic coupled to a 3 element torque converter that incorporates a free wheeling stator has evolved as the best overall compromise in performance, durability and cost. Mechanical gearing is still the most efficient means of multiplying torque within the limiting diameters and lengths imposed in automobile applications. All attempts to design a practical CVT must be carefully compared against alternate routes of off the shelf technology improvements such as additional gearing and on the payoff in mpg based on the percentage of time the benefits are realized during a given driving cycle.

On the more positive side, a few of the key conclusions of the JPL report which so far have not been explicitly mentioned in the various critiques are, in my judgement, the major findings on the Otto cycle. They are:

1. Attainable thermal efficiency is limited by compression ratio -- pre-ignition and detonation of liquid petroleum fuels limit compression ratios to between 8 and 10:1 which is far below that required for high thermal efficiency.
2. Post expansion heat recovery is difficult if not impossible -- spatially restricted and of short time interval.
3. NOx emissions are limited by a constant volume heat addition process -- large temperature increases in the working fluid are required for a given quantity of heat addition.

I don't believe anyone would argue with item 2. above. On item 1., the question which remains to be answered is whether a fuel additive now exists or could be economically developed that would allow higher compression ratios, but this may be unnecessary if it is agreed that a three-way catalyst or some such other add-on device cannot be developed to reduce NOx emissions generated as a result of item 3. The latter consideration depends on future legislative action.

Finally, it should be emphasized that the desire to get a socially desirable result is not to beat the auto industry over the head. You cannot legislate if you are unsure that the auto industry has the bogey to do it. Emission standards should be legislated to meet the air quality standards when the standards required for safe health are defined. They should not exceed these standards. Likewise, the fuel economy standards should be legislated to meet the nation's energy demands. On this point it may be far easier to legislate the fuel consumption in terms of allocation rather than fuel economy which would avoid speculative forecasting by even the most competent and respected experts. This would preserve the free enterprise system and remove government doubts on what the industry can do because they will then have greater incentives for change should these be possible.

Robert A. Mercure
Office of Highway Vehicle Systems
Div. of Transportation Energy Conservation
Office of Conservation

cc: G. Thur
J. Brogan
S. Luchter
P. Sutton
B. Schulz
S. Kramer

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

JAN 20 1976

R Rhoads Stephenson

JAN 26 1976

Dr. R. Rhoads Stephenson
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Dr. Stephenson:

Thank you for forwarding me a copy of the report entitled, "Should We Have a New Engine? - An Automobile Power Systems Evaluation."

The study is, in my opinion, very well done and I believe it will serve as a valuable reference for a long time. I am particularly pleased to see an unequivocal answer to the question - Should we have a new engine?

In reading the report, it strikes me that perhaps the conclusion pertaining to the recommendation for development and introduction of alternative powerplants (Brayton or Stirling) is highly dependent on your forecast of supply of domestic liquid fuels through the year 2000, e.g., Fig. 17-2. It is unfortunate that the published literature on this subject (e.g., Ref. 17-7, 17-8) is being rapidly outdated by domestic and foreign economic and political events.

Simply stated, my concern is that the time period examined by the study is, in reality, very short when viewed within the perspective of a new auto technology such as Brayton or Stirling. My concern can perhaps be expressed by a scenario as follows.

A major Brayton or Stirling R&D program, such as the study recommends, is started in government fiscal year 1977. The R&D program produces a technically and economically viable prototype powerplant in 1985. Accelerated engineering development permits the introduction of the powerplant in 1990 and the incorporation of the powerplant in <u>all</u> new vehicles by 1995. By 2008, the fleet will be a Brayton or Stirling fleet. By 2010, liquid fuel prices are such that only "essential" markets (e.g., aircraft transportation, petrochemicals) can afford to use liquid fuels. Surface transportation is, in the main, shifting rapidly to electrification. As a result, the Brayton or Stirling powerplant has a lifetime of only 20 years, stated in terms of production manufacturing. I realize that this

AMERICAN REVOLUTION BICENTENNIAL 1776-1976 is an oversimplified scenario; however, I believe it is reasonable to consider this scenario possibility as a potential drawback to the initiation of a major new engine R&D program. The argument is also being made that we should improve the Otto cycle - personal auto to its technical limit while preparing for electrified land transportation.

My own personal opinion is that we should pursue all options - the Brayton-Stirling, the electric and Otto cycle improvements. Even if we spend several hundred million dollars on development of the heat engines and then discard them before marketplace introduction, I believe the money will be well spent as insurance. I emphasize that these are my personal thoughts and not the position of the Energy Research and Development Administration.

I believe the "weakness" of the study is the reliance on the future certainty of liquid fuels. In our energy analysis the demand side of the equation can be analyzed and forecast with a reasonable level of confidence. On the supply side it is impossible to use conventional economic analysis with confidence. In my opinion, the 1970-71 NPC studies on energy supply are quite inadequate; however, I understand the dilemma -- this is probably the most detailed and exhaustive study available on the subject.

You state the energy uncertainty regarding electric cars very well (p. 17-29) by stating: "Whether or not that potential (electric car) could be realized, or do anything to increase efficiency of total fuel utilization, depends on factors not yet analyzed....More detailed analysis than has heretofore been done with harder data than are now available is required to answer that question." The question -- Should we have an electric car? -- is clearly a very difficult question to analyze, and accordingly a very difficult question to answer unequivocally. We have been studying the impact question of electric passenger vehicle for two years and we will continue further impact analysis, as well as examination of coal to electricity energy supplies and net energy efficiencies, so that we can provide substantive data and information on the question of electric versus advanced heat engine personal transportation.

With regard to this most important question (electric versus advanced heat engine vehicles) your study is a valuable and much needed work.

Sincerely,

Graham L. Hagey
Acting Assistant Director
Systems Analysis, Evaluation
and Implementation

cc: J. Brogan
R. Kirk
G. Thur

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

November 6, 1975

TO: Tom Sebestyen

FROM: R. A. Mercure

SUBJECT: Comments on JPL Report "Should We Have a New Engine" and Recommendations For an ERDA Sponsored Program

Robert A. Husteds' memorandum of Oct. 8, 1975 to Richard L. Strombotne, attached hereto* summarizes the comments made by members of DOT's Automobile Design Panel on the major findings of the JPL report. I am in general agreement with these comments except for differences in projected potential fuel economy of the mature and advanced engine configurations.

ERDA's projected fuel economies were summarized in the attached table of August 14, 1975 prepared for the Panel Report that was sent to Dick Strombotne by George Thur. Here the mature configurations are represented by the "Evolutionary Developments Completed" or year 1985 and the advanced configurations are referred to as "Potential Benefits Realized" or year 1990. The higher fuel economies projected by EPA for the advanced and mature Diesel do not appear compatible with the limitations of higher compression ratios or more significantly the higher peak temperatures of intermittent combustion while simultaneously maintaining low NO_X formation as is discussed in the JPL report. With strict emissions as a mandate, JPL's assessment of the Diesel does not appear to underestimate its potential. This position is supported to some extent by General Motors recently announced plans for introduction of a Diesel powered automobile being contigent on legislative action to preserve present emission levels. All evidence to date does not show the Diesel as being capable of meeting the 0.4 gpm NO_X level. VW's Diesel was apparently targeted at approximately a 1.2 gpm NO_X level with performance equivalent to a smaller gasoline Otto engine.

My specific criticisms on the JPL report in general, some of which may be characteristic of most studies; are as follows:

1. Limited to past or presently conceived designs and/or systems that fail to represent a given engines' true potential.

2. Limited to cursory stress analyses which neglect vibrational and thermal fatigue and their effects on endurance.

---

* See Section 5, page 4, of this document.

3. Dismissal of mechanical design problems as being simply developmental.

4. Overly optimistic about the application of ceramics based on limited laboratory demonstrations.

5. Failure to identify performance limitations imposed by high Mach/low Reynolds number effects.

6. Lacking design and manufacturing anomalies acquired by years of experience that industry often considers proprietary.

The shortcomings listed above, however, do not significantly affect the Reports' major findings which were based entirely on the mature configurations.

Aside from my criticisms, the report is, in my judgement, an excellent treatment of a complex subject and, no doubt, the most comprehensive publication of its type available to date. The objectivity of the groundrules established combined with the analytical techniques developed can provide ERDA with a means of comparing alternative engines from a systems engineering point of view. The report can provide a valuable baseline for further investigations.

I have therefore prepared a list of areas which might be further explored by JPL under contract with ERDA. These recommendations are tentative and should be reviewed by other staff members at ERDA and JPL for additions and deletions. Present ERDA priorities and budget will probably influence the areas finally selected. The proposed topics for future JPL studies sponsored by ERDA are therefore listed as follows:

1. Further investigate potential performance improvements and limitations of specific engine types. Define what could be done to:

   a) Cold wall effects and hot wall limits of Otto and Diesel engines of fixed and variable displacement.

   b) Aerodynamic improvements required to improve part load SFC of Brayton engines.

   c) Turbocharging, intercooling, aftercooling, and bottoming improvements on the Diesel.

   d) Limitations of more complex Rankine cycles.

   e) Thermodynamic limits resulting from the dynamics of rhombic and swashplate drive mechanisms on the Stirling.

2. Fluid dynamic component efficiency potentials of positive and variable displacement compressors and expanders characteristic to each engine type. Identify Reynolds and Mach. No. effects, flow range, etc.

3. Potential performance improvements by optimized system engineering using presently achievable component efficiencies and projections of mature and advanced technology. Include multi-stage components, matching, design, etc..

4. Consider advanced configurations without the use of ceramics.

5. Detailed analysis on the basic mechanisms of heat transfer peculiar to each engine.

6. Detailed stress and vibrations analyses in critical components including manufacturing limitations on geometry and resulting performance penalties in order to predict engine endurance during a specified driving cycle over 50,000 miles.

7. Performance comparison of all engines equipped with an infinitely variable transmission identifying particular problems characteristic to intermittent combustion engines.

8. Cycle sensitivity/tradeoff analyses to determine the effects of small comprimises.

9. Comparison of required volume, frontal area, and packaging compatibility with front wheel drives.

10. Considerations of reduced parasitic losses through employment of variable accessory drives, improved accessory efficiencies and vehicle aerodynamics.

11. Engine serviceability and maintenance.

12. Alternative engine candidates for truck and bus duty cycles.

The extent of JPL's participation in the above tasks will need to be scrutinized as to their specific capabilities as well as assigned areas of responsibilities within the ERDA organization.

Robert A. Mercure

Robert A. Mercure

PROJECTED FUEL ECONOMIES OF FUTURE AUTOMOBILES

POWERED BY CANDIDATE POWER SYSTEMS

	Otto			Diesel			Brayton			Stirling			Rankine		
Test Wt.	ERDA	EPA	JPL	ERDA	EPA	JPL	ERDA	EPA	JPL	ERDA	EPA	JPL	ERDA	EPA	JPL
Current Technology Extrapolated															
2800	29	29.3	-	31	30.9	-	30	-	30	31	-	34.5	22	-	21.5
3600	22	21.7 (28)*	-	29	29	-	25	-	25.5	25	-	29	18	-	18
4600	16	16	-	24	23.5	-	21.5	-	22	20	-	23.5	15	-	15
Evolutionary Developments Completed															
2800	35	36.9	-	44	50.8	-	36	-	-	34	-	-	28	-	-
3600	26	27.2	-	36	37.5	-	30	-	-	28	-	-	23	-	-
4600	19	20.1	-	30	27.8	-	26	-	-	24	-	-	20	-	-
Potential Benefits Realized															
2800	39	55.8	-	46	57.5	-	48	-	42	46	-	39	34	-	30
3600	29	43.4	-	37	44.6	-	41	-	35	39	-	33	29	-	25
4600	21	34	-	30	35	-	36	-	30	33	-	26.5	25	-	21

* 1975 Monza 3.0 GPM NO_x

8/14/75

Critique by

American Motors Corporation
Vehicle Environmental and
Energy Regulations Staff
·Detroit, MI 48232

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

7

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-167-7

June 29, 1977

Mr. Carl E. Burke, Director
Vehicle Environmental &
Energy Regulations
American Motors Corporation
14250 Plymouth Road
Detroit, MI 48232

Dear Mr. Burke:

Subject: Your Critique of JPL Report SP43-17, "Should We Have a New Engine?"

We appreciate receiving a copy of your letter to Mr. W.E. Stoney of the Office of the Secretary of Transportation regarding the subject report. Our heat engine program has been restructured since its receipt. The highlights of the program as reoriented are summarized in the enclosure.

In the current program, the earlier performance projections that were of concern to you are being extensively reviewed. Our goal is to refine our predictive ability in assessing the effects of substituting alternate engines. In addition, the computer simulation we used to generate performance data has been substantially revised and refined, and documented results of this continuing activity will become available in the Fall of 1977.

Of major importance to us is the validation of our computer simulation program through comparisons with experimental data obtained from the automotive industry. We would greatly appreciate any assistance in this validation that may be available. We would be pleased to visit American Motors at an early date to discuss these and related elements of the study. We look forward to hearing from you.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:cr

Enclosure

Telephone 354-4321 *Telex 675421* *Twx 910-588-3294*

7

American Motors Corporation
14250 Plymouth Road
Detroit, Michigan 48232

October 6, 1975

Mr. W. E. Stoney
Acting Assistant Secretary for
Systems Development and Technology
Interagency Task Force
Office of the Secretary of Transportation
Washington, D.C. 20590

Dear Mr. Stoney:

We have your letter to our F. A. Stewart dated September 26, 1975 requesting our critique of the recently released by California Institute of Technology, Jet Propulsion Laboratory, report "Should We Have a New Engine." We have received copies of this report and are in the process of its review.

The scope of this report is of such magnitude that it does not lend itself to a quick superficial critique, therefore, we will not be in position to submit comment by October 15, 1975.

Our review of this report must of necessity be a long term process since we do not have manpower available to devote full time to the task. In reviewing the power plant costs, tooling costs and lead time requirements reported we are at a disadvantage since we lack detailed knowledge of the designs referred to or the background data from which the authors drew their conclusions submitted in the report.

On the whole it appears to be a thorough study and of good reference value for all segments of industry and government involved in this matter.

We tend to feel the projections in some areas are optimistic and further study may find us in firm disagreement. We believe the Ford Motor Company should be given the recognition due for their investment in this type of program to fund a study designed to give the maximum in objectivity that can be achieved in this area.

Yours truly,

C E Burke

Carl E. Burke
Director
Vehicle Environmental and
Energy Regulations

CEB/jmt

Critique by

Petro-Electric Motors, Ltd.
342 Madison Avenue
New York, NY 10017

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

8

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-178-8

June 29, 1977

Dr. Victor Wouk, President
Petro-Electric Motors, Ltd.
342 Madison Ave.
New York, New York 10017

Dear Dr. Wouk:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We would like to acknowledge receipt of and thank you for your numerous written and verbal communications on the subject of heat-engine/electric hybrids. Subsequent to the time we received your letter of April 21, 1976, our automotive technology studies were restructured, as summarized in the enclosure, and a response plan developed for coping with the many critiques received.

In the present study to date we have been concerned exclusively with heat engines and currently there are no approved plans for extending the study efforts beyond heat engines. Should such go-ahead be received, however, your comments and data will be available for reference in executing work in this area. The key points of your critiques have been well delineated.

As Dr. Stephenson's letter to you pointed out, we feel it is inappropriate to attempt piecemeal changes in our configuration, analysis, and results without considering all the factors (cost, fuel consumption, emissions, etc.) involved in our study methodology. In addition, the hybrid vehicle would have to be configured so as to be equivalent to the baseline Otto-engined car. The analysis will have to be performed in a thorough and systematic fashion.

We acknowledge with thanks receipt of the hybrid vehicle cost information which you enclosed, although the value of your Appendix H will be greatly enhanced if you can send us a copy of the full SAE paper. As you are keenly aware, the cost/benefit ratio of the hybrid automobile will be a major factor in its acceptance. Thank you again for your inputs.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

(212) 986-3173
(212) 986-2873

CABLE ADDRESS: WOUKA

PETRO-ELECTRIC MOTORS, LTD.

342 MADISON AVENUE

NEW YORK, NEW YORK 10017

September 23, 1975

Dr. R. Rhoads Stephenson
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Dr. Stephenson:

This is a follow up to the telephone conversation I had on September 16th with H. C. Vivian. I appreciated the time he took and his sympathy to our problem.

At the outset, I can state my sympathy to the fact that in general, enthusiasm for hybrids is alloyed. Mine is unalloyed. The negatives are due to experience with hybrids, highly concentrated in the Southern California area, around 1969-70. Our project benefitted from the inexperience of both those who built hybrid hardware, and those who did hybrid computer studies. The hardware was admittedly elementary in approach and frequently unrefined, and the theoretical studies did not take into account all possibilities.

I am hoping that as a result of the information which I am briefly outlining below, you will ask for further details with the eventual goal of an addendum for "Department of Greater Amplification" which you might develop and which might take onus off our project.

Before I go into details, I will repeat that I am surprised that although Petro-Electric is referred to on several occasions in volume 2, we were not communicated with when the material was going into final form. I understand from Mr. Vivian that he tried to call us in October or November of 1974, when our project was far from finished at the EPA in Ann Arbor, and final evaluation by both EPA and us had yet to be done. If we had been called during, let us say, March of this year, much of what is included in volume 2 would read differently.

By far the most telling bit of information is that the report used by Mr. Vivian as a basis of analyzing our vehicle, reference 9-11 on page 9-19, the EPA report of January 1975, report 75-14 was withdrawn. The report was withdrawn because it was circulated before we had an opportunity to read it, and, when we did read it in February, we had a list of 75 challenges to the report.

Without going into the emotionalism, I can state that the report had errors of fact, errors of innuendo, errors of improper analogy, and represented such a strong bias against hybrids in general, and our particular project in particular, that the author of the report was accused by his supervisor of having approached the project with antipathy to our hybrid, and having written the report so as to put our vehicle in the most unsatisfactory light, independent of any facts. The supervisor went so far as to say (and we have this in writing) that the report was written as though the author wanted to prove a preconceived notion that the Petro-Electric hybrid was no good.

Therefore, using this report for basis of your conclusions, without having communicated with us explains some of the problems, and I hope you will take that into consideration. I outline them only briefly.

1. First and foremost is the fact that our vehicle was designed for low emissions. As part of the Clean Car Incentive Program we had to meet the serious requirements on page 9-4, Table 9-2, and we met them. The fuel economy requirements did not exist, and all we had to do was show potentiality of 10 miles per gallon.

We took two serious fuel penalties, one known and one unknown. The known one was a differential ratio of 5/1, and the unknown was using a Wankel engine. You indicate an improvement in your report of 14.1 on the urban cycle using an Otto engine, but disregard the rear end ratio which you knew nothing about. Taking a reasonable 40% improvement in going from 5/1 to 2.8/1, we come close to 20 mpg.

In addition to the above, we have recorded data showing that during the tests the fuel/air ratio was much higher than required for the emissions that we achieved. The thermal reactor exhaust temperature was frequently above 1800°, whereas for low emissions 1550° would be adequate. The EPA did not allow us to make any adjustments on fuel/air ratio once this became apparent. We could probably go up a conservative 10% with proper fuel/air ratio, bringing the figure up to 22 mpg.

There are other fuel economy increasing factors, beside the recognized one of engine-off mode, which start to give us a realistically expected 30 mpg on the FDC.

2. Emissions:

This vehicle was designed to meet stringent emission requirements of the Federal Clean Car Incentive Program, and we risked $400,000 of our own money to prove that we can do it. That we did this is shown both in 9-2 and Table 9-5 on page 9-12. I certainly would have been much happier if this had been pointed out, and emphasized. In comparison to any other vehicle listed on Table 9-5, you can see that we beat everyone hands down in experimental data, except on NOx. We did not have to meet anything better than 1.0, and I assure you we can do better than 0.8.

If the HC is compared to the GM STIR-LEC, note that ours was on an FDC, whereas theirs was 30 mph continuous. When we are tested on continuous speed dynamometer checks, we frequently have HC below background, which shows up as negative values. This means that if we drove our car around Southern California at constant speed on the highways, we would clean up the air.

I believe that when you know more about what we did with emissions, you will be willing to make much more positive statements about hybrids.

3. The TRW parallel hybrid system, page 9-6, when used as a model for computer calculations will of necessity give pessimistic results. From Fig. 9-2, (c), the planetary differential is complex and costly, and the separation of functions of dc generating and dc motoring are complex. On the other hand, our system, which is inherently quite simple, and resembles Fig. 9-2 (b) in some respects, is used. It is most similar to Fig. 12 (h) of Volume I, but is even simpler because there is no controller between the storage batteries and the electric dynamoter armature. There is a very small controller in the field, something which is mentioned in the report. I believe that if you analyzed our system, you would again come up with results much more favorable to hybrids.

I am enclosing herewith a copy of the testimony I presented to the EPA in January of this year. Slide 1 shows the emissions, already reproduced in your report. Slide 2 shows the basic block diagram, and I can state that there are no high power semiconductors, no complicated transmission, no complex electronics. Four transistors in parallel in the field of the dynamotor control the mode of operation from generating to motoring, with automatic current flow back and forth. A separate enclosure, page 10 from our report #9960 to EPA, shows the great simplicity of our system. The simplicity contributes to the high electrical efficiency and potential excellent fuel economy.

Dr. R. R. Stephenson September 23, 1975

4. The statement in 9.3.4, page 9-15, third paragraph that the generator/alternator must operate in less efficient speed power regimes for parallel hybrids is qualitatively correct, but the quantitative result is not necessarily serious. If the efficiency is not at maximum, but the power being handled is light power, then the net effect on efficiency is frequently unimportant.

5. The cost figures of Table 9-7 based on the TRW design: you can see from the TRW configurations and from our configuration this is of necessity substantially more complicated. We have made cost studies which we will be glad to send to you. The results are summarized to some degree in the testimony, page 11. We recognize increased costs in slide 11 and offsetting cost decreases in slide 12. The simpler emission controls are far from negligible. We have assumed on page 12 an $800.00 penalty, in which case the system becomes cost effective over the vehicle life with 60 cents per gallon cost of gasoline, and is attractive even for an initial buyer at $1.00 per gallon.

6. Off-board energy use.

I believe you will agree that a report which is comprehensive should consider the concept of use of off-board energy for driving the vehicle, rather than depending 100% on liquid fuel, on board. Our hybrid allows for this, and is referred to briefly. This is particularly so for the common application of vehicles for commuter purposes, 100 miles per week. The mission could be run during the day with batteries being partially depleted. In some of our tests where there has been partial battery depletion we have increased fuel economy as much as 50%.

Finally, as a not too detailed introduction to what I hope will be a much more extensive dialogue, our hybrid can be mated with any type of engine, something which you recognize. If the Stirling is the way to go, then our hybrid concept still is unmatched in removing some of the drive energy from the form of on-board liquid fuel. For an analysis of the entire automotive problem extending for several decades, this concept should be considered seriously. I hope you will agree with me, and that my requested modification or addendum is not out of the question.

Thank you again for your concern.

Very truly yours,

PETRO-ELECTRIC MOTORS, Ltd.

Victor Wouk

Victor Wouk
President

:mc
:10522
encls.

(212) ~~986-3173~~
(212) 986-2873

CABLE ADDRESS: WOUKA

PETRO-ELECTRIC MOTORS, LTD.

342 MADISON AVENUE
NEW YORK, NEW YORK 10017

October 22, 1975

Dr. R. Rhoads Stephenson
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Rhoads:

Thanks for taking the time to discuss with me on October 20th my proposition that a complete analysis of an optimum system for fuel economy in automotive power applications should properly consider the heat engine/battery electric hybrid. The hybrid has the unique ability to shift some of the drive energy from limited resource liquid petroleum carried on-board, to less limited off-board energy sources in the form of electricity derived from coal, nuclear power, etc.

Because it is so important that we concentrate on this specific point, I am refraining from sending the revised EPA analysis of our hybrid as I said I would do. This is done deliberately to emphasize the fact that my thesis at present is confined to what I feel cannot be challenged technically, the shift of some of the drive energy from on-board liquid petroleum to off-board electricity.

If we get involved in the question of overall efficiency, relative merits of one hybrid versus the other, the economics of hybrids, we get into emotionalism. Naturally, everyone thinks that his particular approach to an efficient engine or drive system is the best in the world. I can sympathize with your problem of having been inundated by those who feel they have been given short shrift in your report.

I therefore will concentrate on the one point which I presented recently to the FEA, and I am enclosing herewith excerpts from my presentation to them. To simplify some of your reference problems, I include material with which you may be familiar. The first chart is of automobile usage by trip length, the second, the automobile usage by daily mileage. The second chart is the basis for my subsequent analysis, which I request you consider seriously. If I am wrong, I will quit. If I am right, I believe a statement to this effect should be forthcoming from JPL. I hope you will make it at the ERDA meeting in Ann Arbor on November 17th.

Dr. R. R. Stephenson October 22, 1975

The color xerox is an analysis of a hypothetical 10 miles trip. One can argue back and forth as to how realistic the trip is, but I will be surprised if you disagree with my contention that this particular drive mission is as good as any for the subsequent analysis.

The first set of tables analyses what I refer to as a "present production car", and I show the increase in mpg of 64%,driving a portion as all-electric and portions with different degrees of electrical assist. The batteries are depleted less than 20% before recharge.

I might interpolate here that I agree wholeheartedly that if for every gallon of gasoline saved in this mode we burned 5 times as many btu in coal, then my reasoning is, although technically accurate, grossly improper from an overall energy point of view. However, I believe you will find that, per my annotated paper herewith "Electricity as a 'Fuel' for Autmobiles", the difference cannot be serious. Therefore, the saving of the more limited resource, petroleum, is to be considered seriously.

One of the arguments I always get when I present these figures is to the effect that future Detroit production is going to be of smaller cars with higher miles per gallon, and therefore "who needs your hybrid?". I have to point out to them that no matter what engine is developed, Stirling, Brayton, Diesel, our hybrid, taking advantage of the actual vehicle usage (and this means 50% of the cars in the country) will have their gasoline consumption decreased by our technique. Hence the second set of tables which takes a 27.3 mpg figure on the drive mission and raises it to 46.2.

I am aware that many minor points can be brought up with regard to this presentation, but the basic concept is still not vitiated.

The last table shows the spectacular figure with regard to the "second car". Here, with 10 miles per day, and the very attractive 29.4 mpg for the future, "bantam weight" Detroit production car, we get over 66 mpg.

As you properly pointed out, our vehicle can be considered a "hybrid hybrid". This is exactly how I referred to our hybrid when I was first explaining it to the EPA in 1970. It is not a "series hybrid" in accordance with the well known terminology, and it certainly is not a "parallel hybrid" of the type that TRW had been experimenting with during that period. Since the EPA people wanted to know which classification the hybrid fell in, and they did not like "parallel hybrid" because they could see nothing in the block diagram that is in parallel with anything else, I called it the "hybrid hybrid" and they were happy.

Dr. R. R. Stephenson October 22, 1975

I am also enclosing a copy of a brochure describing our vehicle, and a photograph of the vehicle. It may still be in the Detroit area when you deliver your talk at the ERDA meeting. If so, I will welcome the opportunity to demonstrate it to you.

I look forward to hearing from you.

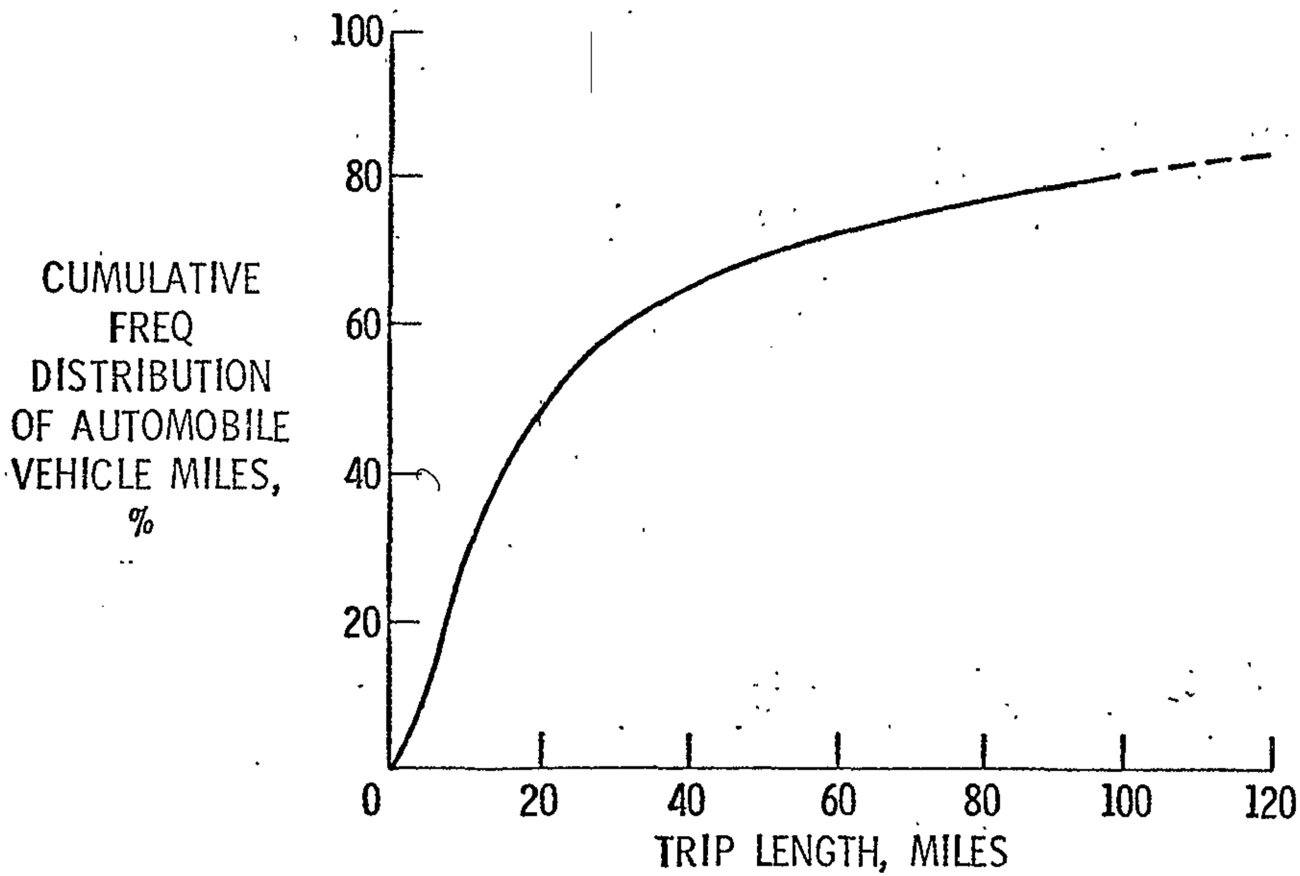
Very truly yours,

PETRO-ELECTRIC MOTORS, Ltd.

Victor Wouk
President

:mc
10568
encls.

AUTOMOBILE USAGE–BY TRIP LENGTH



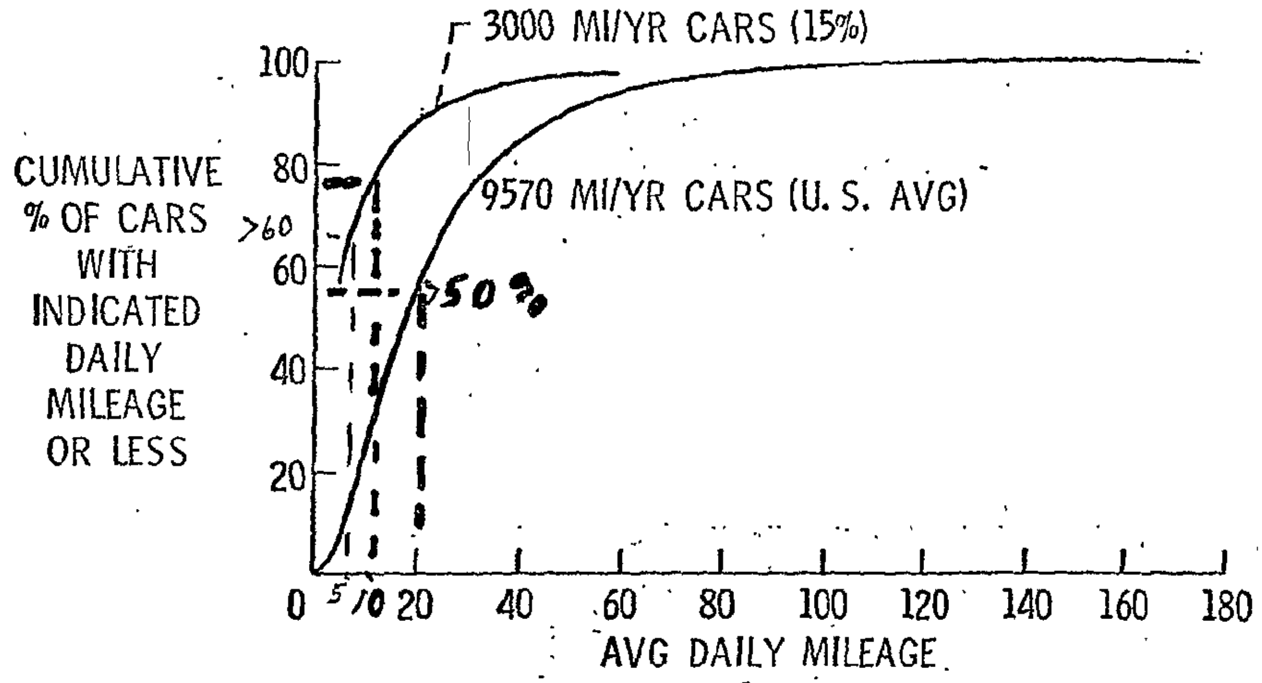
8-10

77-40

2

3.9.51

AUTO USAGE BY DAILY MILEAGE



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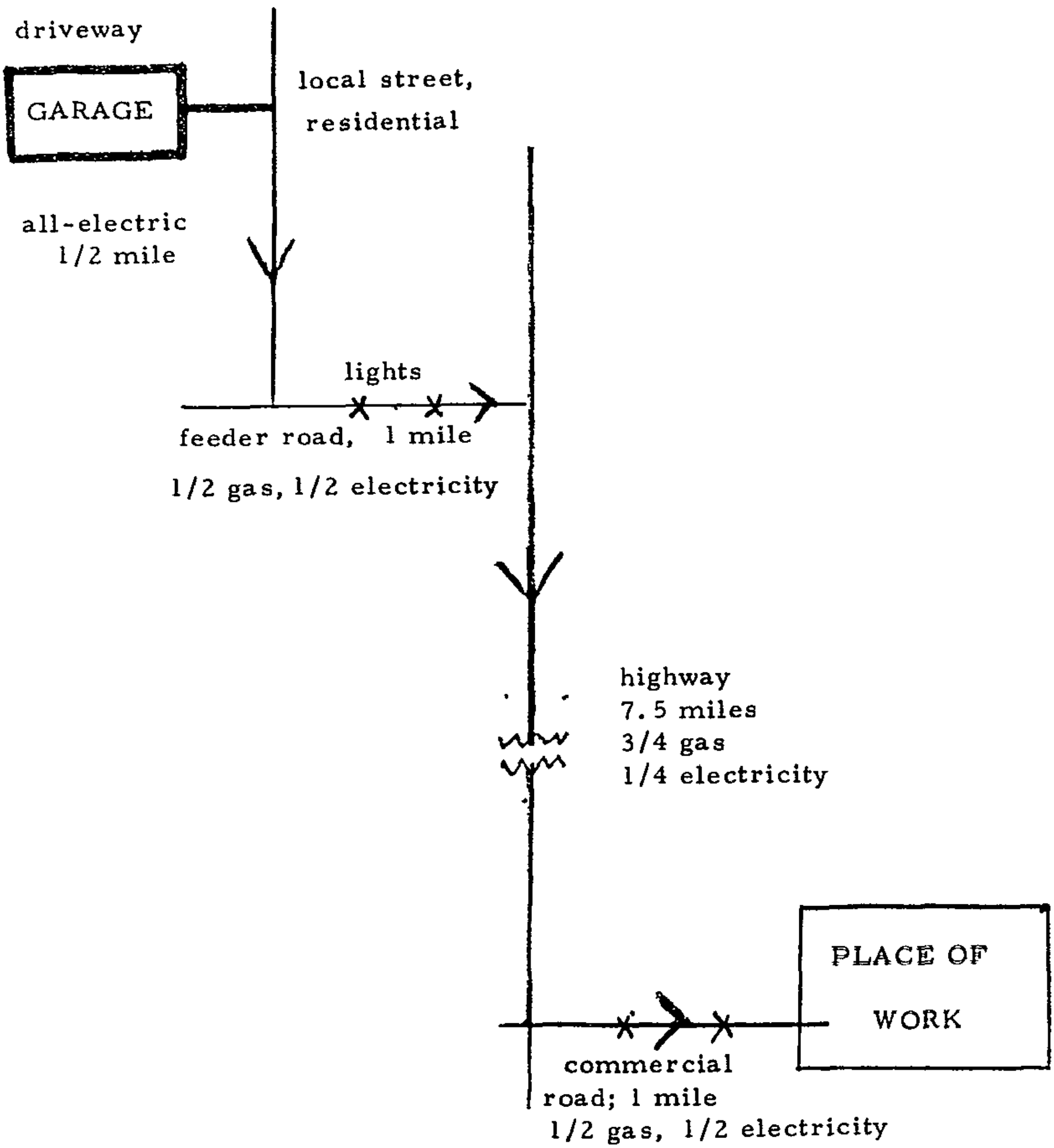
BY V. W. DATE 30/9/75 SUBJECT HYPOTHETICAL COMMUTER DRIVE MISSION, 10 miles SHEET NO. 1 OF

CHKD. BY DATE JOB NO. 3.9.51



WHY ACTUAL EXPERIENCE IS USUALLY

LESS THAN EPA RATINGS:

(1) ENGINE CONDITIONS

(2) TERRAIN

(3) WEATHER

(4) DRIVING HABITS

3 9 51

5

PRESENT PRODUCTION CARS
POTENTIAL REDUCTION OF GASOLINE CONSUMPTION WITH HYBRID; COMMUTER APPLICATION, 100 MILES PER WEEK

Part of mission all-electric, balance with less than 20% battery depletion.

Drive portion	Function	Conventional Car Distance miles	EPA mpg	Actual mpg	Gallons used	As Hybrid % gas	% electric	Gallons used
1	Garage to feeder road, on local residential streets: startup, engine warmup; stop-go traffic	1/2	20	10	0.050	0	100	0
2	feeder to highway; further warmup; stop-go traffic	1	20	15	0.067	50	50	0.033
3	on highway, warmed up; cruise, acceleration, deceleration, road undulations	7 1/2	30	25	0.300	75	25	0.225
4	feeder to work, local commercial street; stop-go traffic	1	20	15	0.067	50	50	0.033
	TOTALS:	10			0.484			0.291

$$MPG = \frac{10}{0.484} = 20.7 \qquad MPG = \frac{10}{0.291} = 34.1$$

$$\text{Ratio} = \frac{34.1}{20.7} = 1.64; \quad 64\% \text{ increase in mpg}$$

8-14

3.9.51
6

77-40

FUTURE HIGH MPG PRODUCTION CARS
POTENTIAL REDUCTION OF GASOLINE CONSUMPTION WITH HYBRID; COMMUTER APPLICATION, 100 MILES PER WEEK

Part of mission all-electric, balance with less than 20% battery depletion

	Conventional Car				As Hybrid		
Drive portion	Distance miles	EPA mpg	Actual mpg	Gallons used	% gas	% electric	Gallons used
1	1/2	24	12	0.0415	0	100	0
2	1	24	18	0.0556	50	50	0.0278
3	7 1/2	42	35	0.2140	75	25	0.1605
4	1	24	18	0.0556	50	50	0.0278
TOTALS:	10			0.3667			0.2161

$$MPG = \frac{10}{0.3667} = 27.3 \qquad MPG = \frac{10}{0.2161} = 46.2$$

$$\text{Ratio} = \frac{46.2}{27.3} = 1.69;$$ 69% increase in mpg

3 9.51

7

8-16

FUTURE PRODUCTION CARS
POTENTIAL REDUCTION OF GASOLINE CONSUMPTION WITH HYBRID; SECOND CAR APPLICATION; 50 MILES PER WEEK

Part of mission all-electric, balance with less than 20% battery depletion

Drive portion	Function	Conventional Car Distance miles	EPA mpg	Actual mpg	Gallons used	As Hybrid % gas	% electric	Gallons used
1	Garage to local residential streets: startup, engine warmup; stop-go traffic	1/2	35	25	0.02	0	100	0
2	Shopping and other secondary uses; return to home	4 1/2	35	30	0.150	50	50	0.075
	TOTALS:	5			0.17			0.075

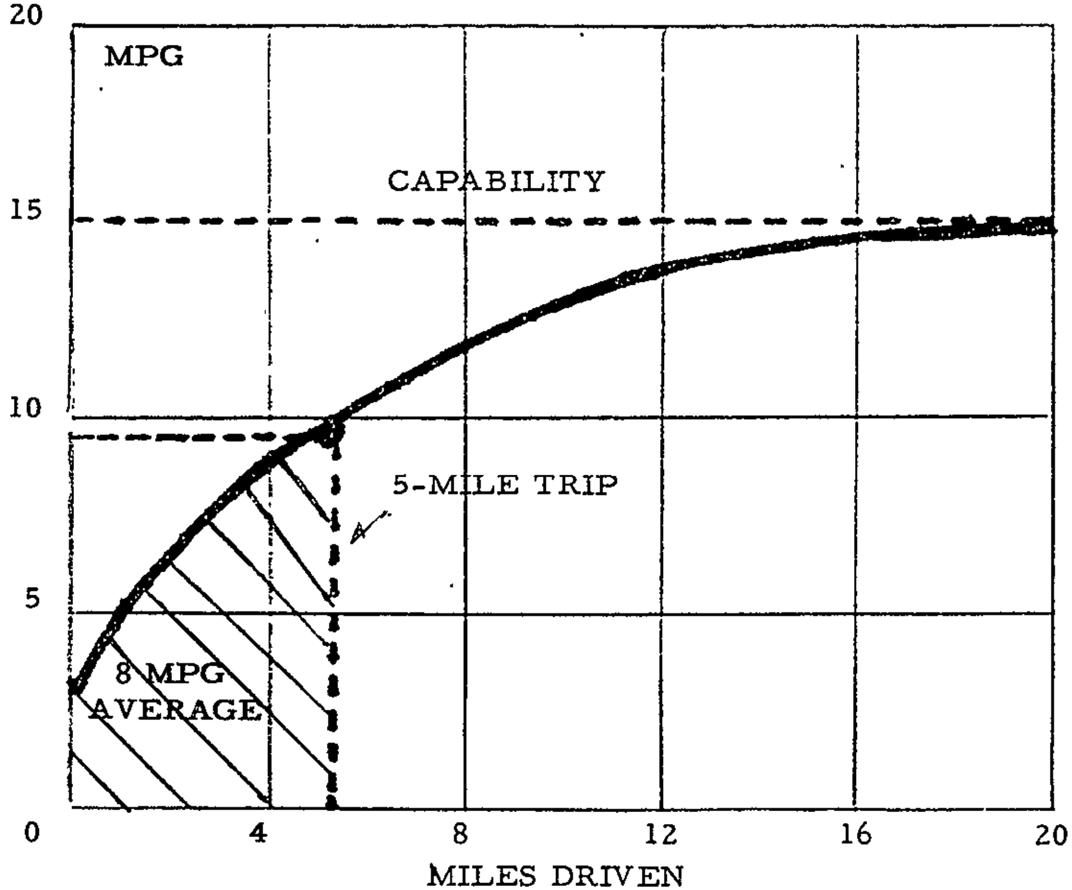
77-40

$$\text{MPG} = \frac{5}{0.17} = 29.4 \qquad \text{MPG} = \frac{5}{0.075} = 66.67$$

$$\text{Ratio} = \frac{66.67}{29.4} = 2.27;$$ 127% increase in mpg (more than double)

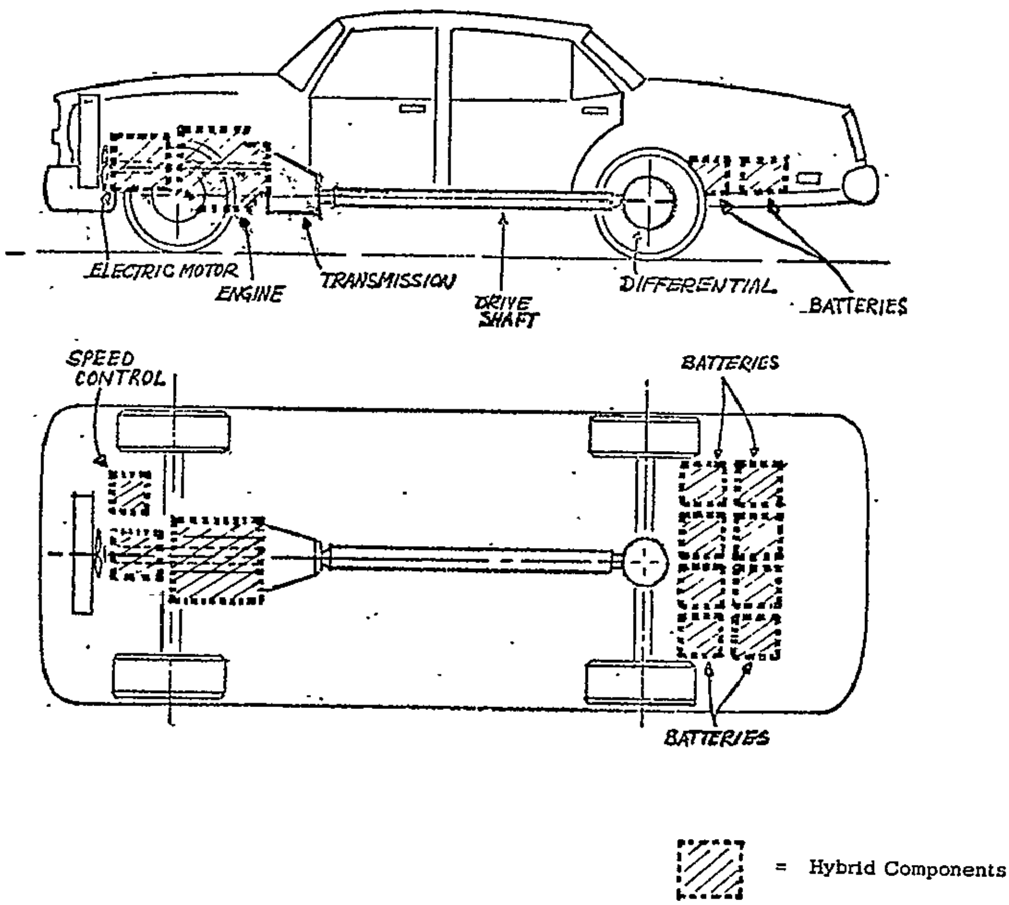
3.9 51 8

BY ______ DATE ______
CHKD. BY ______ DATE ______
SUBJECT Vehicle Warm-Up Cycle
SHEET NO. 9 OF ______
JOB NO. 3.9.51



PETRO - ELECTRIC MOTORS LTD.

HEAT ENGINE / BATTERY ELECTRIC HYBRID VEHICLE



Designed; Produced and Tested
under the EPA/ERDA - AAPS
Federal Clean Car Incentive Program

May, 1975

INTRODUCTION

This Prototype Hybrid Vehicle was developed with private funds under an EPA/AAPS Test and Evaluation Contract 68-0004-0008. This Prototype is part of the Federal Clean Car Incentive Program which has, as its objective, the financial incentive stimulation of private industry to undertake their own research for development of commercially acceptable low pollution passenger vehicles.

This FCCIP Program was, when AAPS was a Division of EPA, a concurrent Program to the Advanced Automotive Power Systems' Research and Development Programs on Steam, Turbine and Fuels.

CONTENTS

This Prototype Vehicle consists of the following:

- Basic 1972 Buick Skylark Body, Chassis, Suspension System
- A Toyo Kogyo RX-2 (1972) Rotary Wankel Engine
- A 15 hp Electric Motor
- Gould 12V Automotive Batteries
- Electronic Controls

BRIEF THEORY OF OPERATION

The Petro-Electric Hybrid Power Train consists of:

- a small internal combustion engine
- a dc motor, operating from a bank of batteries, to augment the acceleration power of the internal combustion engine

The gasoline engine and electric motor are mechanically coupled to rotate at the same speed and drive the vehicle through a conventional transmission.

The accelerator pedal operates electronic controls that cause the motor to act either as a generator or a motor, depending on the speed of the vehicle and the accelerator pedal position. The accelerator pedal does not operate the engine throttle, except under very high power demand conditions.

The emission control is based on the use of a thermal reactor and EGR.

RESULTS TO DATE

As part of the FCCIP Program, this Prototype Vehicle was extensively tested by the Emission Control Technology Division of EPA. The results were as follows:

- Emissions:

	1975 Federal Stds.	FCCIP Goals (gpm)	Avg. of Tests	Better than Goals	Better than '75 Stds.
- HC	1.5	0.41	0.38	12%	76%
- CO	15.0	3.40	2.41	33%	83%
- NOx	3.1	1.00	0.76	23%	75%

- Startup: - 1/2 - 2 seconds
- Acceleration: 0-60 w/ 4,950 lb. gross weight - 16 seconds
- Top Speed: - over 80 mph
- Range: - over 200 miles, at 60 mph
- Reliability: - no component failure during 11,000 miles of operation
- Passengers: - 5 - 6
- Weight:
  - Drive Train - Approximately 1,000 lbs with batteries
  - Curb - 4,100 lbs.
- Fuel: - Standard gasoline
- Noise: - 78 dba

POTENTIAL RESULTS/BENEFITS OF HYBRID CONCEPT

The various reasons for anticipating improved fuel consumption are:

- The ability to use a smaller engine while maintaining an adequate performance level
- Recovery of some of the braking energy
- Easier implementation of such fuel saving techniques as automatic idle shut-off, and use of lower gear ratio during cruise
- The ability to use constant speed accessories
- Energy conservation of scarce material resources
- Implementation of the general national mandate conerning alternative automotive developments.
- Transitional to all-electric

PETRO - ELECTRIC MOTORS, LTD.

SUMMARY OF FACTS

* High mileage per gallon; projections of over 20 mpg for a full size car
* No catalysts needed; uses thermal reactor
* Hybrid concept applicable to any size car from subcompact to luxury
* Can run as an all-electric, using no gasoline for short trips
* Can be produced in quantity
* Prices comparable to Detroit's projections
* Practical for both city and highway driving
* Smooth, stall-free operation in stop-and-go traffic
* Immediate startup in coldest weather
* Batteries automatically recharged
* Taxis, delivery vans, and buses cheaper to own and use than conventional vehicles
* Patented combination of electrical motor with gasoline engine
* Driver controls identical to conventional vehicle

NOTES

Further Details can be obtained from:

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"ELECTRICITY AS A 'FUEL' FOR AUTOMOBILES"

by

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New York, New York 10017

Presented at the

International Conference of Automobile Pollution
ROYAL YORK HOTEL
Toronto, Canada

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"ELECTRICITY AS A 'FUEL' FOR AUTOMOBILES"

by

Dr. Victor Wouk

INTRODUCTION

This paper could be short and sweet, or long and bitter. I prefer to make it short and sweet, but it should be long and bitter, because there are people who object to electric automobiles! Therefore this will be of moderate length, hopefully pleasant to all.

The main objective of this paper is to refute objections raised against electric automobiles as a solution to vehicular air pollution. A secondary objective will be to indicate how we can expect electric vehicles to be a solution not only to automobile air and noise pollution problems, but also a solution to the depletion of fossil fuels' supplies.

THE ELECTRIC VEHICLE: (Nice things about them).

An electric automobile has no noxious emissions due to its on-board drive system. [I disregard the microscopic effects of "rubber pollution" from tires, and "asbestos pollution" from brake linings. Even the latter is reduced by regenerative braking (1) in electric vehicles.]

If one stands beside an electric vehicle that is "idling," one hears no loud noises and smells no exhaust smells, etc., from the electric car. At present, gear shifting may be employed for certain electric vehicles (2). If this is the case, then the vehicle is not completely silent during "idling," and some energy is being drawn from the batteries. However, it is true that during "idling" of an electric vehicle there is no noxious exhaust, as is characteristic of an idling internal combustion engine vehicle (ICE). The noise from any properly designed electric vehicle is lower than its ICE counterpart.

ELECTRIC VEHICLES: (Objections to them, valid or not)

Objections to electric vehicles include the following:

1. Generation of Ozone: I will not dignify this objection to electric vehicles by a reference note. (Also, I must confess I do not remember where this objection appeared in print). Someone stated that ozone generated by contactors opening and closing frequently to control the vehicle speed, would present a health hazard. This objection is unadulterated engineering nonsense.

In a modern electric vehicle, speed is controlled not by contactors, but by semiconductor devices. Hence, there is ozone generated only when the vehicle, under certain very unusual circumstances, is brought to a stop, and the main contactor is opened under load. The amount of ozone generated is so small that it would be immeasurable on a Los Angeles "Freeway," where traffic is moving bumper-to-bumper. The ozone from dc motor commutator brush arcing is similarly negligible. But the smog-generating ozone from ICE fumes is far from negligible.

2. Sulfuric Acid Fumes: Another objection is that batteries emit sulfuric acid fumes. The quantitative aspects of this statement are so ridiculous as to warrant no response. But let us swallow our professional pride, and reply. Fumes may be released during battery recharging. These fumes are in general negligible, and are normally developed in a controlled atmosphere, readily dissipated in a harmless manner.

Further, as predicted in 1967 (1), sealed batteries may be developed for electric cars. A recent article by Salihi (3) implies that such batteries may soon be a commerical reality.

Therefore, no matter how hard one tries, one cannot make a convincing case that an electric vehicle itself emits any type of noxious gas, mist, fine powder, or what-have-you.

Let's go to another objection:

3. Enormous electrical power generation capacity required to supply power to electric vehicles: This is worthy of serious consideration. An article appeared in early 1967 by David Ash, an internationally recognized expert on automobile performance, being optimistic about electric automobiles in the not-too-distant future (4). In a rebuttal two weeks later (5) some one wrote in essence the following:

> "Don't those stupid electrical engineers, who are enthusiastic about electric cars, know that if all vehicles were converted to electric vehicles overnight, the electrical power generating capacity in the United States would have to multiplied 100 fold?"

Since, as we are aware, engineers of all types have been guilty of some major boo-boos (viz., the Tacoma Bridge, "Galloping Gertie", ca. 1941, the Great Blackout of 9 November 1965) this type of quantitative criticism warrants quantitative examination.

In Appendix A it is shown how, if all vehicles were turned into electric vehicles overnight, the amount of electrical power generating capacity in the United State would have to double, not be multiplied 100 times. Admittedly even a doubling would be a serious problem. However, vehicles would not multiply overnight. Their growth would be over a period of decades. Salihi (3) has analyzed the problem, and has shown that the impact of electric vehicles is small, in comparison with other electric power growth demands. Fig. 1, reproduced from (3), shows that the additional power requirements due to electric vehicles will be, by year 2000, only 10% of the total electrical power generating capacity in the USA.

4. Pollution from Electric Power Generating Stations: Another possible objection to electric vehicles is that electric power generating stations that burn fossil fuels, produce noxious emissions from their smokestacks. Hydro-electric generating stations often offend ecologists. Nuclear power generating stations tend to send otherwise reasonable people into paroxyms of fear about radiation, explosions, spills on highways, etc.

What are the QUANTITATIVE facts?

Much to the amazement of the proponents of electric cars, calculations have been made that purport to prove that electric cars are MORE polluting than ICE's (6)!

In the paper by Dr. Agarwal, (and Dr. Agarwal is an honorable man), he calculates that due to the inefficiencies involved in the train of:

(a) burning fuel to generate electric power in a power station,
(b) transmission to a load center,
(c) distribution to an automobile,
(d) charging a battery,
(e) discharging the battery and supplying power to the wheels,

the net inefficiency of the (a - e) sequence is such that the total pollutants emitted at the power stations' smokestacks, to generate the energy required to drive the "electrics", is much greater than the pollutants that would be emitted from ICE automobiles.

The balance of this paper is devoted mainly to analyzing the qualitative and quantitative errors in Dr. Agarwal's thesis, and to reinforce the intuative conclusion that eventually one must look to electric power for individual ground transportation. Further, in Appendix C it is shown that even if Dr. Agarwal's conclusions were correct (they are not), it is feasible to control the effluents of 1 dozen smokestacks in a metropolis, whereas it is NOT possible to control 1 million car tail pipes.

One feels intuitively, instinctively, or one might say, by experience, that electric vehicles are less polluting than internal combustion engine vehicles. For example, on a very snowy day in New York City, where the snow is so deep that vehicular traffic is virtually non-existent, experience indicates that the air is clear and fresh. Consolidated Edison is burning fuel at a merry rate to provide the requirements of our electricity-oriented civilization. Yet, despite this fact, the air is clean and breatheable. Now, let a bus or truck lumber by, and one gets a noticeable whiff of unpleasant emissions.

Consider another extreme. A clear, beautiful spring day, the sun shining brightly, the wind scarcely stirring, and street traffic is at a maximum. It does not require much imagination to reproduce mentally the miasma of odors in which one will be steeped at a typical corner, such as 42nd Street and Madison Avenue. Buses will be belching their diesel fumes. Taxis will be emitting not only the racous noises of the horns, and the penetrating epithets of the taxi drivers, but an overwhelming amount of noxious emissions, from the idling engines of the bumper-to-bumper traffic.

I could make the picture even more vivid by throwing in the characteristics of delivery vans and monstrous trucks, with their ear-shattering din, when they rev-up, after the traffic light changes to green. However, this would be "over-kill".

With the above experiences so widespread, how can anyone conclude that electric vehicles would be more polluting than internal combustion engine vehicles?

According to Smith (7), this is a plot by the automobile and the petroleum industries to discredit electric vehicles. I do not accept this hypothesis. I assume that the critics are sincere.

Hence, we must conclude that there was a serious basic error in the presentation (6), and upon analysis this proves to have been the case.

Although the total emissions into the atmosphere from systems that produce energy for electrically driven vehicles might be of the same magnitude as emissions into the atmosphere from internal combustion engine vehicles, (a fine philosophical point, see appendix B), to paraphrase a popular commercial for a device that pollutes air very locally, i.e., a cigarette, "It's down where the people breathe the stuff that counts."

Automobiles emit their noxious fumes at ground level, where the human being can inhale the pollutants.

Fuel-burning electric power generating plants emit their emissions at a high level above the ground.

By the time the emissions from smokestacks reach ground level, there has been an enormous dilution of the noxious gases.

A study (8) that included a realistic appraisal of the effects of dispersion from a high level smokestack, and which took into account the fact that there is also some dispersion from the highly concentrated noxious fumes of a tail pipe of an automobile, produced the following startling results:

> The gasoline powered motor vehicle (GMV) overall system produces approximately 100 times as many noxious emissions of all types, than does the overall system for powering electric motor vehicles (EMV). This factor of 100 is at ground level, where the noxious emissions can be inhaled.

The Mencher-Ellis (8) recognizes that one must analyze the <u>entire</u> complex of production of motive energy, beginning with removal of the fossil fuel from the ground, and processing and distributing it for final use, in the case of a gasoline powered motor vehicle. Then, one must also compare the entire impact on the environment for obtaining the fuel for a stationary electrical power generating plant, processing it, using it to generate power, transmitting the power to the vehicles, etc.

Fig. 2 shows the major elements of the energy supply to, and use by, the GMV and the

EMV, that have impacts on the environment. These include:

Drilling for crude oil.
Transportation of the crude oil.
Refining of the crude oil, and preparing it for gasoline.
Preparation and distribution of fuels to provide the process energy requirements of oil refineries for gasoline production.
Distribution and storage of gasoline at gas stations.
Operation of gasoline motor vehicles.

In each of these steps, there is energy required, which normally involves either use of electricity, or burning of fuels, and/or an impact on the environment due to hydrocarbon evaporation, spillage of hydrocarbons into waterways, etc.

The electrical system has a similar, but less extensive an impact. It includes:

Drilling, transport and refining of coal, oil, natural gas and uranium, as fuels for power generation.
Electric power generation and transmission.
Operation of the EMV.

The report by Mencher and Ellis is elaborate and is referenced in detail. Therefore, only the major results are discussed here.

Table I shows the comparative environmental impact in 1980 of gasoline powered motor vehicles versus electric powered motor vehicles. It can be seen that, superficially studied, the apparent advantages, it any, of EMV versus the GMV for total emissions seems to be small.

Thus, in total particulates, the EMV has more than twice the yearly emissions than the GMV, smokestacks versus tail pipes.
In respirable particulates, the EMV is 30% better than the GMV.
In BaP, the EMV seems to be 20 times as good as the GMV.
In sulfur dioxide, the EMV is 4 times as bad as the GMV.
In nitrous oxide the GMV is 50% worse than the EMV.

The two very obvious advantages of the EMV are in carbon monoxide and hydrocarbons, where the GMV is 100 times and 40 times as bad respectively than its electrically driven counterpart.

Both systems produce approximately the same amount of carbon dioxide, and the same amount of total waste heat. This is understandable, in light of the philosophy of Appendix B.

Noise pollution from the GMV is significantly greater than EMV. Oil spillage into waterways is 5 times as bad for the GMV.

However, this is not the whole story. The figures of Table I are for the total emissions into the atmosphere. What about the emissions down at ground level where people breathe? Fig. 3 shows the basic technique for analyzing the ground level concentration due to a given source of emissions with known parameters that affect vertical concentration distributions.

An analysis is made in (8) for the dispersion of emissions from vehicles (assumed to be on a four-lane highway) at a receptor some reasonable distance away from the highway. Thus, it is not assumed in the Mencher-Ellis analysis that one is standing next to a line of vehicles that are whipping by and belching noxious fumes right into the victim's face.

When all of these factors are taken into consideration, the startling data of Table II are developed.

Examining this, we see that down at ground level, the total particulates emitted for EMV impact had been reduced by a factor of 100, as are all other factors. The reduction for the GMV is also included, but the ground level reductions of Table II vis-a-vis Table I are scarcely of the order of 1/100, for the GMV, as is the case for the EMV.

Therefore, whereas originally in Table I the EMV was poorer than the GMV in total particulates, where it comes to ground level emissions' equivalents, on total particulates the GMV is now 20 times as bad as the EMV.

On respirable particulates, the GMV is 100 times as poor as the EMV.
With respect to BaP, the GMV is about 2,000 times as bad as the EMV.
On sulfur dioxide, the GMV is 10 times as bad as the EMV.
On nitrogen oxide, the GMV is 100 times as bad.
On carbon monoxide, the difference is more than a factor of 1,000, as the case for hydrocarbons.

The data in Table II confirms the empirical experience of most human beings in congested urban areas, to wit:

> At ground level the effects from internal combustion engine vehicles are, in general, much worse than the effects from electric power generating stations.

The above data lay to rest once for all the objections that the electric vehicle require electric energy generation which will result in emissions at least as bad as those of internal combustion engine vehicles.

As a final note with respect to the Mencher-Ellis analysis, the following two points should be made:

1. These projections are for the estimated number of vehicles in 1980, namely, 142,300,000 motor vehicles.

2. It is also assumed that internal combustion engine vehicles, and electrical power generating stations, will be cleaned up in accordance with Federal and Local law requirements. (See Appendix C for further discussion of this.)

*

FUEL AVAILABILITY

Both the popular and technical literature abound with dire predictions of an imminent shortage of fossil fuels, i.e., petroleum, natural gas and coal.

The literature abounds equally with popular and learned analysis that shows that more sources of these fossil fuels continue to be found. Further, extremely extensive sources such as the shale oils of the Rockies have abundant oil reserves, the extraction of which is basically a matter of relative economics. This also applies to converting coal into petroleum products. Since there are acknowledged thousands of years of coal reserves, the attitude seems to be "Don't worry, we'll always have enough gasoline quivalent, even though it may be expensive."

The known and projected reserves of readily extractable fossil petroleum can be pessimistically estimated in decades, and optimistically in two or three centuries at the most. Fig. 4, from Salihi (3), is pessimistic. Should we be concerned with this now? The answer has already been made in at least two areas.

1. In the United Kingdom, there are approximately 60,000 electric delivery vans used for delivery of dairy products, bakery products, etc. for the consumer.

2. The RWE (Rheinisch-Westfalisches Elektrizitatswerk) in West Germany is undertaking a program to develop a viable electric vehicle system by the year 1980, because of the simultaneous problems of reduction of available fossil fuels, and air pollution.

The 60,000 electric vehicles in the United Kingdom have been developed commercially because of the high price of petrol, plus such other factors as the high maintenance cost of an ICE van vis-a-vis the low maintenance costs of an electric vehicle.

The reason why the electric vehicle cannot compete at present with the internal combustion engine (in range and speed) is the fact that the energy density of gasoline is approximately 1,000 watt hours per pound, whereas a lead-acid battery has only 10 watt hours per pound (9). Extensive work is being done to develop batteries with energy densities of 100 watt hours per pound (3). When this 200 WH/kg comes to pass, the electric vehicle will be competitive with the ICE for everything except very long range drive across country, etc. Since well over 90% of cars travel less than 100 miles on a trip (10), we can look to the day when electric vehicles will be quite viable.

Where will all the electrical power come from?

My operating hypothesis is that there will not be a change in either our mode of living, nor in our rate of increase of general affluence. Despite all the jeremiads, there will be more use of electrical power for individual comfort and convenience, and for industrial processes which will make for "the better life." No responsible scientist or engineer will accept the continuing rate of growth of electrical power generation without introducing nuclear power as a major source of growth. Mencher and Ellis take this into consideration. They consider the hazards. If we accept nuclear power generating stations, starting with uranium fission, and going to plutonium breeder reactors, we can project sufficient electrical energy for personal automotive use, in conjunction with improved batteries. Batteries need be improved only by a factor of two, i.e., about 50 WH/kg, in order to make a ten-minute battery exchange system completely feasible technologically, and acceptable economically.

One need not go into "Buck Roger" techniques of individual atomic reactors activating each automobile [the "Atomobile" of Fig 5 is impossible (9) due to shielding and many other problems], nor to fusion power generating stations. The latter, though extremely attractive in principle, have yet to be demonstrated scientifically as being feasible.

* *

CONCLUSIONS

Our society must begin to take electricity seriously as "fuel" for automobiles. It has already been taken seriously as a fuel for delivery vehicles in the United Kingdom, and is being studied seriously in other foreign countries. Since there is probably no alternative, the sooner we take this seriously in the Western hemisphere the better.

* * * * * * * * * * * * *

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* * * * * * * * * *

APPENDIX A

The claim that if all conventional vehicles were converted into electric vehicles overnight, it would cause a required increase in electrical generating capacity of 100-fold, is assumed not to have been pulled out of empty air as an arbitrary figure.

In an effort to determine how such a figure could conceivably have been arrived at in a systematic, although erroneous engineering calculation, below are calculations that might yield such a conclusion.

The following figures are based on data in a region such as New York State (as of 1967), and are rounded off for ease of calculations.

(1) Assume number of vehicles = $10,000,000 = 10^7$.
This value is the correct order of magnitude for New York State.

(2) Assume horsepower per vehicle = 250hp.
A reasonable assumption; horsepower of buses and trucks is higher, and of many small cars lower.

(3) From (2), kilowatts per vehicle $= 250 \times 0.746 = 200$ kilowatts.

(4) Assume present electrical-power-generating capacity in New York State $= 20,000,000 = 20 \times 10^6$ kilowatts.
This value is fairly close to the actual figure.

(4) (cont'd) At first glance, it might appear as though the additional power required is indeed formidable. From (1) and (2), the additional capacity needed =

(5) 200 (kilowatts per vehicle) x 10^7 (vehicles) = 200 x 10^7 kilowatts.
From (4) and (5) the additional power required is

(6) (5)/(4) = $200 \times 10^7 / 20 \times 10^6 = 100$.
i.e., the generating capacity would have to be increased 100-fold.

This figure looks formidable. However, the reasoning incorporates two major fallacies.

FALLACY 1: The 200-kilowatt power figure of equation (3) is peak power, used only infrequently, when the vehicle accelerates rapidly or moves up hills rapidly. The average power required is substantially less.

Taking into account the lower average power requirement, plus the acknowledged greater efficiency of a battery-electric motor system, one might estimate the average power requirement for a car at 20 kilowatts. So. from (6):

(7) $100 \times \frac{20 \text{ kw}}{200 \text{ kw}} = 10$, or a tenfold increase.
The tenfold increase is still substantial.

FALLACY 2: Vehicles are NOT used 24 hours a day. Considering values from 24 hours a day for some taxis to 2 hours a week for some suburban cars, we can reasonably estimate an average use of 2.4 hours a day. Using (6) and (7) and 2.4 hours, we get

(8) $100 \times \frac{20 \text{ kw}}{200 \text{ kw}} \times \frac{2.4 \text{ hr.}}{24 \text{ hr.}} = 1$

i.e., the order of magnitude of increased electrical power required is a doubling, not a 100-fold, multiplication.

Independent analyses of the petroleum fuels consumed by all types of internal combustion vehicles in the United States, automobiles, trucks, buses, taxis, etc. indicate that the BTU equivalent of the product actually burned (after refining), when converted into kwh, is of the same order of magnitude as the total kwh generated per year in the United States by all generating stations. Therefore, the doubling of equation (8) is confirmed independently.

Further, the information in the paper by Salihi (3) shows that the energy demand if all cars were electric cars in the year 2,000 is about 1/2 of the present electric generating capacity in the United States.

Hence, we can lay to rest the fear that electric cars will strain the nation's electrical power generating systems.

APPENDIX B

Philosophical note on GMV vs. EMV total impact: Upon consideration of an over-all picture of an electric vs. a GMV, if the fossil fuel is going through a series of processes which will eventually drive a vehicle, one will recognize that the fossil fuel will have an impact on the environment.

If one looks at the fossil fuel withdrawn from the ground, refined, etc., and then put into a vehicle which will operate from an internal combustion engine, the overall effects must of necessity be reasonably close in the two systems, unless one system is extremely more efficient than the other system.

There may be portions of each complicated system that is more efficient in one than the other, the utilization of on-board stored energy by an electric motor is much more efficient than the utilization of on-board stored energy in a ICE., ~~then~~ one vehicle would be vastly superior to the other. However, on the other hand, the energy lost in storing the energy on-board the electric vehicle is much greater than that lost in getting the gasoline on board the internal combustion engine vehicle.

Therefore, one should not be too surprised that the total impact on the environment from both systems is essentially the same.

It is when one analyzes the method in which the pollutants are distributed into the atmosphere that one obtains the factor of almost 100 of superiority of the electric vs the gasoline.

A corollary of this would be that if a system is developed for converting fossil fuel on-board a vehicle into electrical power with little impact on the environment, this would undoubtedly be the best from an air pollution control point of view. Implied is "fuel cells", for which there is present little practical enthusiasm in the realm of vehicular propulsion.

APPENDIX C

Maintaining smokestacks clean, vs. maintaining automobile tail pipes clean. In the analyses referred to herein, particularly Salihi (3) and Mencher and Ellis (8), it is assumed that the air pollution controls that have been legislated for 1975 and 1980 will actually be in effect.

Many responsible people refer to this as "abject optimism". Although it is reasonably possible to maintain policing pressure on public utilities and the relatively few smoke-stacks in a given area, doubt has been expressed in virtually all quarters about the ability of keeping a hundred million automobiles properly tuned so as to maintain all of the air pollution control devices in proper operating condition.

The consensus seems to be that mandatory inspection will be necessary, and that this in itself will be an expensive program, not very popular with the electorate (11). One therefore concludes that if the realistic aspects of inclusion of pollution control devices is taken into account, there is probably another factor of at least 10 in favor of the EMV vs. the GMV.

TABLE I

THE COMPARATIVE ENVIRONMENTAL IMPACT in 1980 OF GASOLINE - POWERED MOTOR VEHICLES (GMV) VERSUS ELECTRIC-POWERED MOTOR VEHICLES (EMV)

POLLUTANT	1980 POLLUTANT EMISSIONS DUE TO: EMV	GMV
TOTAL PARTICULATES	821,960 tons	343,768 tons
RESPIRABLE PARTICULATES (under 5 microns diameter)	133,829 tons	189,190 tons
BENZO(a) PYRENE PARTICULATES	0.53 tons	11.26 tons
SULFUR DIOXIDE	5,773,618 tons	1,717,620 tons
NITROGEN OXIDES	2,857,000 tons	4,470,400 tons
CARBON MONOXIDE	130,858 tons	21,322,250 tons
HYDROCARBONS	100,826 tons	4,744,050 tons
CARBON DIOXIDE	1,068,100,000 tons	1,531,450,000 tons
TOTAL HEAT	$21,702 \times 10^{12}$ BTU	$19,450 \times 10^{12}$ BTU
RADIATION	Added radiation that in no case exceeds 5% of natural background radiation for the general population and that averages far less than this over the entire U.S. population	
NOISE	- - -	Significantly greater noise from operation of the GMV relative to the EMV
MISCELLANEOUS	5050 tons of oil emitted into waterways, aesthetic impact of additional transmission & distribution lines for the added electricity requirements of the EMV	29,348 tons of oil emitted into waterways

TABLE II

THE EQUIVALENT GROUND-LEVEL EMISSIONS OF AIR POLLUTANTS IN 1980 FROM THE GMV and EMV TRANSPORTATION SYSTEMS

POLLUTANT	EQUIVALENT GROUND-LEVEL EMISSIONS DUE TO THE:	
	EMV	GMV
TOTAL PARTICULATES	8,220 tons	194,613 tons
RESPIRABLE PARTICULATES	1,338 tons	135,714 tons
BENZO(a) PYRENE PARTICULATES	0.005 tons	11.2 tons
SULFUR DIOXIDE	57,736 tons	609,196 tons
NITROGEN OXIDES	28,570 tons	3,846,304 tons
CARBON MONOXIDE	1,309 tons	21,306,162 tons
HYDROCARBONS	1,008 tons	3,177,820 tons

BY____________ DATE________ SUBJECT________________________ SHEET NO.________ OF________
CHKD. BY________ DATE________ JOB NO.________________

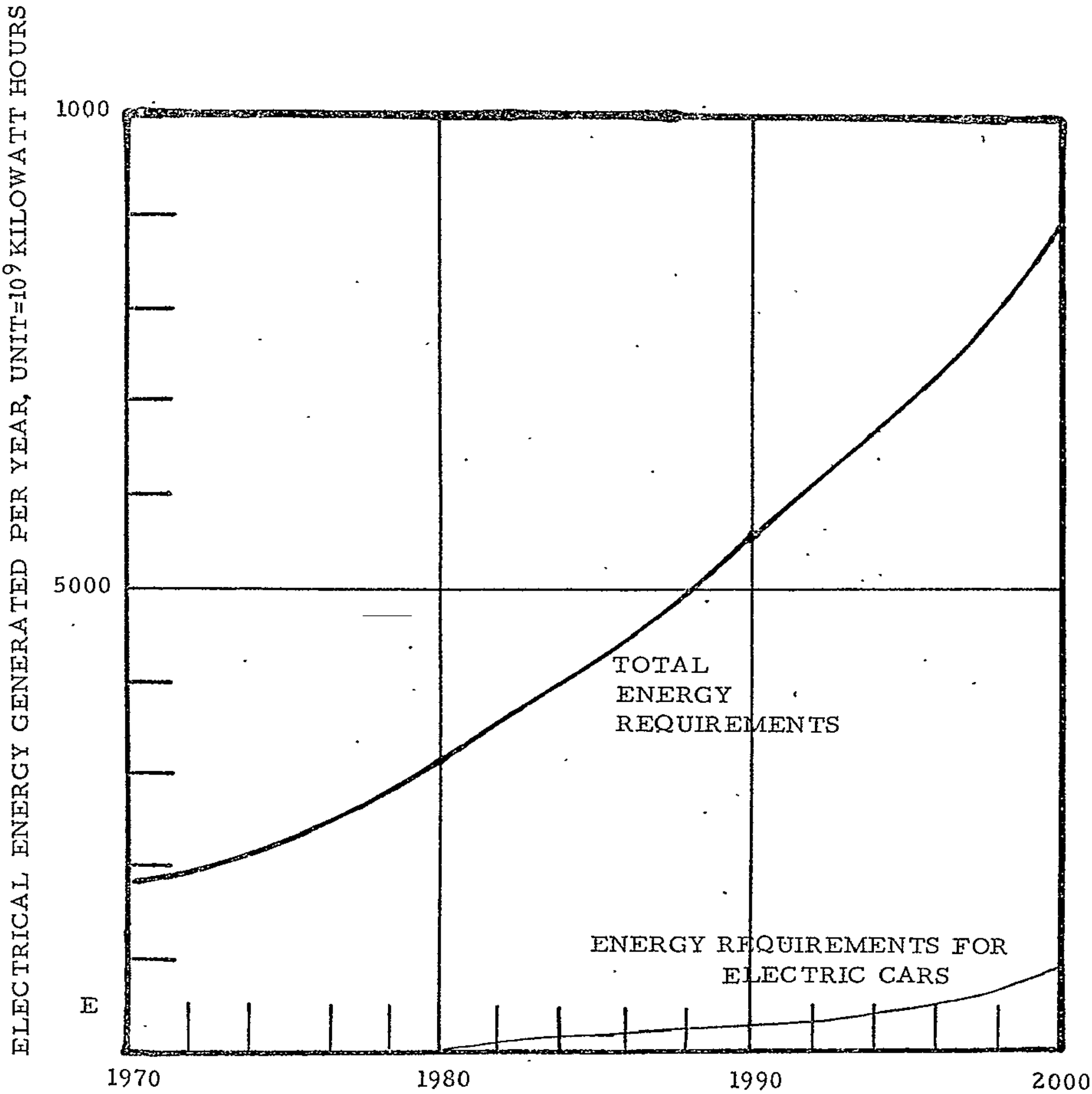


FIG. 1

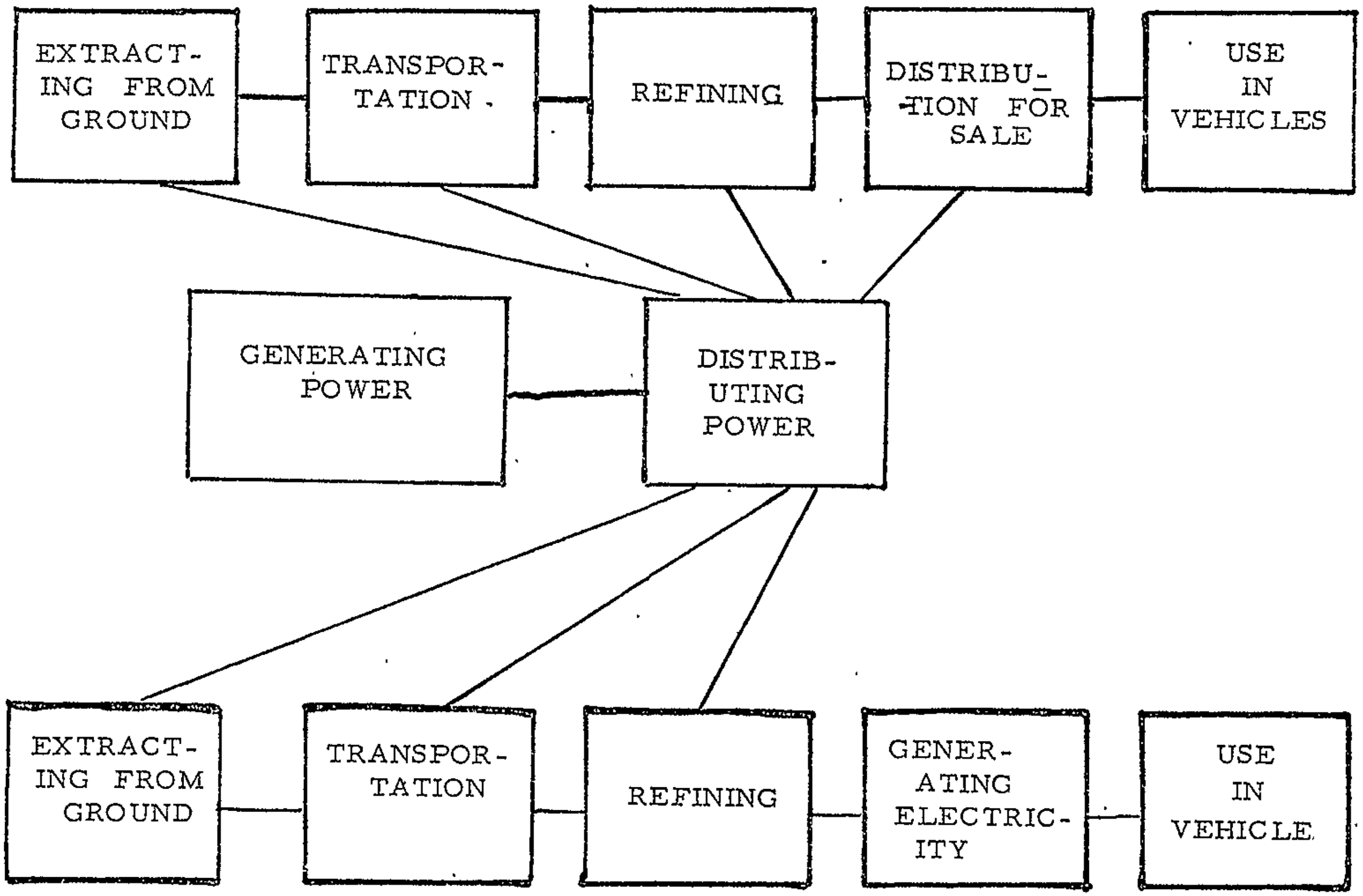

EXTRACT-ING FROM GROUND
TRANSPOR-TATION
REFINING
DISTRIBU-TION FOR SALE
USE IN VEHICLES
GENERATING POWER
DISTRIB-UTING POWER
EXTRACT-ING FROM GROUND
TRANSPOR-TATION
REFINING
GENER-ATING ELECTRIC-ITY
USE IN VEHICLE

FIG. 2

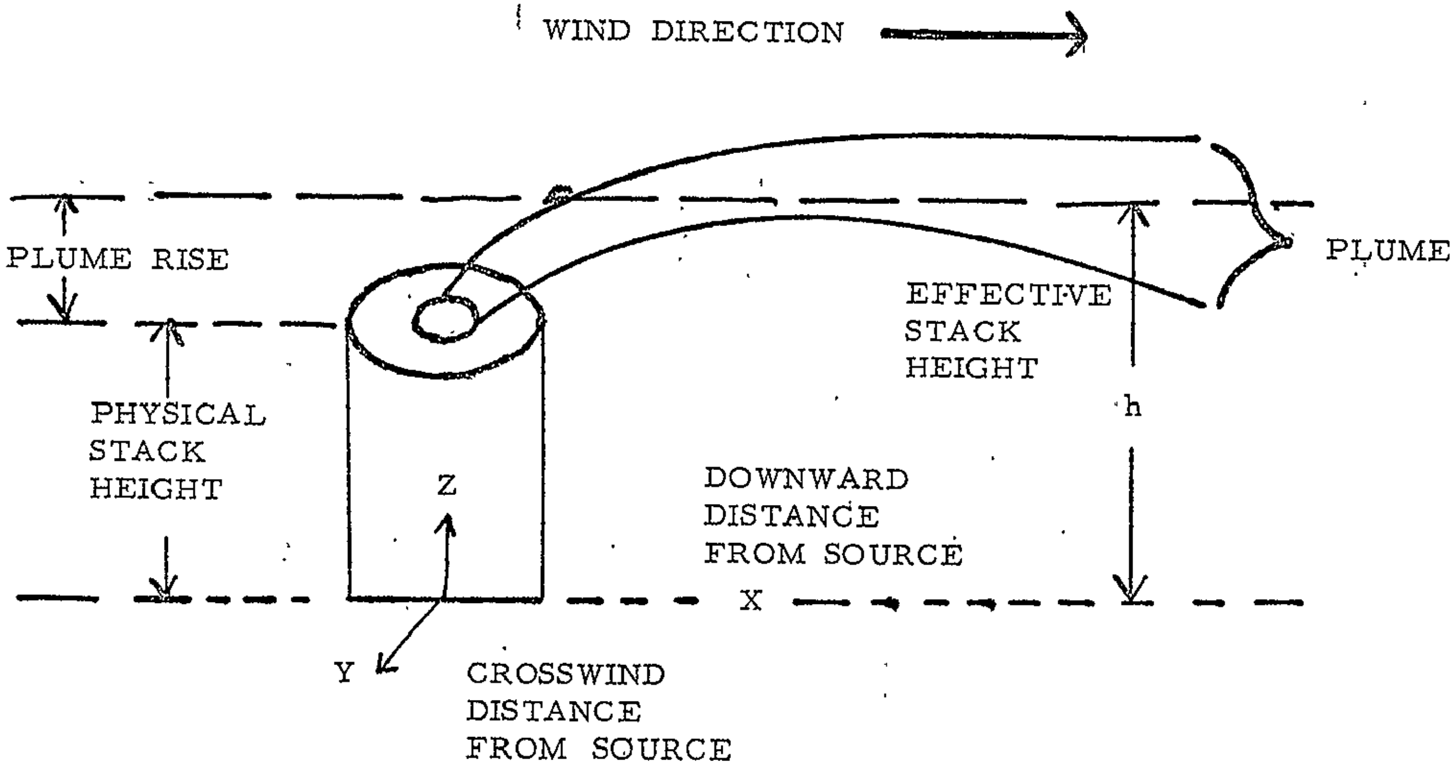

WIND DIRECTION
PLUME RISE
PHYSICAL
STACK
HEIGHT
EFFECTIVE
STACK
HEIGHT
h
PLUME
Z
DOWNWARD
DISTANCE
FROM SOURCE
X
Y
CROSSWIND
DISTANCE
FROM SOURCE

FIG. 3

BY____________DATE________ SUBJECT________________________________ SHEET NO._______OF_______
CHKD. BY______DATE________ ________________________________ JOB NO.____________________

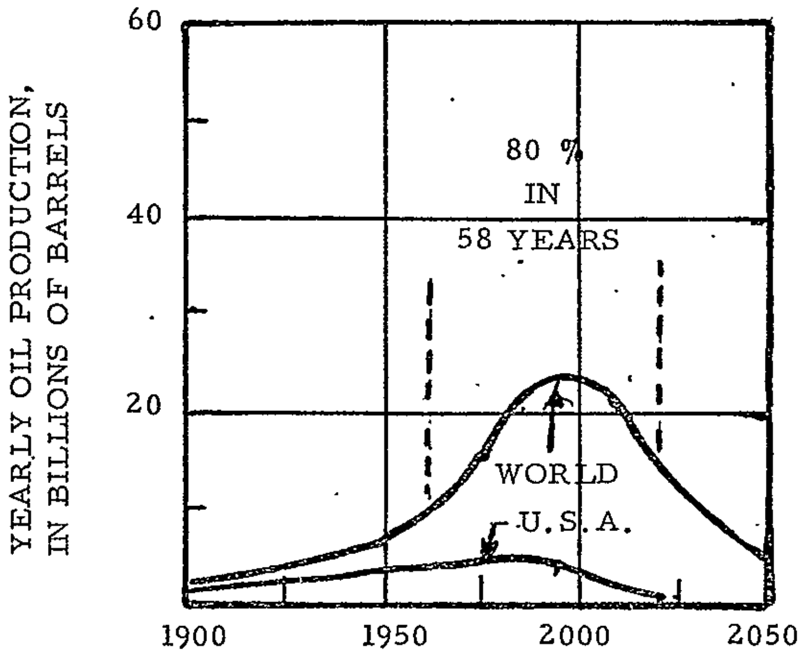
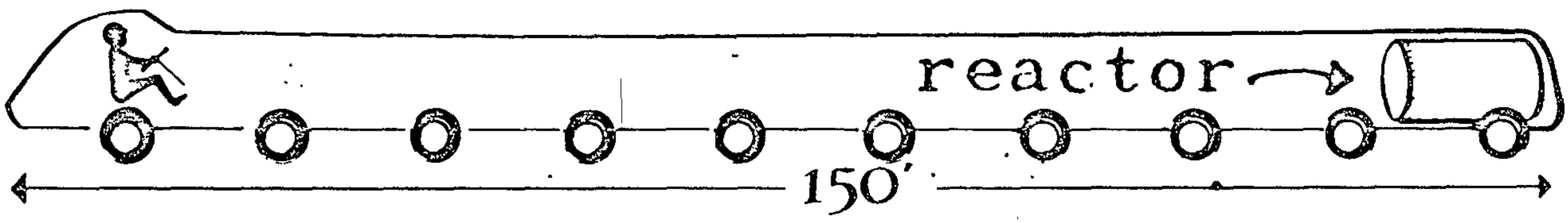


FIG. 4



THE AAAS "ATOMOBILE"

FIG. 8-40

77-40

PETRO - ELECTRIC MOTORS, LTD.
342 MADISON AVENUE
NEW YORK, N.Y. 10017

November 19, 1975

Mr. Howard Vivian
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Vivian:

Here are the major cost items of the PEM "compound hybrid". You can see how much lower the costs are than the JPL estimate of a hybrid, based on the much more complicated TRW type of parallel hybrid. The cost premium of the PEM hybrid is approximately one quarter of the $1,600 you told me the JPL report shows.

The enclosed data are three years old and show only a $330 difference between the PEM hybrid and a conventional vehicle. Since that time we have learned a great deal from experience with the vehicle, we have gotten more accurate cost figures, there has been inflation, and fuel cost savings have become more important. Thus, we estimate that the cost differential now might be as much as $450, about one fourth of the JPL figure of $1,600. I doubt that further elaborate analysis would produce substantive changes.

At the ERDA contractors' meeting in Ann Arbor on November 17th, Dr. Stephenson repeated the JPL report's statement that the advantages of the hybrid cannot justify the high cost. From the above, you will see that this statement is erroneous. I cannot stress strongly enough how unfair this statement is to the entire concept of hybrids and how detrimental it is to PEM.

A JPL statement rectifying this error should in all justice be made at once.

Very truly yours,

PETRO-ELECTRIC MOTORS, Ltd.

V. Wouk

Victor Wouk
President

:mc /10630

encl.: Fig 23, #8169

cc:. Dr. Stephenson

4,000 POUND FAMILY CAR

COST COMPARISON

CLEAN CONVENTIONAL CAR VERSUS HYBRID

	Conventional ICE Car	PEM Hybrid
BODY	$ 1,260	$ 1,300
ENGINE	835*	480
RADIATOR, EXHAUST	170	150
STARTING MOTOR	45	-
GENERATOR	55	-
MOTOR	-	550
DRIVE TRAIN LOGIC	-	50
BATTERY**	30	275
BATTERY CHARGE CONTROL	10	50
TRANSMISSION	205	205
DIFFERENTIAL, AXLE, DRIVE SHAFT	245	245
ACCESSORIES (A/C, RADIO, POWER STEERING)	545	545
HYBRID INSTRUMENTATION	-	30
EMISSION CONTROL EQUIPMENT	250***	100****
INITIAL COST	$ 3,650	$ 3,980
COST OF FUEL*****	3,300	2,900
TOTAL COST OF OWNERSHIP	$ 6,950	$ 6,880

* Add $150. for 20% larger engine and $50. for fuel injection.

** Pricing experience has shown automotive supply prices to be at low end of spectrum due to large volume. Battery prices based on 40¢/lb.

*** Includes hardware for reactors, catalysts & EGR. Allowance made for inspection or replacement of catalysts.

**** Includes hardware for exhaust manifold reactor, EGR, spark retard, and lean mixtures.

***** Based on 100,000 miles, 40¢/gal., 13.3 mpg (Department of Transportation Estimate), 20% higher fuel consumption for clean conventional car, (industry estimates go as high as 30% additional fuel for lowering NOx).

FIG. 23

(212) 986-3173
(212) 986-2873

CABLE ADDRESS: WOUKA

PETRO-ELECTRIC MOTORS, LTD.

342 MADISON AVENUE
NEW YORK, NEW YORK 10017

December 4, 1975

Mr. Howard Vivian
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Re: PYM Hybrid Cost Analysis

Dear Mr. Vivian:

My letter of November 19th was sent to you from my office while I was out of town. I had to use my memory to instruct the office staff what to send to you. Therefore, only Fig. 23 of our Third Status Report to the Federal Clean Car Incentive personnel was included. There are understandably some ambiguities, although the basic concepts and conclusions still apply.

In order to complete the information that you have, I am submitting herewith the full relevant information, from our document #8169 as follows:

1. Page 37, with "Vehicle Costs" starting as item (5).

2. Page 41, with a more comprehensive analysis relating to Fig. 23, page 39, the cost comparison of the clean conventional car versus the hybrid.

On page 41, item (1) explains the mysterious footnote about having added $150 to the cost of the conventional car engine for 20% larger engine, and $50 for fuel injection, which we believe was required in a "clean conventional car" as explained.

We must emphasize over and over again that our analysis is for vehicles of equal emissions. On page 41, item (5) you will see that the Aerospace report on which you make your base estimates did not make any allowance for emission equipment that will be mandatory for the conventional car to meet the 1976 standards. We made an arbitrary figure as to how much more emission control equipment would cost on a sales price basis (which are all of the costs). These estimates are fairly accurate, as it turns out. The catalyst costs about $125, and the factored sales price is therefore approximately twice as much in the retail cost.

As I state in the letter, no substantive changes exist, and the 1.6 figure in the JPL report certainly is not warranted when applied to the PEM hybrid.

The discrepancy between the battery price of 40 cents per pound and the $275 in the hybrid is accounted for by the fact that the 40 cents would be O.E.M. price, whereas the $275 is retail price.

As an interesting point we include page 40, Fig. 24, a "Urban Vehicle" which has 60 mph top cruise speed, rather than the 100 mph of the previous vehicle. This starts being close to what would exist today with the new speed limit of 55 mph. Because of the much smaller engine we save on the engine. Because we assume the vehicle is for urban use, the emission controls on the conventional car are much more expensive. We therefore come up with the interesting fact that the hybrid could be cheaper.

Even if these figures are slightly off, the basic concept still holds.

Also enclosed is page 42, Fig. 25, the cost comparison. Please remember that we were not allowed to consider operation with the batteries partially depleted during the course of the day. This gives an enormous additional advantage to the PEM hybrid as documented in the figures sent to Dr. Stephenson on October 22nd. For ease of reference, that entire presentation is included herewith.

Thanks for your continued understanding and cooperation.

Very truly yours,

PETRO-ELECTRIC MOTORS, LTD.

Victor Wouk
President

:mc
12/8: 10665
encls.
cc: Dr. Stephenson

case (II), 30% of the forward power is recoverable then a 30% increase in SFC for the hybrid engine would mean that the hybrid vehicle would utilize approximately 40% less fuel than the conventional vehicle to drive the same mission. (point B)

An increase in stop-and-go driving increases the amount of kinetic energy available for recovery by electrical braking as well as increases the overall specific fuel consumption of the energy (i.e., more losses in accelerator pump, enrichment, and maldistribution of fuel). For most hybrid vehicles the fraction of the average engine power that is cycled through the electrical system also increases with increases in the amount of stop-and-go driving. This decreases the magnitude of some of the potential hybrid fuel savings.

4.1.1 SPECIAL FEATURES OF PEM HYBRID

In the PEM hybrid the fraction of the engine power that is sent straight through to the wheels can be readily adjusted to produce the optimum balance between engine, size, emissions, and fuel consumption. For example, by decreasing the distance the accelerator pedal must move before it engages the engine throttle (Fig. 22) the fraction of forward energy going straight through can be altered; (n.b., decreasing the distance the accelerator pedal must move before engaging the engine throttle reduces the vehicle load at which changes in engine power from the pre-set levels are called for). If 2/3 of the power goes straight through, and we utilize the vehicle in stop-and-go urban traffic (where upwards of 50% of the forward power is recoverable) then if the SFC of the hybrid is 30% better than that of a conventional engine, we would expect the fuel consumption of the hybrid to be 65% of that of a conventional engine, (part #1, Fig. 20, pt. B).

From this analysis, it is seen why it is important to size the battery and electrical system for efficient battery recharge capability, as well as discharge capability, in order to achieve the maximum fuel savings. See Addendum (1).

5. VEHICLE COSTS

Figs. 23 and 24 are our estimates of the cost of PEM hybrid vehicles as compared to clean conventional cars. The basic data for the costs and sizing of components were obtained from the Aerospace Report (10). We have applied their data to our hybrid vehicle.

The various areas in which our cost estimates differ from the Aerospace cost estimate are the following:

1. Cost of Engine : We have assumed that the use of EGR will be required in a conventional car to control NOx. In order to compensate for the power loss due to the use of EGR we have added $150.00 to the cost of the conventional car engine for a 20% larger engine. We have also added $50.000 for fuel injection, which we believe will be required in "clean conventional cars" to reduce pollutants caused by changes in the air-fuel ratio, due to rapid changes in the throttle. These added costs are not needed in the PEM hybrid engine.

2. Starting Motor and Generator : The PEM hybrid will use the dynamotor to accomplish the starting and recharging tasks. This eliminates the starter motor in the PEM hybrid.

3. Motor and Drive Train Logic : The PEM hybrid will use an overexcited shunt wound motor. The PEM motor is estimated to cost $550.00 in production, as compared to the Aerospace estimate of $350.00 for a series motor. The PEM motor controls should cost $50.00, as compared with $125.00 for the Aerospace drive train logic. This is due to the elimination of high power choppers, smoothing chokes, etc.

4. Batteries : Pricing history has shown automotive supply prices to be at the low end of the battery cost spectrum, due to large volume of production. Therefore, PEM based its prices on 40¢ per pound for batteries, a price that has been confirmed by battery manufacturers.

5. Emission Control Equipment : The Aerospace Report (10) did not make any allowance for emission equipment that would be mandatory for a conventional car to meet the 1976 Standards. Thus, Aerospace comparison was between a hybrid that met 1976 Standards and a conventional car that met 1970 Standards. We are comparing a 1976 hybrid with a 1976 conventional car. We did not do a detailed analysis of how much extra hardware, how much catalyst, etc. would be needed to clean up a conventional car......but arbitrarily multiplied the figure for a hybrid by 2.5 for the family car, and 5 for the urban car. These costs include an estimate of replacement costs of emission control systems over the life of the vehicle.

Fig. 25 represents graphically the data presented in Figs. 22 and 23. An examination of this figure shows the increased importance of the cost of fuel for an urban vehicle as compared to a vehicle driving the FTC.

4,000 POUND URBAN VEHICLE

60 MPH TOP CRUISE SPEED - 75 MPH TOP PASSING SPEED

COST COMPARISON

CLEAN CONVENTIONAL CAR VERSUS HYBRID

	Conventional ICE Car	PEM Hybrid
BODY	$ 1,260.	$ 1,300
ENGINE	835*	380
RADIATOR, EXHAUST	170	150
STARTING MOTOR	45	-
GENERATOR	55	-
MOTOR	-	550
DRIVE TRAIN LOGIC	-	50
BATTERY**	30	275
BATTERY CHARGE CONTROL	10	50
TRANSMISSION	205	205
DIFFERENTIAL, AXLE, DRIVE SHAFT	245	245
ACCESSORIES (A/C, RADIO, POWER STEERING)	545	545
HYBRID INSTRUMENTATION	-	30
EMISSION CONTROL EQUIPMENT	500***	100****
INITIAL COST	$ 3,900	$ 3,880
COST OF FUEL*****	5,700	4,500
TOTAL COST OF OWNERSHIP	$ 9,600	$ 8,380

* Add $150. for 20% larger engine and $50. for fuel injection.

** Pricing experience has shown automotive supply prices to be at low end of spectrum due to large volume. Battery prices based on 40¢/lb.

*** Includes more extensive hardware for reactors, catalysts & EGR than family car due to greater frequency of high load conditions in urban driving. Allowance made for inspection & more frequent replacement of catalysts needed in an urban vehicle.

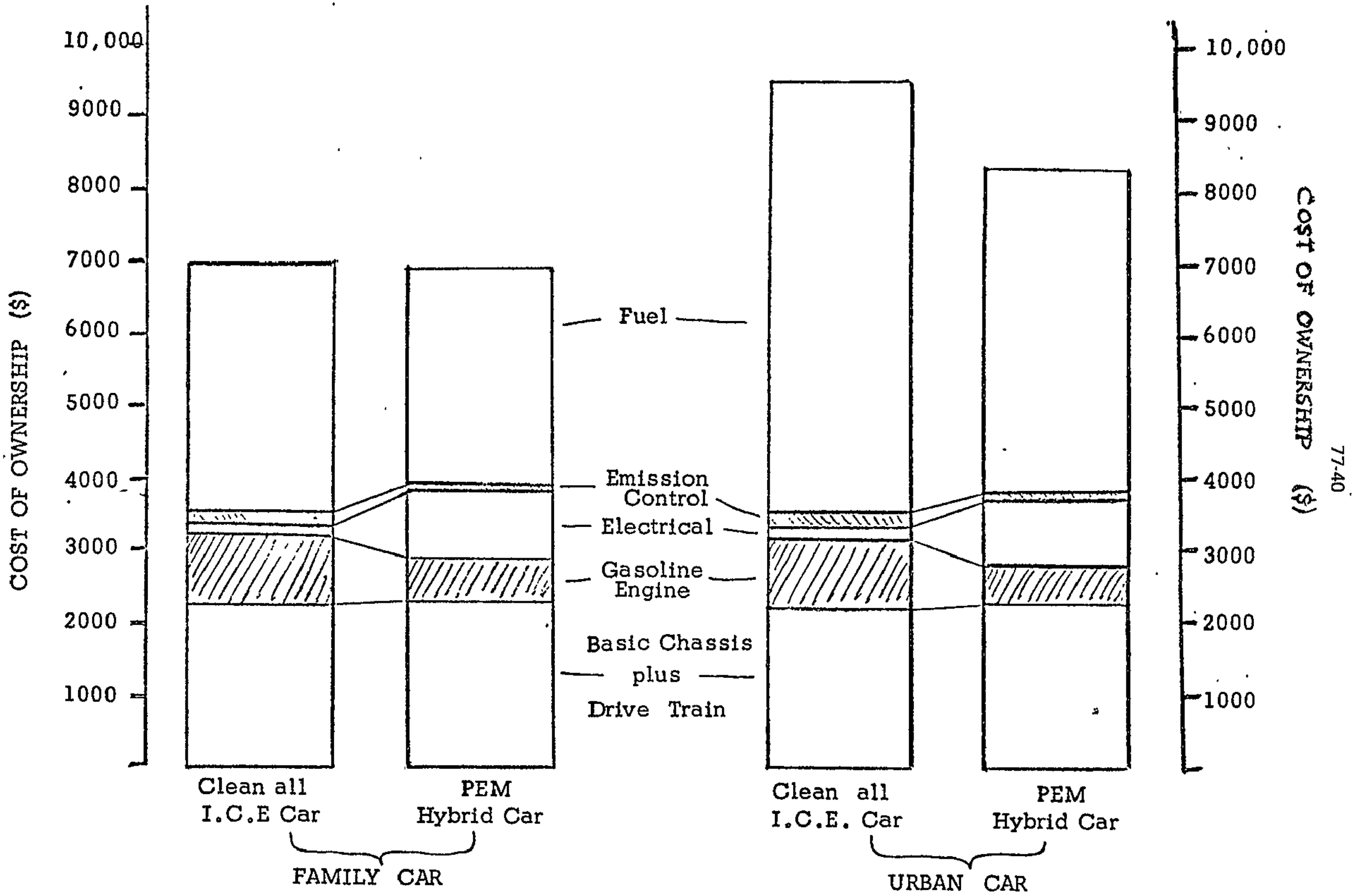
**** Includes hardware for exhaust manifold reactor, EGR, spark retard, and lean mixtures.

***** Based on 100,000 miles, 40¢/gal., 7 mpg for clean urban gasoline car and 9 mpg for urban hybrid.

FIG. 24

PEM. HYBRID VERSUS CLEAN CONVENTIONAL CAR

COST COMPARISON



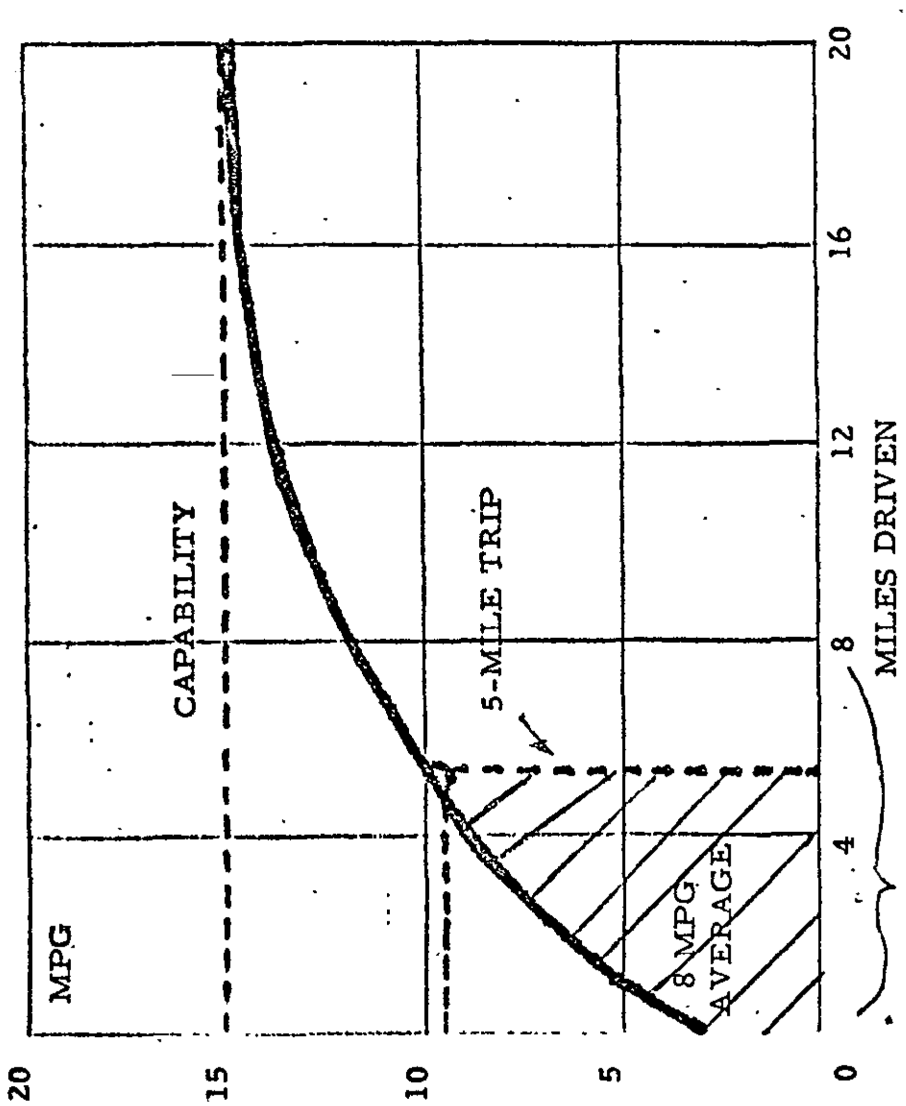
60 MPH Cruise - 75 MPH Pass Speed

FIG. 25

77-40

BY ____ DATE ____ SUBJECT Vehicle Warm-Up Cycle SHEET NO. 9 OF ____

CHKD. BY ____ DATE 12/10/75 JOB NO. 3.9.51



~~(212) 986-3173~~
(212) 986-2873

CABLE ADDRESS: WOUKA

PETRO-ELECTRIC MOTORS, LTD.

342 MADISON AVENUE

NEW YORK, NEW YORK 10017

March 4, 1976

Dr. William H. Pickering
Director
Jet Propulsion Laboratories
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Bill:

I realize you have other matters more pressing than my particular problem, but I did hope you would have a chance to call me by now, as you indicated in December you would. Rather than burdening this letter with copies of correspondence between me and Dr. Stephenson, I will emphasize two points on which I am trying to get a statement of concurrence.

1. Saving of Gasoline: in Rhoads' most recent letter to me he agrees after extensive initial denial, that the hybrid can decrease substantially the use of gasoline by partial battery depletion. I would like this statement to be made without further qualifications.

Rhoads' qualification is that he says if it's important to save gasoline in cars, then why shouldn't we try to save petroleum in heating of houses and have houses heated electrically? I don't quite get the non sequitur.

The qualification is in direct conflict with the statement in the JPL report, page 20-11, section 20.4 "Potential Effect on the Nation's Balance of Payments". Rhoads emphasizes the important effect on the nation's economy in cutting down the use of imported oil.

2. Costs: I sent cost information to H. Vivian almost 4 months ago. Over the telephone Vivian and I were able to compare major items, and it was a matter of 15 minutes for agreement that the JPL estimate is high. A cursory examination will indicate that the hybrid will not cost 1.6 times a conventional vehicle. There is no necessity for committees, computers, etc. Maybe an in-depth analysis would be necessary to narrow our claim of 1.1 - 1.2 or to push it up to 1.25.

There are other items in this vein, but I don't want to belabor the issue.

PETRO - ELECTRIC MOTORS. LTD.

March 4, 1976

Dr. W.H. Pickering

Rhoads' testimony and public statements have been damaging to hybrids, and to the efforts of ERDA to obtain Congressional support for electrics and hybrids. I believe that the hybrid requires more serious consideration before it is either dropped or is given heavier support. ERDA was anticipating funding at a level of 10 million dollars yearly for electrics and hybrids. That has recently been cut back to 1 million dollars for FY'76.

I hope for a JPL statement to the effect that limited information available at the time of the report was the basis of the pessimistic conclusions re hybrids, and that information obtained since then would warrant reconsideration of the conclusions. I am not asking for specific endoresements. I am asking for reconsideration and elimination of the "shutout bids".

I repeat my offer to come out at any time to discuss this further.

Sincerely,

PETRO-ELECTRIC MOTORS, Ltd.

Victor Wouk
President

:mc
2/3: 10814

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

December 8, 1975

Dr. Victor Wouk
Petro-Electric Motors
342 Madison Avenue
New York, N.Y. 10017

Dear Victor:

I would like to thank you for and acknowledge your various written and verbal communications.

As I indicated on November 26th, I do not consider it appropriate to make piecemeal changes in our configuration, analysis, and results without ensuring that we have understood all the ramifications (cost, emissions, fuel consumption, materials consumption, etc.) of a given "suggestion". We, therefore, wish to consider your recent inputs on the PEM hybrid in a thorough fashion. As I indicated, this will require funding and we will not be able to start until January at the earliest. At a very minimum we would need a detailed parts breakdown (see, for example, Table 6-3 of Volume II of our report) so that we could perform an independent cost estimate in a consistent manner with the pure heat engine portion of our report.

You have raised the point of using the hybrid in a mode where the batteries are depleted at the end of a mission and are recharged from external electric power. This, of course, will result in less gasoline being consumed, but accompanied by an increase in electrical energy consumption. In fact, the total energy consumption will likely be higher (we assessed the hybrid as having a higher energy efficiency than the pure electric) This would only be a desirable trade when adequate supplies of environmentally acceptable, non-petroleum power plants (coal and nuclear) are on-line. I also assert that conversion of any current user of petroleum to electricity would have the same qualitative effect. Which users, if any, it makes sense to convert to electricity, must be determined considering the costs, the supply of electricity, and the relative energy efficiencies of petroleum versus electric energy usage.

Telephone 354-4321 *Telex 675421* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Your suggestion also raises the interesting question of the control strategy of the hybrid. How does the vehicle operator indicate to the control system that it is okay for the batteries to be depleted when he is reaching the end of his mission? Does this require an additional control input from the driver? (Of course, it is not appropriate to pre-design a control strategy to work on one particular mission, e.g. the Federal Urban Driving cycle). A related observation is that the battery depletion mode will probably result in an increase in battery capacity (and weight) and thus result in somewhat more energy consumption under all modes of operation.

I hope this letter explains what may be possible in terms of further consideration of your system as well as my preliminary thoughts on the battery depletion mode.

Very truly yours,

Rhoads Stephenson

R. Rhoads Stephenson
Systems Analysis Section Manager

RRS:bl

cc: T. Barber
G. Meisenholder
H. Vivian

(212) 986-3173
(212) 986-2873

CABLE ADDRESS: WOUKA

PETRO-ELECTRIC MOTORS, LTD.

342 MADISON AVENUE

NEW YORK, NEW YORK 10017

April 21, 1976

Dr. R. Rhoads Stephenson
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Rhoads:

It was good to learn from our recent conversation that you are not planning to discuss the hybrid at your presentation at Caltech at Alumni Day. If for any reason you do discuss the hybrid, it will be extremely unfair to refer to the cost factor until we have had an opportunity to exchange ideas further.

Enclosed are my analyses of costs, reproduced from the SAE paper which is still not in print. It includes Appendix H, and reference #16 is the JPL report.

You can see from the enclosed tables XII and XIII where the major difference between your report and our analysis arises. I was told by your associate that JPL took at face value the figures from the Aerospace report, reproduced in Table XIII, that gave the 1.6 ratio. This is the devastating ratio that you have been using.

I hope you will not apply a double standard and not take at face value our figures just because they are more favorable. It won't take you very long to go over the figures and see that I am correct. It's not a matter of calling conferences, having meetings, etc. The data is there for anyone who approaches the question in a non-prejudicial manner. You can see the basic cost savings in the simpler hybrid that we have been using so successfully.

I'd like your reaction to this, hopefully without having to wait too long.

Very truly yours,

PETRO-ELECTRIC MOTORS, Ltd.

Vic Wouk

Victor Wouk
President

:mc
10853
encl.

LOW EMISSION VEHICLES: Battery Powered; Heat Engine / Battery Hybrid Systems

APPENDIX H

PROBABLE PRODUCTION COSTS are vital to the decision-making process to determine whether this compound hybrid warrants further serious investigation. If the savings of gasoline cannot offset the initial higher cost of the hybrid, then the compound hybrid, despite the fact that is can be a family sized car, may not be able to compete with smaller sized conventional vehicles of equal fuel consumption.

Note: Gasoline rationing may make the hybrid attractive, independent of any price premium.

Table XII is a comparison of basic costs of a conventional vehicle vs. a compound hybrid, in a 4,000 lb. family car. This was prepared in 1972 (25). Costs reflect retail prices of vehicles; $3,980 for the hybrid vs. $3,650 represents an 11% premium.

It is of major consequence to realize that in 1972 those costs were projected for vehicles meeting the emission requirements of Tables I and III. The hybrid described herein meets the present emission requirements. Doubts are expressed by competent automotive engineers(26) that the fuel economy goals of 27.5 mpg, referred to in Appendix B and the "Energy Policy and Conservation Act" (27), and the emissions goals of Tables I and III, can be met simutaneously in anything but subcompact cars.

Some of the reasoning behind the calculations of Table XII include the following:

(1) In 1972 it was assumed that to meet 0.4 gpm of NOx, EGR would be used. To compensate for the power loss, the projected engine was 20% larger than that in a 1972 model car.

(2) $50 was added for fuel injection, which was believed necessary to minimize the HC and CO levels normally resulting from F/A ratio changes due to rapid throttle changes.

(3) Batteries in this hybrid are conventional automotive types. Such batteries are the lowest in cost of all rechargeable batteries, and are made of materials for which no shortages are envisioned. Further, the lead in lead-acid batteries can be recycled with very high percentage recovery.

The 1972 figures of Table XII included replacement of the batteries once during a vehicle lifetime of 100,000 miles. This is consistent with Fig. 28, and the discussion thereof in Appendix F.

(4) The emission control equipment for the conventional car was calculated by arbitrarily multiplying the costs of the emission controls on the

Victor Wouk

hybrid by 2.5. In 1972 it was believed that a thermal reactor and an electronic feedback system for manifold vacuum control (Fig. 24, Appendix D) would prove satisfactory for emission controls of the hybrid. This has proved to be the case.

The catalyst used in 1976 model cars costs about $125, according to published newspaper reports. The required emission levels of '76 model cars are about three times higher than those achieved with this hybrid. It is reasonable to project that, for equal performance, the cost of emission controls for conventional vehicles would double from the $125 figure to $250, which is the amount shown in Table XII.

The figure of a 60% cost premium for a hybrid (16), is based on analysis of the complicated parallel hybrid of Fig. 16, with its double set of rotating electrical machinery, and a complicated electronic control system (6). The costs estimates from (16) are included here for reference, Table XIII. The very much higher costs of the motor generator pair, and the electronic controls, are apparent.

The above discussion is not meant to be definitive as to absolute levels of costs, but indicative of cost trends. The compound hybrid shows enough potential of saving of gasoline, possibly reducing consumption 50% (effective increase of gasoline "fuel economy" by 100%) to warrant further development. The cost saving in gasoline may well offset the initial price premium of the hybrid for the "first user."

At present, the barriers to further hybrid development are political. If the Clean Car Amendments for 1970 were enforced today, the General Services Administration of the Federal Government would be purchasing at least 5,000 of these hybrid cars yearly. This is mandated by Section 212 of the Act. Such a market would be the basis for penetrating state and municipal governmental agencies, and would bring the vehicle cost into a range acceptable by environmentally conscious drivers.

Further, as detailed by Stephenson (16), reducing consumption of gasoline frees the U.S.A. from dependence upon foreign sources that are politically unstable and potentially disruptable with disastrous consequences, as experienced briefly in the winter of 1973-74.

Finally, (16) points out the enormous importance of keeping the $40 billion of foreign exchange annually in the U.S.A. The socio-economic impact on financial stability of the U.S.A., and increased employment in the alternate energy industries, are all sound politcal reasons for investigating any promising technology that will reduce the consumption of imported fluid fuels in any application. The hybrid automobile is one such technology, in the field of personal transportation.

V. WOUK
Galley 43

Table XII - Cost Comparison, 4,000 Pound Family Car

	Conventional Ice Car (1972)	Hybrid
Body	$1,260	$1,300
Engine	835	480
Radiator, Exhaust	170	150
Starting Motor	45	-
Generator	55	-
Motor	-	550
Drive Train Logic	-	50
Battery*	30	275
Battery Charge Control	10	50
Transmission	205	205
Differential, Axle, Drive Shaft	245	245
Accessories (A/C, Radio, etc.)	545	545
Hybrid Instrumentation	-	30
Emission Controls	250**	100***
Initial Cost	$3,650	$3,980

* Pricing experience has shown automotive supply prices to be at low end of spectrum due to large volume. Battery prices based on 40¢/lb.

** Includes hardware for reactors, catalysts, and EGR. Allowance made for inspection or replacement of catalysts.

***Includes hardware for exhaust manifold reactor, EGR, spark retard, and lean mixtures.

Victor Wouk

 SAE 3.4.61

Table XIII - Cost Comparison of Conventional vs. Hybrid Family Car*

	Conventional ICE Car (1972)	Hybrid*	Compound Hybrid**
Body	$1,260	$1,300	$1,300
Engine	635	480	480
Radiator, Exhaust, etc.	170	150	150
Starting Motor	45	30	-
Generator	55	200	-
Motor	-	350	550***
Generator Control	-	200	-
Motor Control	-	275	-
Drive Train Logic	-	125	50
Battery	30	560	275
Battery Charge Control	10	125	50
Ac Rectificer	-	30	-
Electrical Cooling	-	50	-
Gearing (HE to Gen)	-	60	-
Transmission	205	205	205
Differential, Axle, Drive Shaft	245	350	245
Accessories (A/C, Radio, etc.)	545	545	545
Hybrid Instrumentation	-	30	30
Emission Controls	50	125	100
Initial Cost	$3,250	$5,190	$3,980

Cost Ratios****: Conventional to Hybrid 1.6; Conventional to Compound Hybrid 1.22

* As analyzed in Reference (16).
** From Table XII
*** Dynamotor replaces separate motor and generator of (*)
****Table XII assumes a more expensive engine and emission controls for conventional car, reducing 1.22 to 1.1

Critique by

Scientific Energy Systems Corporation
570 Pleasant Street
Watertown, MA 02172

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-215-9

June 29, 1977

Mr. Roger L. Demler, Program Manager
Scientific Energy Systems Corporation
570 Pleasant Street
Watertown, Massachusetts 02172

Dear Mr. Demler:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

This is in response to your letter and to that of Mr. Pompei which was addressed to the U.S. Department of Transportation, and is in accordance with our restructured heat engine program summarized in the enclosure. The critique response plan is part of the current program. We appreciate having your comments and those of Mr. Pompei, along with the technical analyses attached. These data will be of value in the Rankine phase of our current work which will address the substantive issues raised by all respondees to the Rankine portion of the subject report.

The subject report is the result of a systems level study predicated on the analytical concept of an "Otto equivalent engine" (OEE) as a means for comparing a rather broad spectrum of heat engines. Consistency in adhering to the OEE concept was an essential feature of the analysis, but we recognize that some powerplants, particularly hybrids and electrics, should be evaluated on a different basis than this. But under the ground rules of the study the only Rankine system approaching Otto equivalency is the Carter system described in SAE paper 750071, Feb. 24-28, 1975. The attractive size and weight of the Carter engine are the result of unconventionally high boiler pressures (varying from 300 to 2500 psig), cycle temperatures of about 1000°F, and an expander speed of some 5000 rpm. If such values of pressure, temperature, and speed should turn out to be feasible in a production engine, then of course, our assessment of Rankine engines would change rather dramatically. Weight and size of the SES engine still seem to us as major deterrents to its attaining the status of a mature automotive power system, at least in the near term.

We recognize the versatility of steam systems in respect to their acceptance of, or adaption to, a wide variety of fuels, and likewise their capability in coping with stringent emissions standards - even those not feasible for the Otto engine. We also recognize the superiority of steam systems over gas turbines in respect to fuel economy at part-load. These virtues may well compensate for the higher weight, but under different ground rules than employed in the subject study.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Mr. Roger L. Demler -2- June 29, 1977

We look forward to further discussions with you and others in the field during the course of our upcoming Rankine revisit as mentioned above.

Sincerely yours,

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:nrw

Enclosure

cc: Mr. Francisco Pompei
Program Development Manager

SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 Pleasant Street, Watertown, Mass. 02172   (617) 924-1420

September 10, 1975

Dr. Richard L. Strombotne
Chief, Energy and Environment Division
Office of the Secretary
U.S. Department of Transportation
400 Seventh Street, S.W.
Washington, D.C. 20590

Dear Dr. Strombotne:

Thank-you for the opportunity for our recent discussion on the subject of Advanced Steam Engines. We appreciate the position of DOT in the matter of engine R&D activities, but would like to keep you informed of developments in our field. The questions that were raised during our discussions, primarily concerning more detailed examination of hardware capabilities and composite FDC fuel economy estimates, are helpful in preparing our program presentation.

Enclosed is a set of engine performance maps for the candidate alternative automotive engines which serve as the basis for the comparisons shown in the briefing document which we had discussed (also enclosed). Where indicated the engines have been scaled and/or cylinders added to achieve the same power capability at 50 mph road speed.

As you are well aware, Jet Propulsion Laboratory of Caltech has just published a study entitled "Should We Have a New Engine? An Automotive power Systems Evaluation, 1975". We are taking issue with some of the details and conclusions of the study and have prepared a brief initial review. Due to the rather controversial nature of the study, we expect that quite a number of parties will be commenting on the conclusions. We would be most interested in your comments on the report and also on our review.

Very truly yours,

Frank Pompei

Francesco Pompei
Program Development Manager

FP/lh
Enclosure

SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 Pleasant Street, Watertown, Mass 02172 (617) 924-1420

September 9, 1975

INITIAL SES REVIEW OF THE JPL REPORT
SHOULD WE HAVE A NEW ENGINE? AN AUTOMOTIVE
POWER SYSTEMS EVALUATION, 1975

SES has conducted a preliminary review of the JPL report and even from a first review a number of critical comments are in order. Some of these comments are of a general nature while some are specifically directed at our field of expertise: vehicle performance modelling and optimization, and steam engine research and development.

The report had the potential of providing a major source of reference material on alternative engines and optional approaches. The most significant criticism is that the report does not carry all of the alternative versions of each engine through their potential fuel economy, emissions, weight and cost projections. In most cases the text cuts off the options with a cursory judgement of the results without providing the supporting data. In our particular field of steam engine development, the judgements and resultant data are substantially in error. In short, the errors in fact and judgement detract from the report's credibility.

The following comments address some of the major faults. SES is conducting a more detailed critique particularly of the steam engine section.

1) A fundamental oversight in this report is that the steam engine with reheat was not given consideration. Had the material supplied by SES on the reheat steam engine been examined, the report's conclusions would have been substantially different.

The steam engine would have shown the highest fuel economy of all engines when compared at the same technology level.

2) The high fuel economy projected for future gas turbine engines is dependant upon significant advances in variable geometry component efficiencies and materials technology. The gas turbine has been favored by many years of intensive research and development for both commercial and military applications. The major advances projected for future automotive gas turbines appear to be highly optimistic in this light.

The Stirling engine projected fuel economy is also dependent upon advanced component technology but considering the more limited R&D history this potential may be more realistic.

3) The selection of probable technology advances was arbitrary. Two examples will illustrate the point. The advanced Otto cycle gained appreciably from the assumption of a grossly improved lightweight rotary or Wankel type engine while the Wankel type expander was not considered for the advanced steam engine. A major advance in gas turbine combustors was assumed while no significant improvement in Diesel combustion was envisioned.

4) Conducting such a study is a most difficult task with such a wide diversity of technological maturity between engine types. In the case of the steam engine it is far to early to freeze the design as suggested by the report. A period of applied research is required to explore the performance and durability of alternative high temperature expander types, continued research in boiler response and compactness, and development of control strategies for optimum vehicle performance and economy.

5) The JPL study claims that Diesel cars have only about 10% better fuel economy than the reference Otto engine car. This is too low. The ADL/DOT auto fuel economy study report which we participated in concluded that the Diesel car with equal performance would enjoy a

30% improvement in economy over the urban drive cycle and about 15% improvement over highway cycle for an average improvement over the composite cycle of about 23% greater MPG. Our figures were also based on gasoline as the fuel so they did not include the additional 10% advantage when assuming the more dense Diesel fuel. Ricardos are the experts in this field and the ADL/DOT report results were in good agreement with Ricardos claims from their many reports on this subject. The ADL/DOT report even with a 23% improvement has been widely criticized for underestimating the fuel economy advantage of the Diesel.

6) Some specific comments on the reheat steam engine. SES provided data on a mature steam engine that employed reheat to significantly improve fuel economy. This conservative projection assumed no improvement in steam engine component efficiencies over that already demonstrated, and required superalloys only in expander valves and springs. The proposed variable cutoff expander (rejected by JPL as inefficient) permits matching the engine to produce its best efficiency at one quarter power rather than at half power as is the case with the fixed cutoff expander selected by JPL. The variable cutoff expander also eliminates the need for very high steam pressures, eliminates the need for a torque converter and the associated losses, and also eliminates the need for a variable pressure boiler and its attendant response problems.

The reheat cycle also makes a substantial impact on components because of the increased cycle efficiency. As the cycle efficiency increases, the boiler, condenser and feedpump sizes are reduced dramatically because of the reduced heat rejection and higher specific output. The expander for the compound reheat expansion process can be quite compact at one horsepower per cubic inch of displacement. Among the mature engines only the gas turbine would have a significantly lower weight projection.

7) The enclosed "Summary Briefing" presents the reheat steam engine approach and its relative performance. The supporting engine maps used in this study are all based on published data for the alternatives and present net performance to the transmission after deduction of normal vehicle accessories. Relative fuel economy was calculated assuming constant vehicle weights and torque converter drive trains with the exception of the gas turbine and steam engines. For the latter cases the torque converter is not required for the automatic transmission because of the low speed torque characteristics. The time phased fuel economy projection assumed a modest growth in component performance for all engines except that it conservatively assumed no improvement in component performance for future steam engines.

SUMMARY BRIEFING

AUTOMOTIVE STEAM POWERPLANTS

THE POTENTIAL IS THERE

PREPARED FOR

ERDA - DIVISION OF TRANSPORTATION
OFFICE OF HIGHWAY VEHICLE SYSTEMS

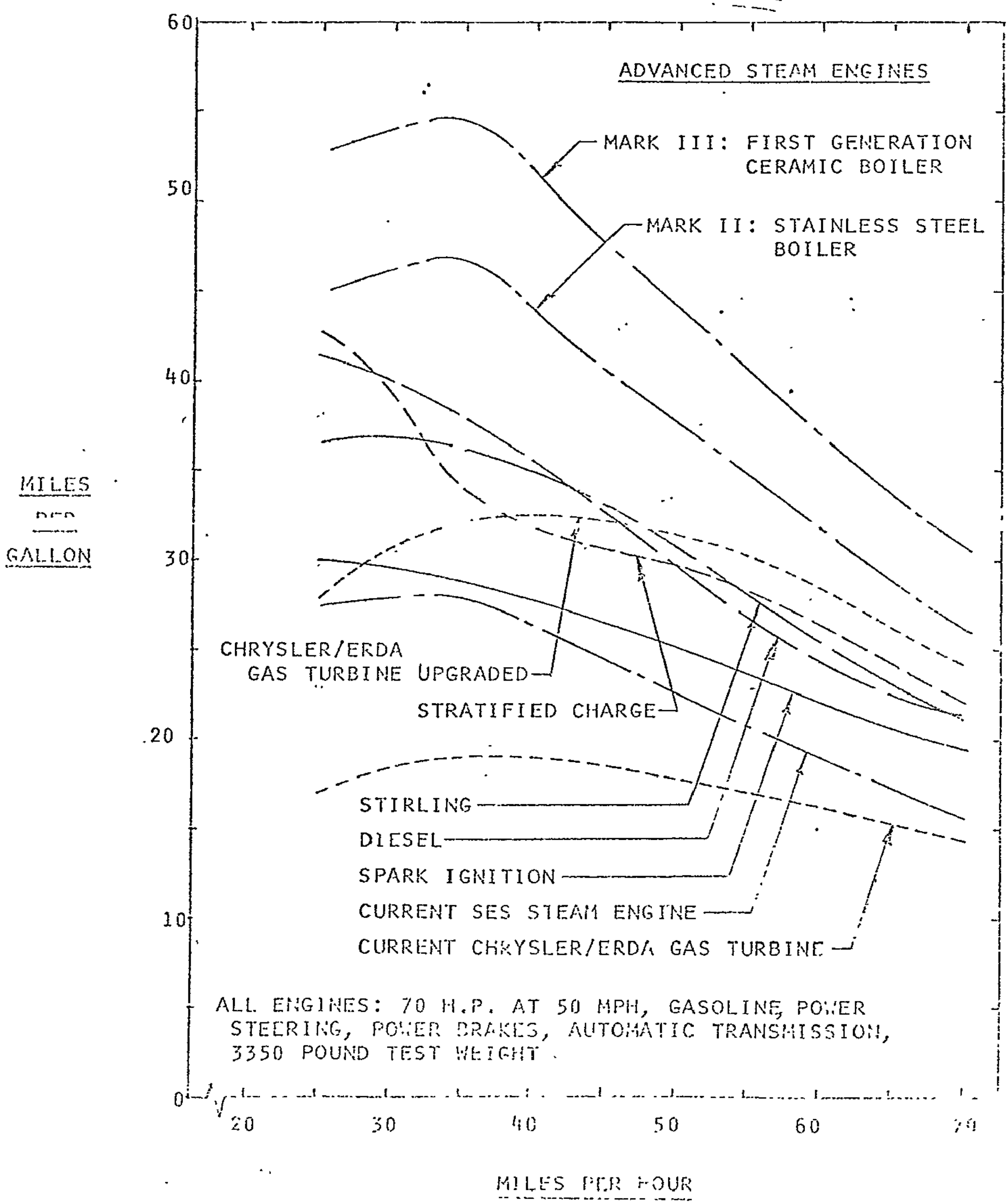
BY

SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 PLEASANT STREET
WATERTOWN, MASSACHUSETTS 02172

AUGUST 1975

CRUISE FUEL ECONOMY

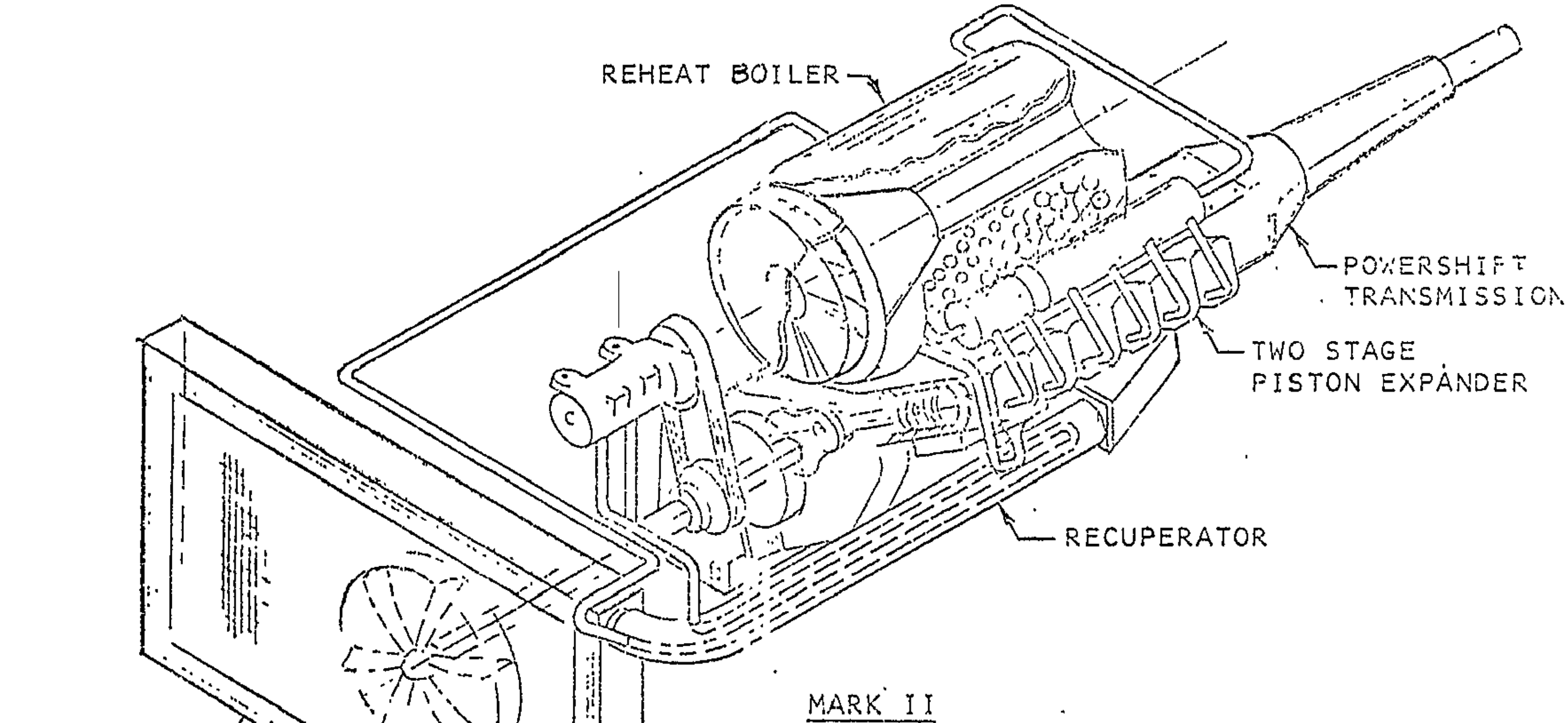
ALTERNATIVE ENGINES



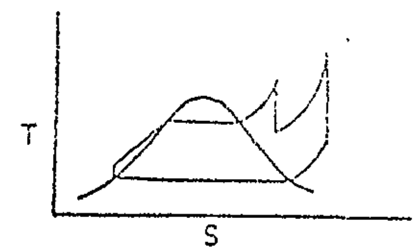
WHAT ARE THE FEATURES OF THE ADVANCED STEAM ENGINE

- BEST FUEL ECONOMY OF ALL CANDIDATE ENGINES
- LOWEST EMISSIONS OF ALL CANDIDATE ENGINES
- BEST DRIVABILITY (TORQUE/SPEED CHARACTERISTICS) OF ALL CANDIDATE ENGINES
- SIMPLEST AND MOST EFFICIENT POWERTRAIN OF ALL CANDIDATE ENGINES
- MULTI-FUEL OPERATION - BEST USE OF A BARREL OF CRUDE
- LOW NOISE
- NO EXOTIC MATERIALS

WHAT IS THE ADVANCED STEAM ENGINE?



MARK II
DESIGN CONCEPT



WHAT ARE THE COMPONENTS AND HOW AMBITIOUS ARE THEY?

(MARK II ENGINE)

VAPOR GENERATOR

- BASED ON SES MODEL 8 - STATE-OF-THE-ART SYSTEM
- ADDITION OF ONE REHEAT PASS
- NO EXOTIC MATERIALS
- NO UNUSUAL PROBLEM AREAS

CONDENSER

- CONVENTIONAL FIXED CORE DESIGN
- NO UNUSUAL PROBLEM AREAS

RECUPERATOR

- CONVENTIONAL FIXED CORE DESIGN
- NO UNUSUAL PROBLEM AREAS

EXPANDER

- RECIPROCATING HIGH & LOW STAGES
- CONVENTIONAL 6 CYL IN-LINE DESIGN
- LUBRICATION DEVELOPMENT REQUIRED
- MODEST EFFICIENCY TARGET (70%)
- NO EXOTIC MATERIALS

FEEDPUMP

- SES DESIGN - DEMONSTRATED 1600 PSI
- NO UNUSUAL PROBLEM AREAS

CONTROLS

- SIMPLER INTEGRATED 2ND GENERATION
- NO UNUSUAL PROBLEM AREAS

WHAT ARE SOME OF THE SPECIFICATIONS

(MARK II ENGINE)

DESIGN POINT

- 100 GROSS HORSEPOWER OUTPUT
- 600 LB/HR STEAM FLOW
- 500 LB TOTAL WEIGHT
  (W/O TRANSMISSION OR VEHICLE ACCESSORIES)

EXPANDER

- 6 CYLINDER IN-LINE, 97 IN^3 TOTAL DISPLACEMENT
- 4300 RPM TOP SPEED
- 285 LB ESTIMATED WEIGHT

VAPOR GENERATOR

- 1250°F 1ST STAGE TEMPERATURE
- 1500°F 2ND STAGE TEMPERATURE
- 38 LB ESTIMATED WEIGHT

FEEDPUMP

- 1650 PSI DELIVERY PRESSURE
- 12 LB ESTIMATED WEIGHT

CONDENSER

- 35 PSIA MAXIMUM OPERATING PRESSURE
- 45 LB ESTIMATED WEIGHT (INCLUDING FAN)

RECUPERATOR

- 700°F MAXIMUM TEMPERATURE
- 10 LB ESTIMATED WEIGHT

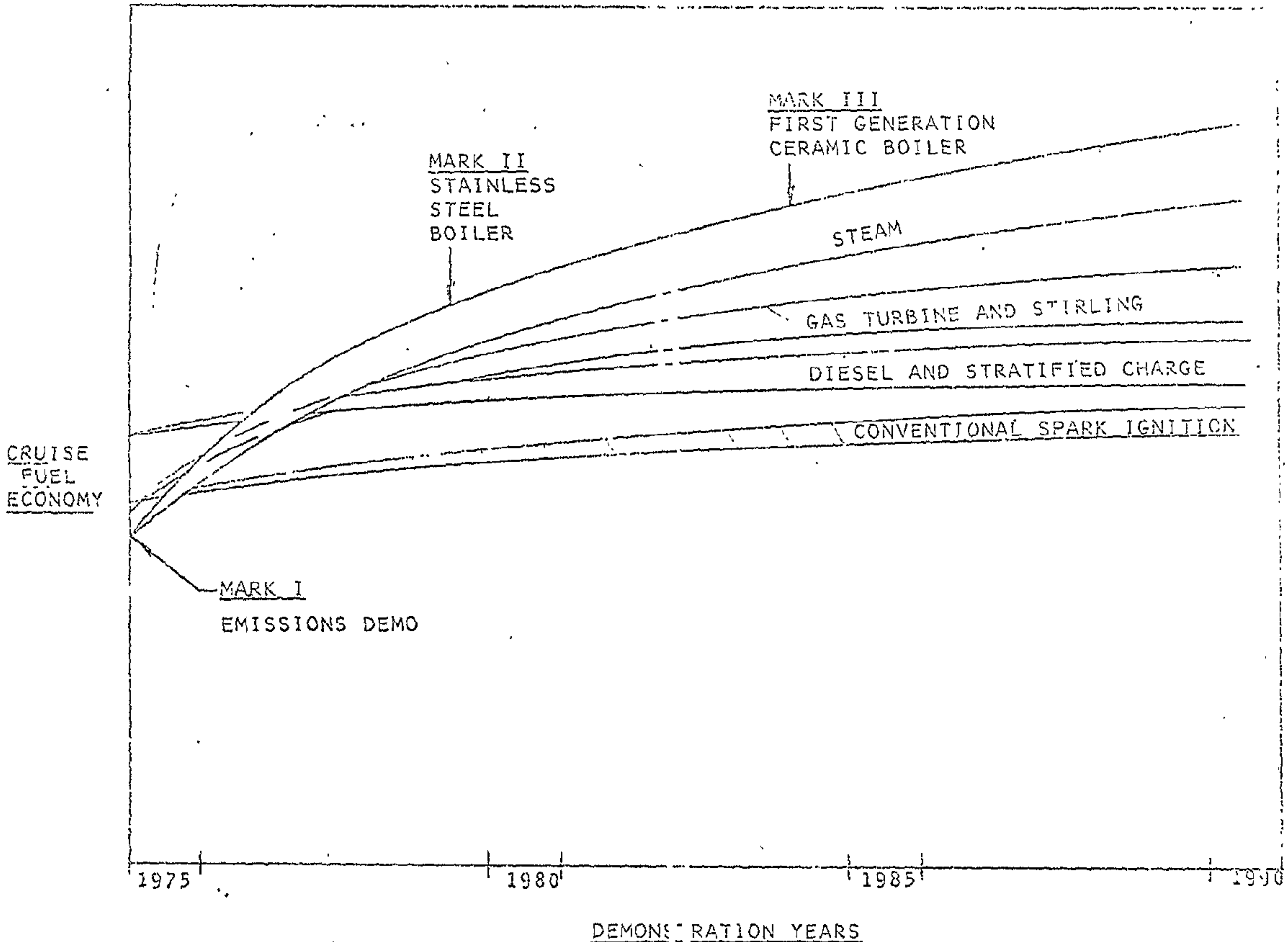
FUEL ECONOMY FUNDAMENTAL BOUNDARIES

- THE SPARK IGNITION AND DIESEL ENGINES ALREADY RUN AT THEIR OPTIMUM CYCLES. ONLY DETAIL REFINEMENTS CAN BE EXPECTED.

- THE STIRLING AND GAS TURBINE ENGINES ARE RUNNING AT THE LIMIT OF CURRENT MATERIALS TECHNOLOGY. MATERIALS AND COMPONENT DEVELOPMENT IS RELATIVELY MATURE. A BREAKTHROUGH IN CERAMIC MATERIALS IS REQUIRED TO BEAT THE DIESEL.

- A MARK II STEAM ENGINE USING A LOW COST STAINLESS STEEL BOILER AND TODAY'S COMPONENT EFFICIENCIES HAS THE SAME ECONOMY POTENTIAL AS THE ADVANCED CERAMIC GAS TURBINE.

- A MARK III STEAM ENGINE WITH AN ADVANCED CERAMIC BOILER HAS AN ECONOMY POTENTIAL SUPERIOR TO ALL ALTERNATIVE ENGINES AT THE SAME TECHNOLOGY LEVEL.


MARK III
FIRST GENERATION
CERAMIC BOILER
MARK II
STAINLESS
STEEL
BOILER
STEAM
GAS TURBINE AND STIRLING
DIESEL AND STRATIFIED CHARGE
CONVENTIONAL SPARK IGNITION
CRUISE
FUEL
ECONOMY
MARK I
EMISSIONS DEMO
1975
1980
1985
DEMONSTRATION YEARS

9-16

77-40

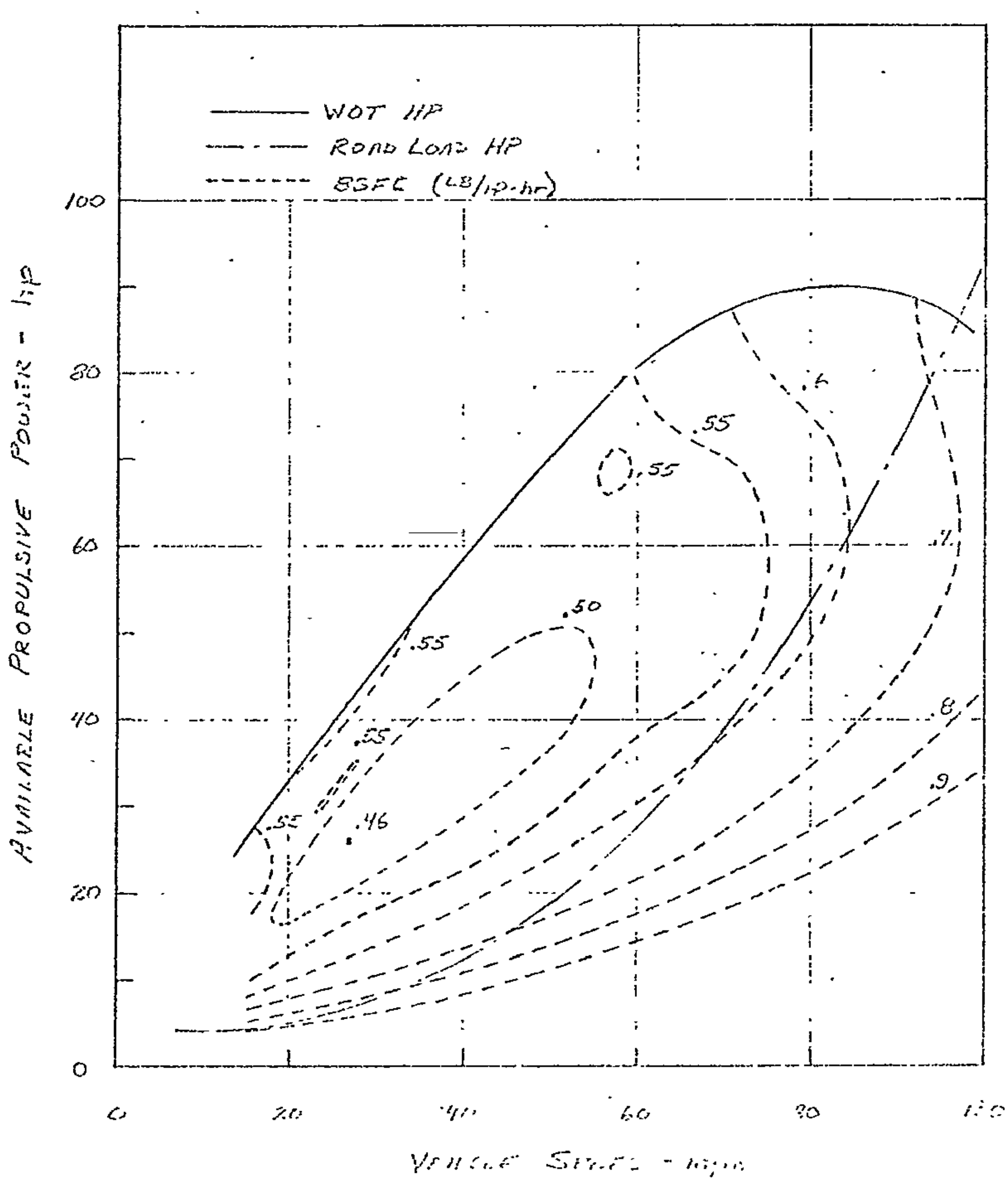
WHY SHOULD THE GOVERNMENT SUPPORT STEAM CAR DEVELOPMENT?

- THE STEAM ENGINE HAS THE BEST POTENTIAL OF ALL THE CANDIDATES
- BY FAR THE MOST INFANT TECHNOLOGY
- NO RATIONAL JUDGEMENT CAN BE MADE AT THE CURRENT TECHNOLOGY LEVEL
- ALL THE OTHER CANDIDATES HAVE HAD LONG-TERM GOVERNMENT RESEARCH SUPPORT FOR MILITARY AND PUBLIC APPLICATIONS
- BIG RISK FOR PRIVATE CORPORATIONS WITH NO APPARENT GOVERNMENT ENCOURAGEMENT
- ONLY THE GOVERNMENT IS IN A POSITION TO ASSUME THE INITIAL RISK AND PROVIDE THE INCENTIVE

INTERNAL COMBUSTION (S.I.) ENGINE

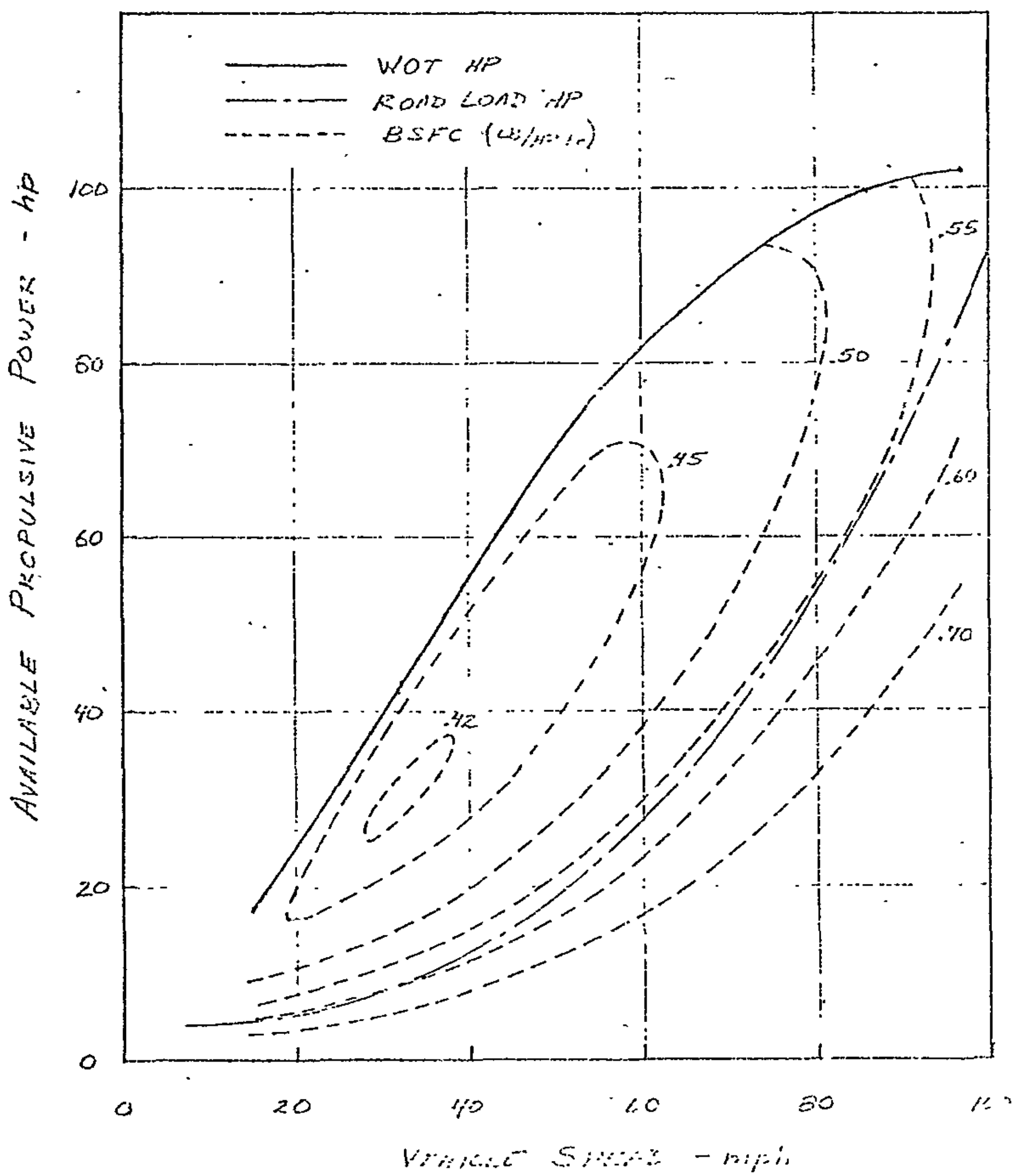
(6 CYL. , 250 CID)

ORIGINAL PAGE IS
OF POOR QUALITY



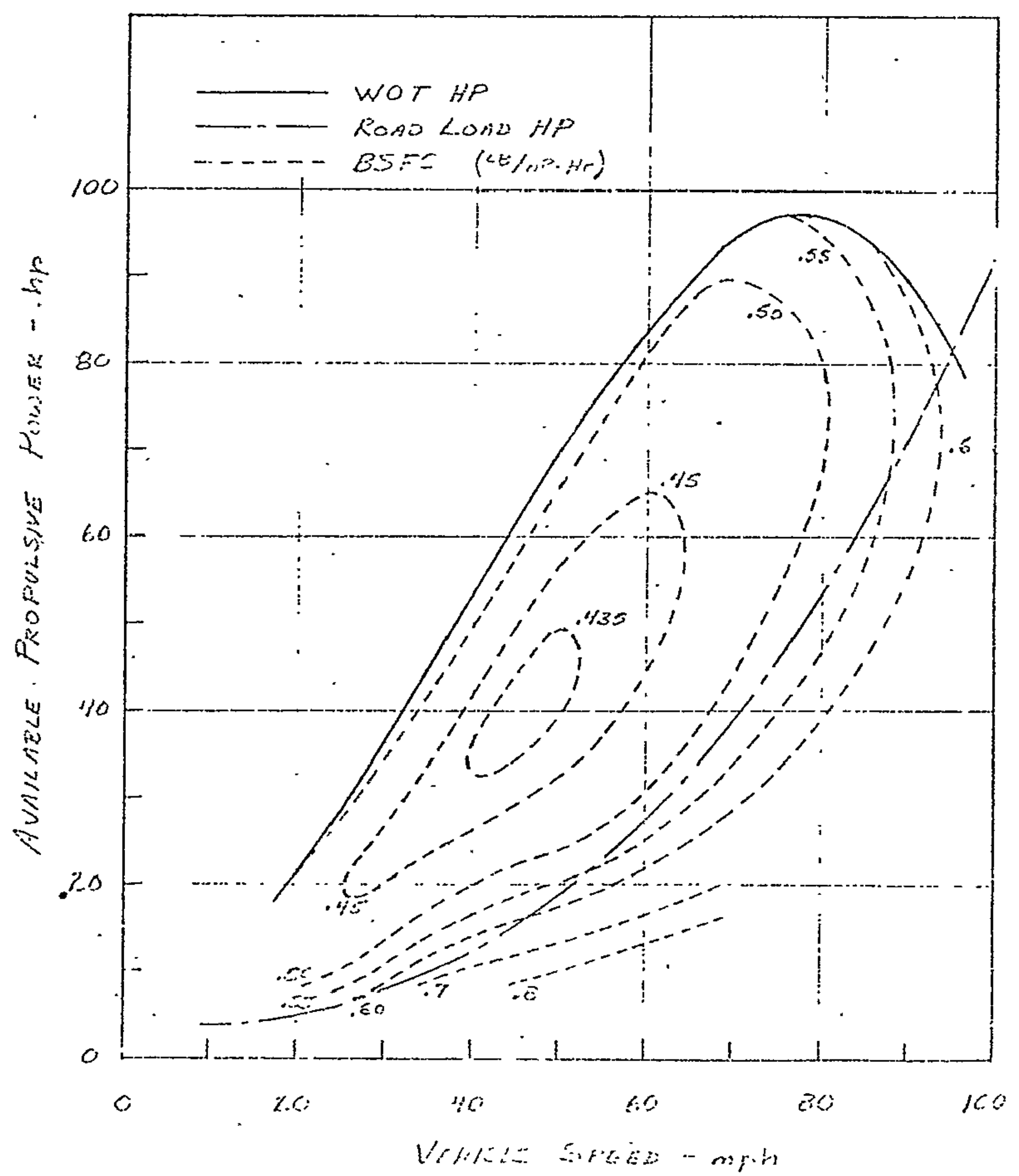
DIESEL CYCLE ENGINE

(DAIMLER-BENZ 4 CYL. - SCALED TO 6 CYL., 251 CID)



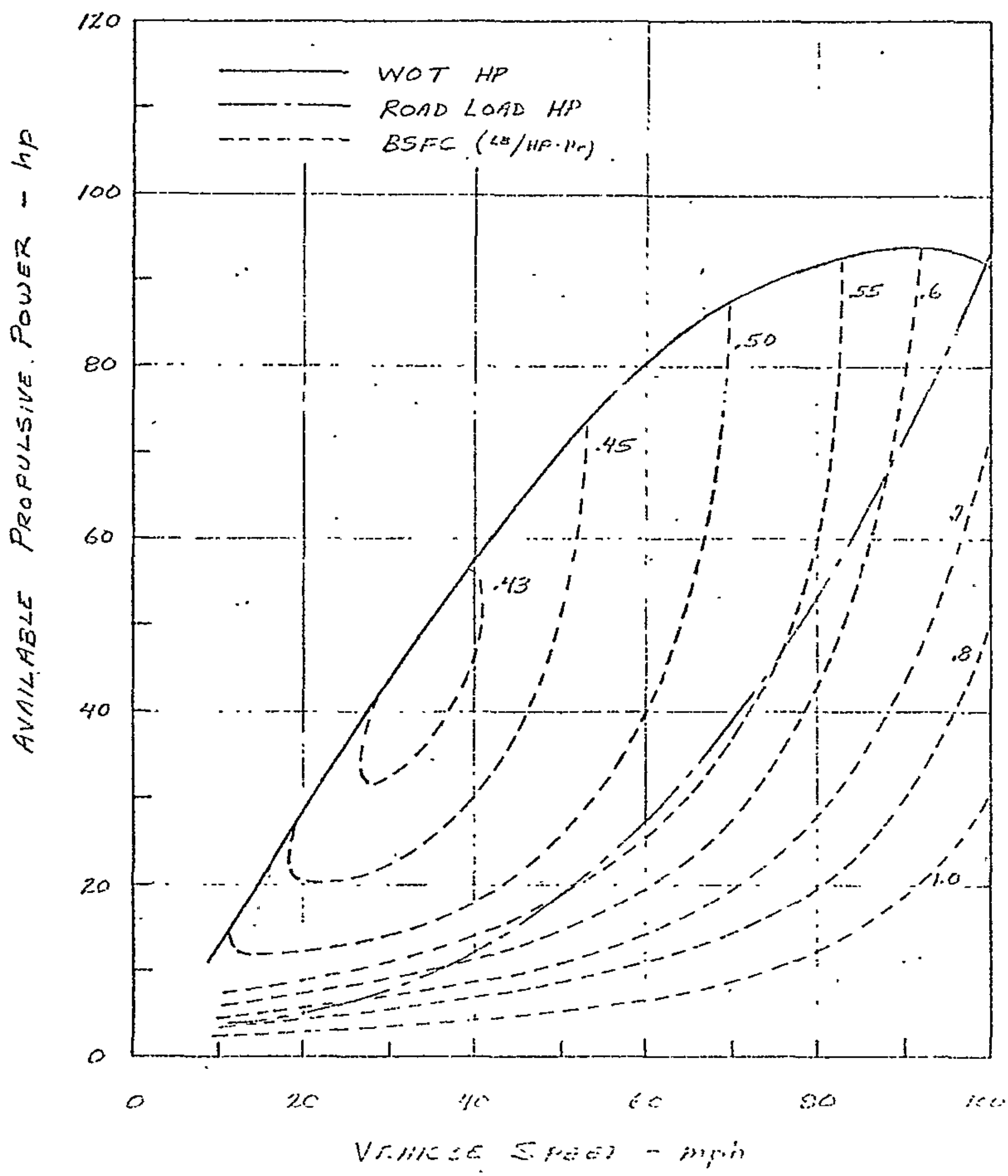
STRATIFIED CHARGE ENGINE

(TEXACO 4 CYL TCCS – SCALED TO 6 CYL., 257 CID)



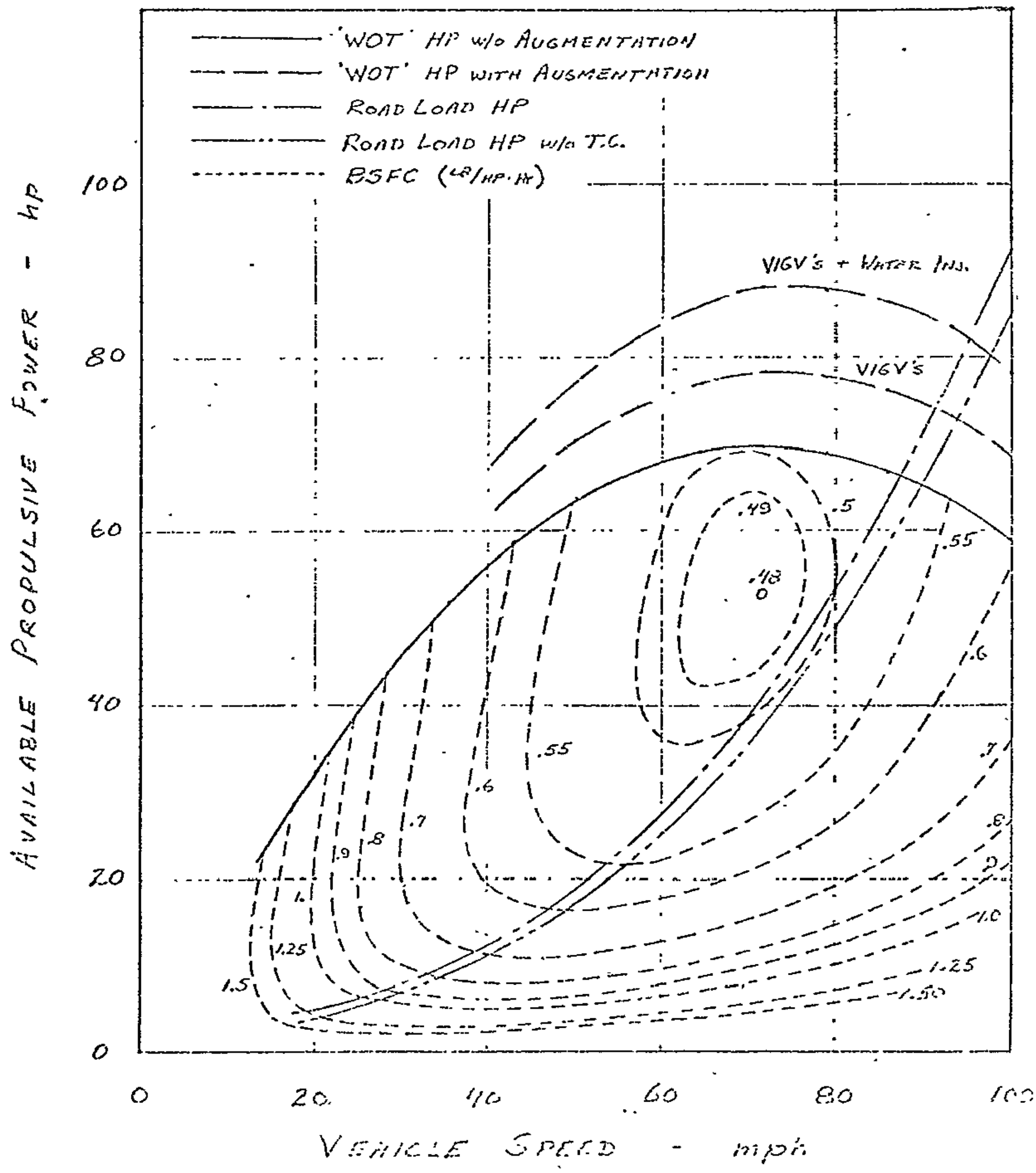
STIRLING CYCLE ENGINE

(N.V. PHILLIPS #4-215, CID SCALED BY 0.428)



GAS TURBINE ENGINE

(UPGRADED CHRYSLER / ERDA - SCALED DOWN)

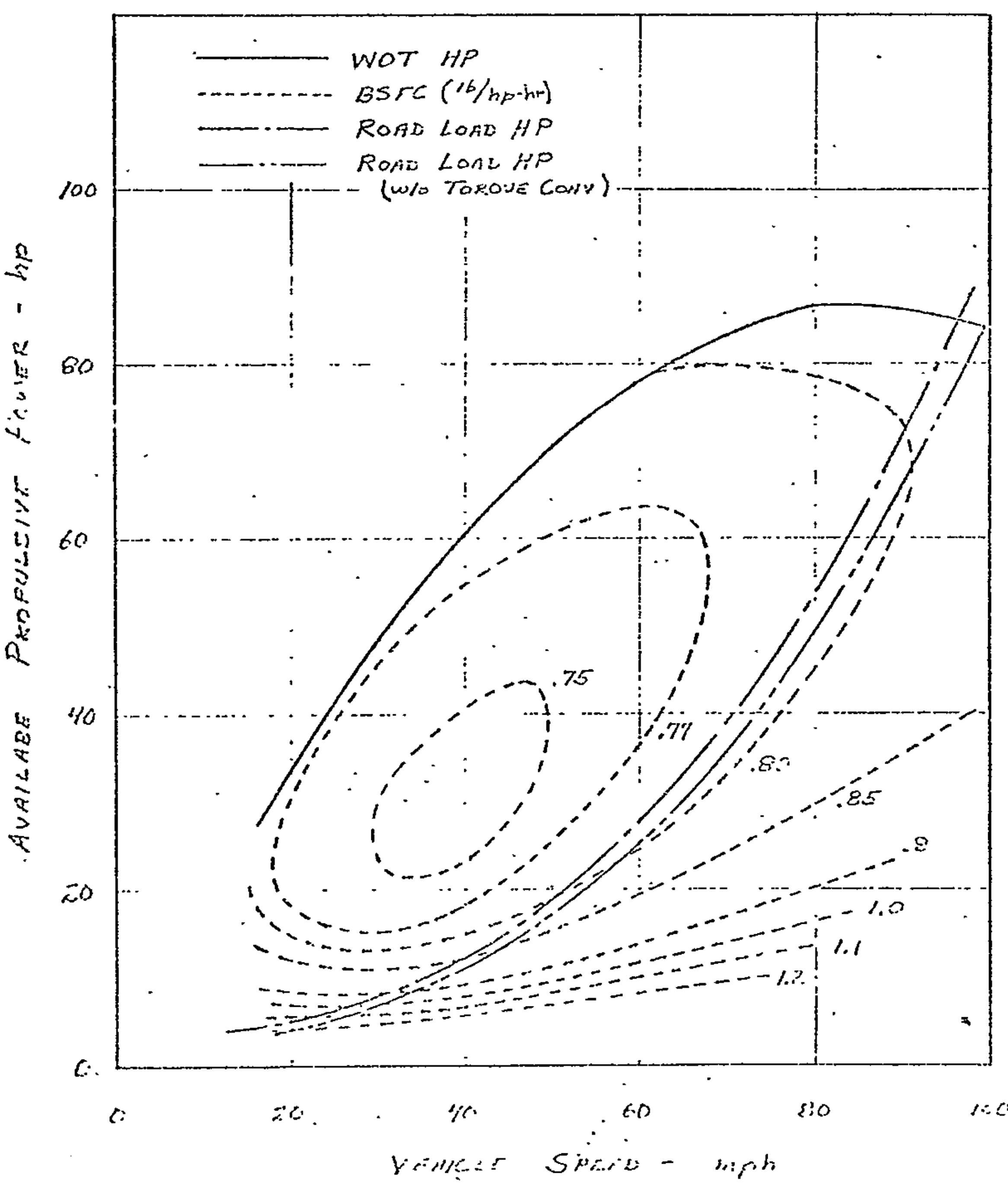


MARK I RANKINE CYCLE

CURRENT S.E.S. TECHNOLOGY - SCALED DOWN

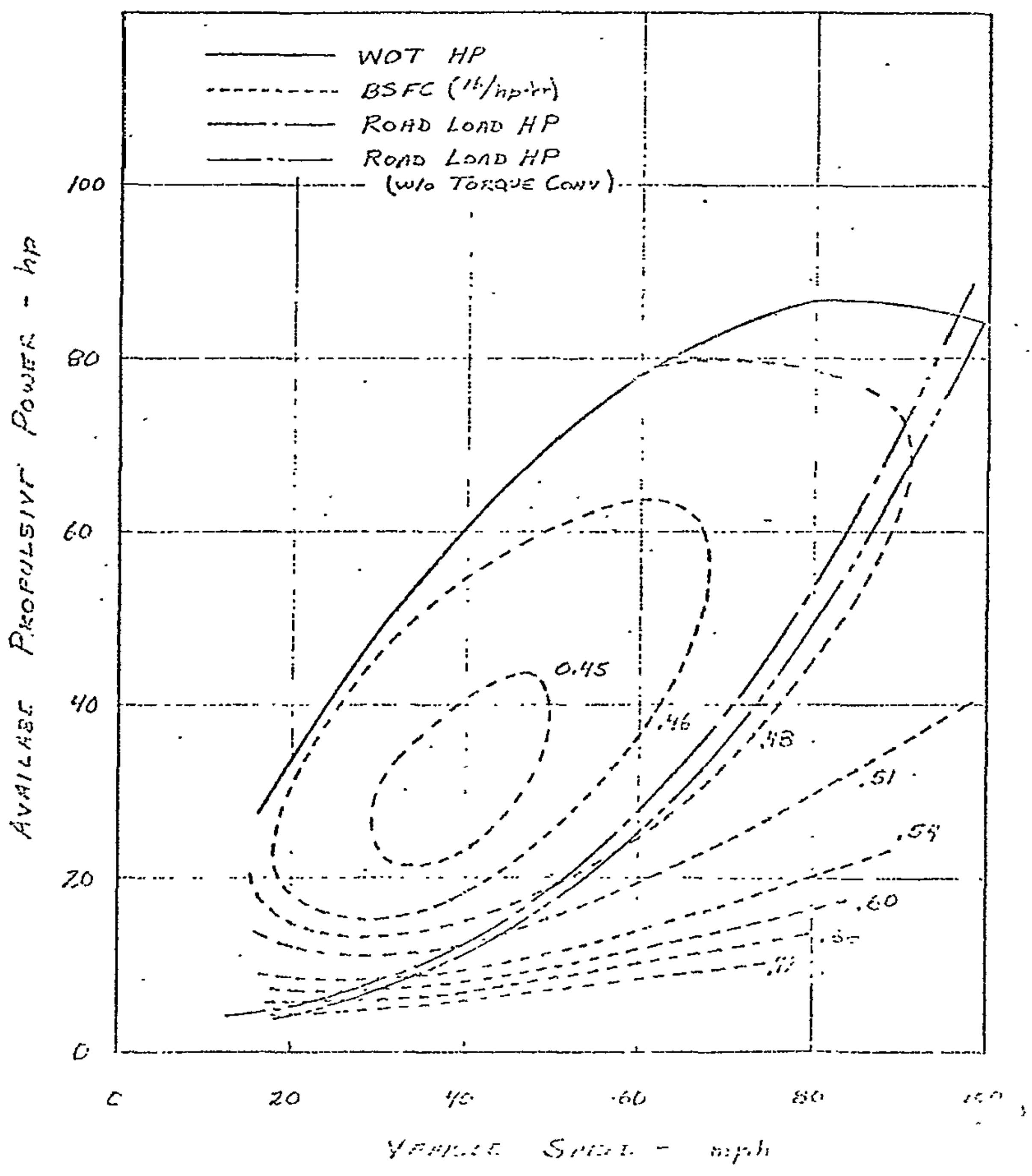
51 Cu In., 4 CYLINDER, SINGLE STAGE

1000 °F, 1000 PSIA



MARK II RANKINE CYCLE

97 Cu In., 6 CYLINDER
TWO STAGE EXPANSION
1250 °F ; 1500 PSIA
1500 °F ; 400 PSIA REHEAT



SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 Pleasant Street, Watertown, Mass. 02172 (617) 924-1420

RLD-293

8 October 1975

R. Rhoads Stephenson
OCT 10 1975

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Attention: Dr. R. Rhoads Stephenson

Dear Dr. Stephenson:

As a leader in the automotive steam engine field, Scientific Energy Systems Corporation has completed a critique of the Rankine engine chapter from your recent report Should We Have a New Engine?. We find that the Rankine engine analysis is technically erroneous and superficial. The JPL conclusion that the automotive steam engine does not have a practical potential for very high fuel economy and competitive cost is also invalid because of these technical errors, superficial analyses and narrow concept evaluation.

SES provided JPL with practical cost competitive alternatives. SES reviewed with JPL the fundamental technical errors during a very early draft phase. JPL has not made use of this support. Of the references cited by JPL in direct support of the steam (water working fluid) engine analysis, 9 of 28 are direct references to SES information. Major misrepresentations by JPL of this information further reduce the validity of the report.

As the JPL study may erroneously influence the Nation's energy conservation programs as well as JPL's reputation we suggest that JPL should endeavor to correct and complete the analysis for a revised chapter on the Rankine engine.

As noted in your report, the Rankine engine analysis did not receive iterative reviews by experts in the field to the extent afforded all other candidate engines. The enclosed critique by SES will serve you as a first major review iteration since the partial draft review of September 1974. We would be pleased to continue this dialogue in support of revisions to the current report on future vehicle studies.

Dr. R. Rhoads Stephenson
Page 2

RLD-293
8 October 1975

The SES critique will be given limited circulation within ERDA and experts in the field pending any comments you may wish to make. I look forward to discussing this matter with you at your October SAE presentation.

Very truly yours,

Roger L. Demler

Roger L. Demler
Program Manager

RLD/lh
Enclosure

cc: F. Pompei
P.C. Ricks

SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 Pleasant Street, Watertown, Mass. 02172 (617) 924-1420

SES CRITIQUE

OF

JET PROPULSION LABORATORY REPORT

"SHOULD WE HAVE A NEW ENGINE?"

"AN AUTOMOTIVE POWER SYSTEM EVALUATION"

1975

TABLE OF CONTENTS

INTRODUCTION

SES has been engaged in automotive steam engine development for seven years. For the past four years SES has been conducting this work under EPA/ERDA contract. A part of this work has been applied to the future potential of the automotive steam engine. With this background, SES has prepared a critique of the Jet Propulsion Laboratory report "Should We Have a New Engine, An Automobile Power System Evaluation", 1975.. This critique has focused solely on the Rankine or steam engine evaluation.

SUMMARY

Six fundamental oversights by JPL invalidate their steam engine analysis:

1. A thermodynamic error in positive displacement expander efficiency analysis results in a significant underestimate of the steam engine's efficiency.

2. The expander analysis error also incorrectly eliminates the variable admission expander. The variable admission expander would have a dramatic impact on cost and fuel economy through a reduction in maximum power required, improved part load efficiency and lower system pressures.

3. Misinterpretation and modification of SES vapor generator data erroneously resulted in a major cost penalty to the steam engine. A state-of-the-art vapor generator design analysis by SES for the JPL mature steam engine results in a 66% lower vapor generator materials cost.

4. JPL, in essence, conducted a cursory cost reduction study of the first modern generation of research steam engines. The necessarily conservative concepts of these research engines were not treated to the same scrutiny and cost conscious projections afforded the other unconventional engines.

5. JPL dismissed without apparent analysis a very cost-effective steam engine design submitted by SES. This reheat cycle, variable admission system is second only to the JPL Stirling engine in efficiency and it is cost competitive. The fuel economy and cost projections by SES for the steam engine are ranked below with the JPL alternatives.

6. JPL was unjustifiably pessimistic in their development prognosis for the steam engine. The "reheat cycle" concept provided by SES requires only two technical advances: the durability demonstration of a reheat expander and the development of the reheat boiler control strategy.

   To achieve the projected efficiency no improvement is required in: component efficiencies, materials, heat exchanger effectiveness, emissions, nor system dynamics.

EQUIVALENT PERFORMANCE COMPACT CARS

MATURE ENGINES

ENGINE	COMPOSITE (1) FUEL ECONOMY	RELATIVE ENGINE SELLING PRICE
STIRLING (JPL)	31 MPG	$100%
STEAM (SES)	29	91%
GAS TURBINE (JPL) SINGLE SHAFT, CVT (2)	28	86%
GAS TURBINE (JPL) FREE TURBINE	25	100%
DIESEL (JPL) (1)	24	92%
STRATIFIED CHARGE (JPL)(1)	23	85%
OTTO (150 HP)	22	82%

(1) 55% Urban FDC, 45% Highway FDC
Less than 0.41 grams per mile NO_x
Except Diesel and stratified charge at 1 to $1\frac{1}{2}$ grams per mile NO_x
(2) Continuously variable transmission at no cost increase

SUPPORTING DATA

A series of SES notes is enclosed with a copy of the JPL Rankine engine chapter annotated with margin keys to the SES notes.

A summary briefing on the reheat cycle steam engine design provides the general strategy of this engine.

(1) Turbine Expanders (JPL Page 7-3)

No modern example of a multistage automotive size steam turbine has been tested. The low efficiencies reported for single or two stage turbines are primarily due to the very high stage loadings, not size. The losses due to small turbine size are not predicted to be extreme. Producibility, efficiency levels, possible with producible hardware, and off design point performance are problems that need empirical investigation.

(2) Alternative Positive Displacement Expanders (JPL Page 7-3)

Positive displacement steam expander types other than the piston and cylinder type are virtual unknowns. Limited data on a proprietery vane type steam expander under development at GE and limited Wankel tests conducted by the Navy do not rule out these types, considering the performance achieved in their first generation tests.

(3) Expander Efficiency - Variable Versus Fixed Admission (JPL Page 7-3)

The limited published data on expander tests of variable admission and fixed admission expanders indicate that the variable admission expander has a higher peak efficiency and a higher efficiency over its entire load range. The SES variable admission expander (JPL Ref. 7-9) and the GM SE-101 fixed admission expander (SAE 729142, Fig. 17) illustrate this point. Note that the SES variable admission expander exhibits higher efficiency, based on the total pressure ratio available, even though it operates at a higher temperature and pressure ratio than the fixed admission expander.

The higher temperature would suggest a lower potential expander efficiency due to increased thermal losses. Higher pressure ratio would also tend to increase underexpansion losses.

That being the case, the variable admission expander is preferred because the best system efficiency island can be positioned close to the road load curve without resorting to very high steam pressures for maximum power, variable boiler pressure power control, and the associated response problem. The variable admission expander can also provide much higher torque backup (constant power over a large portion of the speed range, resulting in a lower peak "installed" power for equal performance).

(4) Expander Speed and Displacement (JPL Page 7-3)

The question of high speed capability for weight and size reduction and reduced thermal loss must be put in perspective. For a given maximum cycle temperature and pressure, reducing piston area will reduce thermal losses. Reduced displacement will also reduce weight and size. Selection of the desired piston speed must be a trade-off between increasing friction and reduced thermal loss. A major advantage of the variable admission expander is that it provdes the ability to minimize piston area and displacement while simultaneously reducing piston speed, resulting in superior part load efficiency because of compactness and low piston speed. As an example, a comparison of the current SES variable admission type expander and the current Carter fixed admission expander can be made: For the same peak cycle pressure of 2000 psi (both having 4 single acting pistons), current piston speed mechanical considerations and expander efficiencies, the following expander configurations result for a maximum horsepower of 70.

	Fixed Admission	Variable Admission
Max hp	70	70
Average Power From 50% to 100% Speed	Approximately 55 hp	70 hp
Maximum Speed	5,000 rpm	4,400 rpm
Relative Piston Area	100%	79%
Relative Displacement	100% (35 cu. in.)	70% (25 cu. in.)
Relative Piston Speed	100% (2300 ft/min)	78% (1460 ft/min)

The variable admission expander was sized to deliver a constant 70 hp in the 50% to 100% speed range by virtue of variable admission, and is obviously oversized for the same application as the fixed admission expander.

This comparison clearly demonstrates that the variable admission expander has the potential for lower displacement, lower thermal loss and lower friction loss than the fixed admission expander, when used in the same cycle.

(5) Erroneous System Efficiency Calculations Based On JPL Thermodynamic Error in Expander Analysis (JPL Page 7-3)

The thermodynamics employed by JPL in calculating expander efficiency are fundamentally in error. The analyst neglected to account for the work done by the steam during the admission period. Based on this error, all of the conclusions reached by JPL concerning potential expander efficiencies, cycle efficiencies, regenerator size and fuel economy are grossly in error. The gross magnitude of this error is illustrated by a moderate power data point taken from SES's expander tests. Properly defining expander efficiency as the net work per pound of steam divided by the ideal adiabatic expansion work per pound of steam through the total pressure ratio across the expander, (boiler outlet pressure to condesner inlet pressure) the comparison of test and theoretical performance of the sample data point is as follows:

ACTUAL EXPANDER EFFICIENCY VERSUS
JPL EFFICIENCY EQUATION

Total Pressure Ratio	50
Actual Expansion Ratio	5.8
Ideal Expander Efficiency: As tested configuration	81%
JPL State-of-The Art Projected Efficiency (η_{exp} = 74% per JPL equation 7-5)	51%
Measured Expander Brake Efficiency	65%
Percent Error in JPL Projected Expander Efficiency	-22%

The 22% penalty in expander efficiency translates into far more than a 28% penalty in fuel consumption for this comparison when the error is carried through the system weight, auxiliary power required, vehicle weight and required total-power model.

Conversely, using the JPL definition of expander efficiency, this SES data point produces a 95% efficiency while JPL claims the state-of-the-art is only 74%. In the extreme case, a 100% admission (zero expansion ratio) expander would have, by JPL definition, infinite efficiency, as such expanders do produce power.

On 30 September, 1974, Dr. L. C. Hoagland of SES visited with JPL staff members to review an early draft of their automotive power system evaluation report. Over a four hour period, extensive comments and corrections were provided and explained to them. JPL apologized for the superficial and invalid thermodynamic analysis and explained that only two weeks were available to pull together this draft. JPL agreed that the thermodynamics, particularly regarding expanders, was invalid. A year later we see that the expander and, therefore, system efficiency analysis is still invalid.

The following ideal gas formulas will provide, with reasonable theoretical accuracy, ideal expander steam flow and efficiency for specific mechanical configurations.

PERFORMANCE EQUATIONS

$$\eta_V = \epsilon_B \left\{ C_o + \frac{C_L}{\gamma}\left[1 - \frac{r_V^{\gamma}}{\epsilon_B r_P}\right]\right\}$$

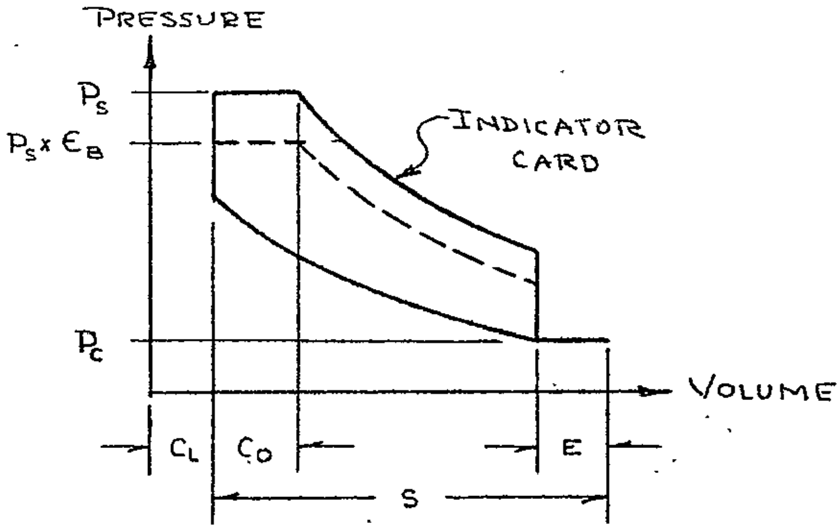
$$F_I = \epsilon_B \left\{ C_o + \frac{C_L + C_o}{\gamma - 1}\left[1 - \frac{1}{r_{V_E}^{\gamma-1}} + \frac{r_{V_E}}{\epsilon_B r_P}\left(1 - r_{V_C}^{\gamma-1}\right)\right]\right\}$$

$$\mathring{\omega} = \eta_V \times \delta \times (\text{PISTON AREA})(\text{PISTON SPEED})$$

$$\text{IMEP} = P_S \times F_I$$

$$\eta_E = \frac{F_I}{\eta_V}\left[\frac{0.11}{C_P\left(1 - \frac{1}{r_P^{\left(\frac{\gamma-1}{\gamma}\right)}}\right)}\right] \times 100, \ (\%)$$

IDEAL INDICATED EXPANDER PERFORMANCE WITH INTAKE PRESSURE CORRECTION



TERMINOLOGY

P_S = Supply Pressure

T_S = Supply Temperature

P_c = Condenser Pressure

C_L = Clearance, C_o = Cutoff, E = Exhaust } Fraction of Stroke

S = Stroke = 1

ϵ_B = Breathing Effectiveness, Fraction of Supply Pressure

$r_{V_C} = \frac{1+C_L-E}{C_L}$ = Compression Ratio

$r_P = \frac{P_S}{P_c}$ = Expander Pressure Ratio

$r_{V_E} = \frac{1+C_L-E}{C_L+C_o}$ = Expansion Ratio

η_V = Volumetric Efficiency (Vol. Steam ÷ Vol. Expander)

F_I = Indicated Work Function ($P_S \times F_I$ = IMEP)

$\dot{w}$ = Steam Mass Flow Rate

δ = Supply Steam Density

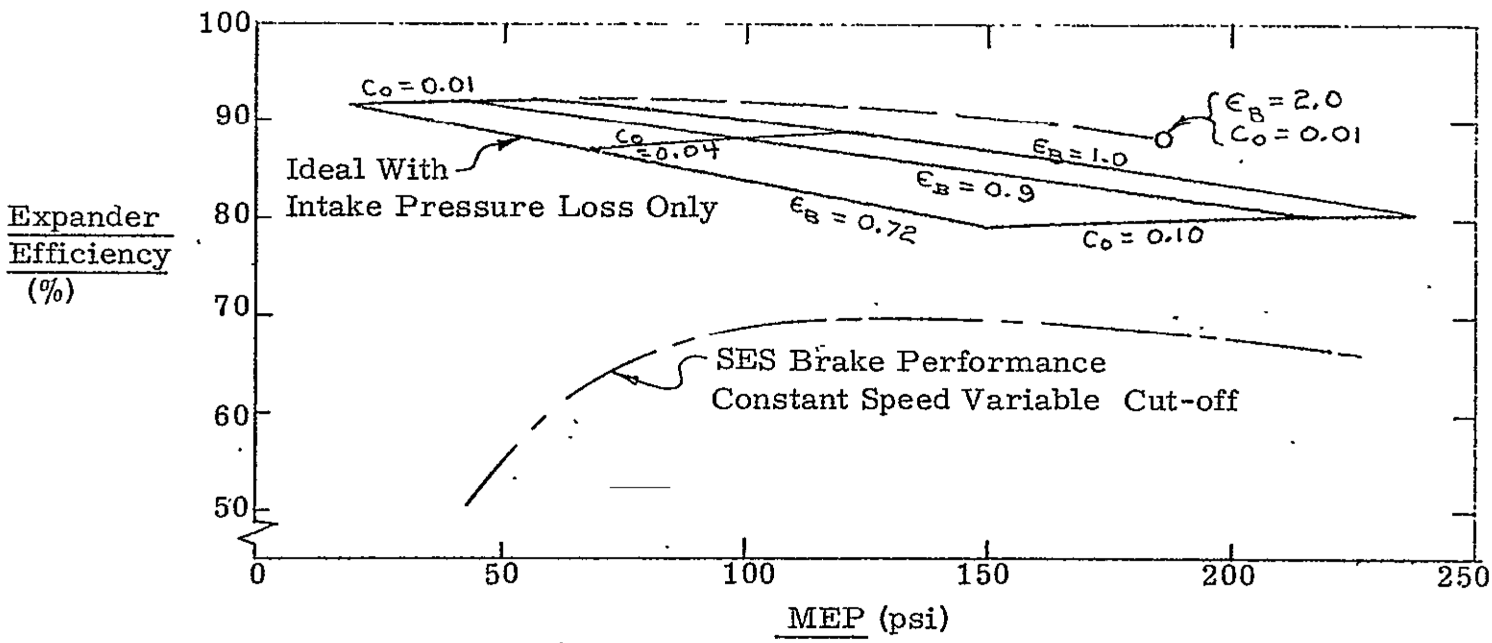
c_p = Steam Specific Heat $\left(\frac{BTU}{Lb.\ °F}\right)$

$\gamma = c_p/c_v$

η_E = Expander Indicated Efficiency

A sample using the current SES expander configuration will illustrate the general characteristics of positive displacement expanders.

For three cut-offs corresponding to expansion ratios of 13.6, 9.4 and 5.8 and for three breathing effectivenesses of 1.0, 0.9 and 0.724, the following ideal indicated expander efficiency curves result.



Notes:

Performance For:

r_{p_c} = 36.2
C_L = 0.057
E = 0.1465
P_s = 1000 psia
T_s = 1000°F
P_c = 20 psia

Except That:

ϵ_B = 2.0, Ideal Point For
P_s = 2000 psia
Without Intake Pressure Loss and Exp. Eff. Increased 5% for Potentially Improved Cycle Efficiency

SES Brake Performance At:

1000 rpm with 4 cylinder 135 cu.in. displ. with breathing, thermal, leakage and friction losses.

Immediately evident from the above curves is the fact that intake pressure loss is primarily a loss in total power, with a trivial loss in specific steam consumption or efficiency. In addition, the cycle efficiency is not significantly affected, since reduced steam flow proportionately reduces total pump work.

This dispells the myth that breathing is a critical component of expander efficiency. A brief explanation of this phenonenom is that the expander work at a given cut-off is primarily a function of inlet temperature and mechanical expansion ratio. The uniflow expander with symetrical exhaust timing either side of bottom dead center always operates over a fixed expansion ratio at a given cut-off, independent of inlet pressure or inlet pressure loss.

The above analysis and curves can also be used to study the fixed admission expander variable boiler pressure case. Interpreting the breathing effectiveness as percent of maximum boiler pressure, the throttling process does not significantly change the indicated efficiency. Extending the 13.6 expansion ratio out to twice the reference pressure ratio, the expander efficiency is about 5 percent higher than the variable admission fixed pressure case at the same bmep. The fixed admission expander efficiency at this point, based on the ideal work of the higher pressure ratio, is actually the same as the variable admission expander, but the fixed admission expander efficiency is given a 5 percent credit for the potentially higher cycle efficiency.

As noted before, the theoretical efficiency gains of high expansion ratios are not realized in actual practice. SES experience indicates that the efficiency is fairly constant over a cut-off range of .04 to 0.15, falling off rapidly below .04, and decreasing slowly above 0.15. Current brake efficiency versus bmep data for the SES expander is also shown on the above graph. Evidently, friction and heat transfer losses dominate the performance at high expansion ratios (low specific power).

The advantage of variable admission over fixed admission now becomes clear. The 0.01 fixed cut-off high pressure case compared to a 0.15 variable cut-off at normal pressure results in fixed cut-off IMEP of 185 psi and a variable cut-off IMEP of 320. Even at twice the boiler pressure, the fixed admission expander produces 42% lower power than the variable admission expander. The light load ideal efficiencies are nearly identical, but the light load brake efficiency of the fixed admission expander will be significantly lower as it either has higher thermal losses, if the displacement is increased to provide equal power, or the friction loss will be higher if a 73% higher piston speed is used to maintain the same displacement.

Raising the fixed admission systems boiler pressure even higher or selecting a higher fixed cut-off can, of course, finally result in a match with the variable cut-off system bmep, but the expander and system consequences are severe. The feedpump, boiler and expander must be designed to adequately cope with the maximum cycle pressure even if the high pressure is only encountered intermittantly.

A significant constraint on the simple bash valve, fixed admission expander is that the intake process is symmetrical around top dead center (TDC). The intake valve opens the same number of degrees before TDC as it does in closing after TDC for ending the admission process. Any steam flow into the cylinder during the compression stroke obviously detracts from the net power and reduces efficiency. A small intake lead angle can be benificial as it improves volumetric efficiency at higher piston speeds. Lead angles of about 10^0 can be used without a substantial loss at moderate loads, but for symmetrical valve timing this results in a cut-off of only .008, and a very low specific output. To avoid this compression stroke loss in a higher specific output fixed admission expander, some type of assymetrical valve mechanism is required, be it a cam and tappet system or some form of timed release latch mechanism on the bash valve. Once the basic assymetrical valve timing system is introduced, only a little additional complexity will provide a variable admission, moderate peak pressure system.

(6) <u>The Near Term Superior Efficiency, "Reheat Cycle" Steam Engine (JPL Page 7-3)</u>

JPL chose not to explore one very efficient, mature engine presented to them; the "reheat cycle" steam engine, (JPL REF. 7-31). The saliant data characterizing heat engines, based on SES estimates for the mature Rankine engine and the JPL data for all other engines, is tabulated on the following page.

The high efficiency Rankine engine can operate at a lower temperature and pressure than the extreme conditions employed by other engines. It can also deliver a higher fraction of the ideal efficiency with regeneration even with modest component performance, by virtue of the extremely low liquid compression work required.

A "Summary Briefing" by SES, August 1975, on the reheat automotive steam engine concept is enclosed for further details. This briefing presents a refinement of the data and concept since JPL's inquiry of a year ago. The Mark II mature engine design configuration has a baseline net engine brake

CHARACTERISTICS OF MATURE HEAT ENGINES
CYCLE THERMAL EFFICIENCY AND ENGINE WEIGHT
MATURE TECHNOLOGY TEMPERATURES

ENGINE TYPE	IDEAL EFFICIENCY	MAXIMUM BRAKE EFFICIENCY	150 HP ENGINE WEIGHT POUNDS	COMMENTS
BRAYTON (REGNERATED)	66%	33%	366	SINGLE SHAFT WITH CONTINUOUSLY VARIABLE TRANSMISSION
PRESS RATIO = 4:1 AMBIENT TEMP = 85°F T_3 = 1900°F ALL COMPONENTS IMPROVED	66%	30%	413	FREE TURBINE WITH CONVENTIONAL TRANSMISSION
STIRLING T_H = 1400°F T_L = 160°F P_H = 2850 PSIA ALL COMPONENTS IMPROVED	67%	36%	710	
RANKINE (REHEAT) T_1 = 1250°F T_{REHEAT} = 1500°F P_H = 1500 PSI T_L = 155°F ALL COMPONENTS AT CURRENT EFFICIENCIES	46%	33%	750	150 HP FROM 50 TO 100% SPEED VARIABLE ADMISSION PISTON EXPANDER
DIESEL (LIMITED PRESSURE) COMPRESSION RATIO = 15:1 EQUIVALENCE RATIO = 0.6	55%	32%	786	TURBOCHARGED
OTTO (SPARK IGNITION) COMPRESSION RATIO = 8:1 EQUIVALENCE RATIO = 0.8	45%	27%	645	

efficiency of 31% at 25% power with current component efficiencies. The actual efficiency of the developed engine will of course be higher as the component technology improves.

You will note in the briefing that the mature steam engine utilizes conservative technology, compact components, and only small quantities of stainless steel. The only fundamental technology that requires feasibility demonstration is lubrication of the expander at higher steam temperatures. Propellant gas expanders for torpedoes have run for extended periods with inlet conditions at 2300°F and 5000 psi. Satisfactory life can be expected for the proposed 1500°F, lower pressure steam engine.

A very significant result of the reheat cycle is that it grossly reduces engine cost. Through increased specific output and higher cycle efficiency, the boiler and condenser sizes are reduced substantially. The complete vapor generator (burner, blower, boiler) is reduced to less than 8 percent of the engine ready-to-run weight. The condenser is only 9 percent of the engine weight.

The JPL suggestion that the reheat system is unacceptably high in cost due to additional complexity, apparently resulted from a superficial analysis. The only component that increases in size is the expander which now requires more displacement through additional cylinders. It is however, no more complicated except that the intake and exhaust functions are performed with four pipes instead of two.

The boiler requires one pass in series with the first stage boiler to accomplish the reheat function. For a 150 horsepower engine the total stainless steel content of the boiler is 14 pounds, and no superalloys are required.

Complexity is increased again, but only by a doubling of the external working fluid connections.

No increase in controls complexity is anticipated, with the possible exception of an additional monitoring station in the vapor generator.

(7) <u>JPL Selected The Least Promising System Concept (JPL Page 7-3)</u>

The fixed admission expander variable boiler pressure Rankine engine is, in fact, the least promising.

(8) <u>Expander Friction Can Be A Minor Efficiency Loss (JPL Page 7-4)</u>

The major efficiency loss of current positive displacement expanders is a complex heat transfer mechanism. At moderate loads and piston speeds the mechanical efficiency of a well designed, high bmep variable admission expander is about 95%. The high speed, high expansion ratio fixed admission expander fundamentally has a lower mechanical efficiency due to its high piston speed and high recompression-to-expansion work ratio.

(9) <u>Correction To Cycle Efficiency As A Function Of Pressure (JPL Page 7-5)</u>

With correct thermodynamics for expander analysis, the cycle efficiency increases steadily with increasing pressure.

(10) <u>High Pressure System Compromises (JPL Page 10)</u>

Higher steam pressures do tend to decrease expander thermal losses and reduce displacement, but a significant compromise must be made in boiler materials content, tubing thickness-to-diameter ratios, pump and expander durability, and expander structural and bearing design.

(11) Empirical System Evidence That JPL Expander Analysis Is In Error (JPL Page 7-6)

As is evident in the JPL references, the SES system delivers its maximum efficiency at expansion ratios as low as 5.2 (40^0 cut-off line). See SES Note (12) and attached system performance map.

(12) Alternative Engine Fuel Economies With SES Reheat Cycle And Party Load Efficiency Matching (JPL Page 7-6)

The engine performance map exhibited by JPL in Figure 7-8 is not for a present Rankine positive displacement variable boiler pressure system as stated by JPL. It is in fact the measured performance map taken from the SES variable admission fixed boiler pressure system. The data provided to JPL in Reference 7-5 is reproduced below ("Enclo (2), Fig. 1") and presents variable admission performance over a range of expansion ratios of 15.5 to 5.2. Note that JPL has added two bsfc lines (0.85 and 0.90) in the 80 to 90 percent power range. At the time of publication of the reference, consistent data above the 70 percent power level and higher cut-offs was not available. Since that time additional data and performance estimations have been obtained to cover the complete power spectrum. The Mark I Rankine Cycle engine map contained in the SES "Summary Briefing" is an accurate representation of the current cycle and component performance for an 87 net horsepower system operating at higher cut-off at maximum power. This map is for available propulsive power and accounts for current automotive accessory losses. Even on this conservative basis, the bsfc at maximum power is less than 0.85.

FIG 1. SES – STEAM SYSTEM POWER MAP

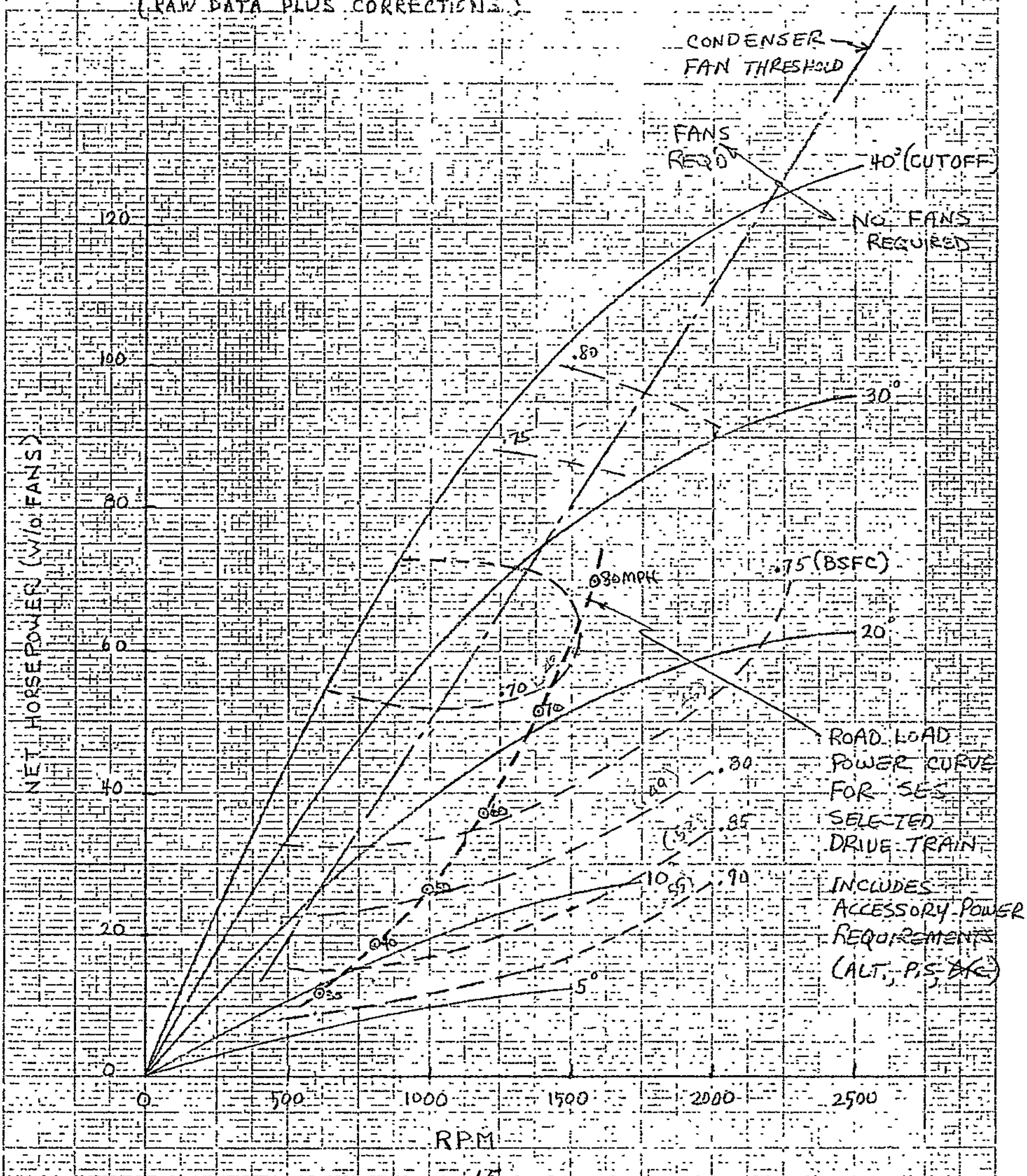
L-4 EXPANDER 3.5" BORE × 3.5" STROKE

REVERSED VALVES

60° ADMISSION CAM – 75° CUTOFF CAM

MAX RPM 2500 MAX PISTON SPEED 1458 FT/MIN

(RAW DATA PLUS CORRECTIONS)



-15-

FIGURE 1

The engine map shown in JPL Figure 7-8 does not represent the complete power envelope used in the current SES system. The current engine actually produces 100 percent power from 50% to 100% speed along an essentially constant steam flow line. As described in SES Note 4, the variable admission expander system requires 15 to 20 percent lower maximum horesepower than a fixed admission system. This installed power reduction carries through to all the component sizes and reduces total engine weight for the same performance.

The comparable torque curve of a 12 to 1 expansion ratio, 1000 psi operating line for the system proposed by JPL can be represented by a 16^0 cut-off line on the original SES system map, well below the best system efficiency potential and extremely low in specific power.

The original SES system map reproduced as JPL Figure 7-8, is, as it states, on a net horsepower basis. The bsfc contours are therefore on a net engine efficiency basis and include auxiliary power reductions for the feedpump, combustion air blower and engine required electrical power. Condenser fan power is not deducted as noted. The condenser fan threshold is shown to be well above normal cruise loads for the design conditions (85^0F day). The normal vehicle accessory powers are included in the road load curve. The present Rankine variable admission engine maximum brake (not cycle) efficiency is threfore 19%.

Comparing the maximum torque curves of the Stirling engine and steam engine maps in the SES "Summary Briefing" shows that the torque speed curves are essentially identical. The engine power to weight ratios are also essentially the same for the JPL Mature Stirling and the SES Mature reheat steam engine at for example, 500 pounds each at 100 horsepower. Thus the installed horsepower and weight should also be identical. The fuel economy then becomes only a function of bsfc versus load. Both the JPL Stirling and SES Rankine engine are matched for high efficiency at light load. The Stirling engine claiming a 9 percent higher maximum efficiency could be used to make a first order estimate of steam engine fuel economy as 9 percent lower than the Stirling. Using this estimate and rearranging the candidate compact cars in order of decreasing fuel economy results in the following table:

MATURE ENGINE FUEL ECONOMY
COMPACT CARS

	Engine	Curb Wt. (lb)	Max HP	Urban FDC, MPG	Highway FDC, MPG
JPL	Stirling	3050	99	26.3	37
SES	Steam (Reheat Cycle)	3050	99	24.1	33.9
JPL	Gas Turbine (Single Shaft)	2660	86	22.9	34.4
JPL	Gas Turbine (Free Turbine)	2710	89	20.8	30.1
JPL	Diesel	3340	131	20.7	27.5
JPL	OTTO (Spark Ignition)	3100	125	18.3	27.3

Unfortunately, the JPL report does not include the various projected engine maps. Judging from the current and near term maps included in the

SES "Summary Briefing", the steam engine would have even higher relative fuel economy since the part load efficiency of the steam engine is a far better match to the duty cycle than any of the candidates in their current or near-term forms. For example, the current Ford-Stirling engine projection has a best efficiency that is 5 percent higher than the SES mature steam engine, yet it has a 16 percent lower fuel economy at 50 mph (after adjustment to a common drive train efficiency). The point of this example is that the JPL projected improvements include a significant state-of-the-art advance in part power component matching just to catch up to the current steam engine light load efficiency advantage.

The case is even more striking for the JPL gas turbine. Again, from the SES "Summary Briefing", the light load efficiency of the Chrysler/ERDA Upgraded Gas Turbine falls very rapidly with load, as shown by the unfavorable divergence in fuel economy relative to the other engine types, as vehicle speed is reduced. Note that this projected gas turbine performance already includes all the part load efficiency props included in the JPL projection (variable geometry compressor, variable geometry power turbine, improved component efficiencies), plus it also incorporates inlet water injection boost to shrink the basic engine size by 19 percent. This feature is projected by Chrysler to require 7.5 gallons of water for every 10 gallons of fuel to cover extreme driver demands. The JPL free turbine mature gas turbine, without inlet water injection, in the same vehicle size, is projected to pay only a 15 percent penalty in miles per gallon relative to the mature Stirling engine, after discounting their relative peak cycle efficiencies.

(13) <u>SES "Projected" System and Performance is Not For an Advanced Engine But Only A Mature Version of The Current Simple Cycle (JPL Pages 7-6, 7-7, and 7-8)</u>

The "Projected" SES steam engine in JPL Tables 7-2 and 7-3 is not an "advanced" engine in the context of the JPL definition. The projected engine is best represented as a mature version of the current concept in that it continues with the conservative first generation cycle parameters and single stage variable admission expander. JPL did not present the mature reheat cycle steam engine projection provided by SES. (See SES notes 6 and 12 for the results).

(14) <u>Clarification of SES Emissions Reduction Technique (JPL Page 7-8)</u>

JPL makes the statement that "step-quenching can be very effective in controlling exhaust NO_x levels (but not more so than charge dilution in continuous combustors). This is misleading because step quenching is more desireable than charge dilution. While it is true that both step quenching and charge dilution (excess air and/or EGR) can be employed to reduce NO_x levels, homogeneous combustion with step quenching is by far the most "effective" method because, unlike charge dilution, it does not require any penalty in either system efficiency or larger component size and weight. When charge dilution is employed to reduce NO_x levels, the total combustion gas flow through the burner and heat exchanger is increased. If the heat exchanger size is not increased to handle the larger flow, then the exhaust gas temperature rises causing increased stack thermal losses and reduced system efficiency.

SES does not use EGR in its burner; rather, hot combustion gas recirculation (CGR) is employed for the primary purpose of increasing mixture temperature for rapid fuel vaporization.

(15) The Reheat Cycle Avoids Extreme Boiler Design Requirements (JPL Page 7-9)

The SES mature "reheat cycle" steam engine avoids the extreme 2500 psi boiler pressure by use of variable expander admission. The SES reheat approach is designed to capitalize on the capabilities of stainless steel through the equivalent of fixed pressure and temperature scheduling. The first expander stage receives 1250°F steam at 1500 psi, and the second stage runs hotter at 1500°F but at a lower pressure of 400 psi. Thus the reheat cycle provides a 40 percent increase in efficiency over the JPL mature steam cycle, while also minimizing the boiler and expander stainless steel content. This is accomplished with high specific output and avoidance of simultaneous operation at high temperature and high pressure in any one system location.

(16) SES Freeze Protection Tests (JPL Page 7-10)

SES has conducted closed loop freeze protection tests consisting of an insulated sump, isolation valves, self draining feed pump and condenser core. The loop was able to self prime and run with 60°F water in the sump and the rest of the loop cold soaked at 0°F. Draining of the very small condenser passages has been a problem and requires additional testing to determine the proper passage size or the effectiveness of draining aides such as wicking or blowdown techniques. Local blockage and freezing could be tolerated if additional core compliance can be built in.

(17) JPL Did Not Evaluate The Reheat Cycle System Submitted By SES (JPL Page 7-11)

The key features of the high fuel economy, low cost steam engine presented by SES to JPL were not given a sound technical evaluation by JPL.

(18) Current Steam Engine Technology Perspective (JPL Page 7-11)

The performance of existing steam engines must be properly placed on the technology learning curve before the future can be judged. All of the steam engines cited in the JPL report as current examples are in fact each companies' first generation attempt to demonstrate the potential of the steam engine. Actually, the most recent technology base for compact transportation steam engines dates back to the limited steam locomotive developments carried out in the 1940's. Primarily because of the fuel employed (coal) and limited materials technology, the steam locomotive ended its career at very modest cycle conditions, typically 250 psi at 500°F. Some of the steam cars of the 1930's were somewhat more ambitious, employing steam up to 800°F.

Necessarily then, all current efforts had to settle for very modest cycles in order to minimize mechanical risk in first generation research engines. None of the current efforts, however, have been given the opportunity to fabricate and test a second generation engine based on the new technology foundation.

SES is a good case in point. The EPA (now ERDA) Contract put first priority on very low emissions in a car with competitive acceleration performance. Potential fuel economy had to be compromised to limit the mechanical development risk. Four years ago, when the basic system concept and cycle had to be frozen, there was no technology base for expander design. The other major system components, however, could be quickly designed and developed with parallel technology developed for other applications.

Very early in the program it was clear that the maximum expander efficiency would occur at very high power due to light load heat transfer losses. At that time, preliminary design was completed for a new four cylinder expander that had one half of the current displacement and higher speed. The smaller expander if fabricated, would have increased the maximum system efficiency somewhat, but more importantly, the maximum system efficiency would have been moved from about half power down to one quarter power. Unfortunately, the combination of program objectives and long lead times prohibited the procurement of the improved expander.

Extensive lubrication research has been conducted at current cycle conditions. A sound technology base is therefore available to conduct the mature engine design and development.

An interesting contrast to the restricted expander technology is the development history of the SES vapor generator. Due to the relative ease of fabrication and fundamental heat exchanger technology base, SES is now running the fourth basic vapor generator configuration since the program was initiated. The present boiler weight and response time is dramicatically lower than the first generations, the weight having been reduced from 165 pounds to 92 pounds. The efficiency has also been improved over the complete operating range.

The missing expander technology base centered on two fundamental problems, 1) high temperature lubrication in a steam environment and, 2) the complex analysis of the periodic flow heat exchanger phenomenon in the steam cylinder. The conservative approach to the lubrication problem is to minimize the expander specific power and steam inlet temperature.

Internal combustion engine technology would indicate that the efficiency loss due to heat transfer would be minimized at higher specific power. The basic cycle efficiency is strongly dependent upon increasing inlet temperature. Thus, the key ingrediants of high efficiency ran counter to conservative lubrication design.

Four years ago the conservative direction was obvious: Design for modest specific power and conservative temperatures. Since that time the fundamental objectives of the preprototype vehicle program have not changed, and the expander retains the original displacement and all of the component concepts, except for a change in admission valve sequence. Because fundamental analytical and emperical research have been conducted in parallel, it is now possible to accurately predict expander performance for advanced engines. Of particular note is that the original design effort accurately predicted performance for those features that had a direct analogy in the highly developed internal combustion engine, such as, valve breathing, bearings, crankshafts and cams.

In summary, the current SES expander cannot be characterized as "something near the upper limit of achievable efficiency for this type of expander" (variable admission). In terms of improved efficiency, only one change in the expander, the admission valve sequence reversal, has ever been implemented.

(19) Superalloys Are Not Required in the Mature Engine Expander (JPL Table 7-4)

Current SES valves are cut-down from production automotive valves made from an austenitic steel alloy and not a superalloy as listed by JPL.

(20) The Reheat Cycle Provides Superior Materials Utilization (JPL Page 7-13)

JPL has overlooked the superior materials utilization of the reheat cycle. A 40 percent higher efficiency is possible at the same temperature level as the JPL Mature Rankine cycle but at lower pressures.

(21) Variable Boiler Pressure System Constraints (JPL Page 7-13)

Only very limited pressure - temperature scheduling is practical since, under dynamic conditions in the actual duty cycle, the coincidence of high pressure and high temperature cannot be totally avoided. Another major constraint must be considered. For the variable boiler pressure, fixed admission expander system, the throttle response is totally dependent upon the pressure response of the boiler. A key parameter in pressure response is the metal thermal energy increase and/or shift within the boiler tubing. As increasing pressure raises the boiling point, a rapid increase in boiler pressure and flow requires a rapid increase in boiler metal temperature and energy content, as well as the rapid increase in net heat transfer to the steam.

(22) Expander Lubrication Analysis (JPL Page 7-13)

The lubrication picture looks fairly bright at this time. SES recently completed a 150 hour durability test with no measurable wear on the liner or rings. The test was conducted with 1000^0F, 1000 psi inlet steam over a variable load schedule up to 230 bmep with hard coated rings, a natural hydrocarbon oil base stock and a high polymer low volatility additive for upper ring protection. The liner temperature reached 700^0F at the top ring travel. Cylinder lubricating oil was provided by the usual automotive practice of crankcase splash lubrication and a lower oil control ring.

Steam engine cylinder lubrication, fortunately, is considerably simplified, in that there is little oxygen, only water vapor in the cylinder and crankcase. There are no combustion products or combustion temperatures to contend with, and there are now available several synthetic lubricants that are compatible with water and that also have much lower volatility.

At the moderate-to-high bmeps that are desired for high expander efficiency, it has been found that expansion and recompression are essentially adiabatic. It is only during this phase that the liner zone traversed by the rings is exposed, suggesting that cooling of this zone to promote lubricant life will not materially reduce efficiency. Steam Power Systems is proceding with this approach for a 1400°F, variable admission expander (Ref: IECEC 949127).

Both liquid and solid lubrication should be researched for the mature expander. The conservative approach for liquid lubricaction would envolve a counterflow expander. While the thermal loss for the counterflow would tend to be higher than for a uniflow expander, the net affect on cycle efficiency could be beneficial. A much higher fraction of the thermal loss would be carried out by the exhaust steam. With the reheat and regeneration cycle, a substantial portion of the thermal loss will be recovered downstream, unlike the early open cycle engines that rejected all heat transfer losses.

Solid lubricants for steam engines have not been extensively researched. The GE carbon ring work, under EPA/AAPS contract, was fairly encouraging based on the short, one-shot project. Skoda built a carbon lubricated steam expander (700°F, 610 psi, 100 bmep, 81 percent efficiency) that had run for 8000 hours at the time it was reported (Ref. The Engineer's Digest, August, 1945).

(23) The Advanced Reheat Cycle (JPL Page 7-14)

An advanced reheat cycle with better materials utilization and a higher ideal cycle efficiency potential could take the following form:

First Stage Inlet:	2000°F, 2000 psi
Second Stage Inlet:	2250°F, 500 psi
Condenser Pressure:	8 psia
Expander Stage Eff.:	75% each
Pump Efficiency:	60%
Regenerator Effectiveness:	90%
Brake Thermal Efficiency:	40%
Ideal Cycle Efficiency:	55%

Note that the regnerated steam engine can deliver a much higher return on its ideal efficiency with a very modest expander efficiency. Unlike all of the other alternative engines that produce their working pressure ratio by compressing a gas, the steam engine generates its pressure with an incompressible fluid. For both the mature and advanced steam cycles, the ideal pump work is less than 1 percent of the net work. Expander inefficiency recovered through the regenerator and returned to the boiler inlet, entails a negligible pump work penalty while being returned through the cycle. The recuperator, at a moderate 90 percent effectiveness, can therefore reduce the expander inefficiency by more than two thirds of the apparant loss. Similarly, the high pressure expander stage inefficiency is substantially recovered since the increased exhaust energy reduces the heating load on the reheat section of the boiler.

(24) Corrections To And Reheat Cycle Results For the JPL Materials And Producibility Section (JPL Pages 7-14 thru 7-19, Section 7.3.3)

There are three areas of comment in this section:

1) JPL misinterpreted and modified the vapor generator data provided by SES.

2) JPL has carried forward to a significant extent the conservative materials employed in the current first generation research engines.

3) JPL, by eliminating the reheat cycle from consideration, has rejected the lowest cost, highest efficiency steam engine.

The mature reheat cycle steam engine design at SES is in the concept formulation and design trade-off stage, so that a complete materials breakdown is not now available. The major design emphasis has been placed on the cost intensive areas. The extensive annotations by SES that precede this section deal primarily with the three way trade-off between fuel economy, individual component cost density, and redistribution of component sizes through cycle changes.

Early in the advanced engine study SES, as has JPL, proceeded on the brute force approach to cycle efficiency with the higher temperature and higher pressure simple cycle. Superficially, the compound and reheat cycle appears to be too complex, and therefore costly. With initial reluctance, the brute force path was abandoned since current materials capabilities could not yield a sufficient advantage over the economy of the spark ignition Otto cycle with its anticipated improvements in a fuel conservative climate. In the past year SES has thus taken a hard look at the first order cost/efficiency trade-offs for a wide range of cycles and materials possibilities. Now that a substantial technology research base has been digested, the evolution of the modern automotive steam engine can be approached with more precision and with a design-to-cost attitude.

The first two areas of comment on costs (miss use of both the SES data and JPL general conservatism) are necessarily directed at the specific system selected by JPL for the mature Rankine engine. As stated above this fixed admission expander, high boiler pressure system is not believed to be the proper direction for development. It is, however, important to point out the errors in the JPL evaluation as they have a critical impact on the overall JPL study results.

1) Misinterpretation and Modification of SES Vapor Generator Data

A major cost disadvantage was attributed by JPL to the boiler stainless steel content. SES provided JPL with a detailed vapor generator materials breakdown of a 150 horsepower system representing a proposed production design of the current conservative cycle of 1000 psi and 1000^{0}F. The JPL materials breakdown for their mature Rankine cycle at 2500 psi and 1000^{0}F is presented below in parallel with the SES materials data.

The similarity of the weights in some key areas is apparent (fins, housing, insulation, and ducts and miscellaneous parts).

VAPOR GENERATOR MATERIALS

COMPONENT OR SUBASSEMBLY	JPL Mature Configuration Weight, lb	JPL Mature Configuration Mat'l	SES Prod. Est. for Current Cycle Mat'l	SES Prod. Est. for Current Cycle Weight, lb	Component Or Subassembly
Preheater Fins	5	Alum	Alum	4.1	Economizer Fins
Evaporator Fins	10	Steel	Steel	10.2	Evaporator Fins
Vapor Gen. Tubing	99	Stainless	Stainless Alloy Alloy	6.7 11.8 5.6 (24.1)	Superheater Tube Evaporator Tubing Economizer Tubing
Vapor Gen. Housing	25	Stainless	Steel Steel (Aluminized)	13.5 7.9 21.4	Blower Casing H-X Casing
Insulation	3	(Insulation)	Fiberfrax Fiberglass	1.4 1.6 (3.0)	Insulation Insulation
Combustor Atomizer	3	Stainless	Steel	0.3	Fuel Nozzle
Combustor Blower	2	Alum	Alum.	1.0	Blower
Combustor Liner	1	Superalloy	- (Inconel) Superalloy	 1.3	No "Liner" Req'd. Inlet (Recirc.) Duct
Ignition Assembly	5	Miscel.	Stainless	0.1	Ignitor & Preheater
Air cleaner, Ducts, Diffuser, etc.	11	Miscel.	Steel Steel Stainless Alum. Steel Alum.	1.8 1.4 0.7 0.9 1.3 0.6 3.0 (9.7)	Inlet Duct Diffuser Flameholder Air Valve Housing Air Valve Assy Flow Straightener Miscel. Structure
Total Wt. Less Drive Motor	164 lb			75.2 lb	Total Weight Less Drive Motor

Materials Summary	JPL, Lb.	SES, Lb.
Superalloy	1	1.3
Austenitc Stainless Steel	127	7.5
Alloy Steel (T-22)	None	17.4
Carbon Steel	10	36.4
Aluminum	7	6.6
Insulation	3	3
Miscellaneous	16	None
	164	75.2

The mature system boiler was apparently derived from the SES data but the results are illogical.

SES has reviewed the design requirements of the JPL mature Rankine engine boiler. Based on current SES design practice for the SES reference vapor generator, the same pressure drop, gas side heat transfer coefficient and stress margins, results in a superheater weight for the JPL boiler of twice the reference design weight. For a conservative estimate, the entire tube bundle would double in weight with constant fin weight. JPL increased the tubing weight by 310 percent and changed all the tubing to stainless steel, adding 92 pounds of stainless steel to the reference design. The SES design analysis added less than 7 pounds of stainless steel.

JPL added another 25 pounds of stainless steel by making the outer skin or housing out of stainless steel. The SES reference design carries the insulation inside of the relatively cool skin. Even the exhaust duct should be carbon steel since the maximum exhaust temperature will be about 550^{0}F.

The basic weight of the non-heat exchanger components, including the housing, would be reduced in size. For a constant gas side velocity the dimensions would decrease by 10 percent, and the volume and weight would be reduced by 28 percent.

The total vapor generator weight, on this basis, for the JPL mature configuration is summarized as:

	JPL Mature Vapor Generator, 150 hp	SES Vapor Generator State-of-the-Art Est. For JPL Mature Cycle, 150 hp
Stainless Steel	127 lbs	13 lbs
Super Alloy	1 lb	1 lb
Alloy Steel	-	35 lbs
Other	36 lbs	26 lbs
Total	164 lbs	75 lbs
Mat'ls Variable Cost	$129	$44
Retail Price Reduction	-	$160

The JPL variable material cost projection is higher than the SES design by about $85 (per JPL Table 11-10), and would reflect in a 12 percent reduction in total engine variable costs and a retail price difference of $160 in JPL Table 11-15. With this single correction, the Rankine cycle system now contains 20 percent less stainless steel than an equal power Stirling, rather than 105 percent more stainless steel as shown in JPL Table 18-5. Similar reduction in chromium and nickle consumption would reduce the United States' consumption of these metals below the values shown in JPL Table 18-6.

In support of the original SES data provided to JPL, the current vapor generator now used in SES vehicle tests and having the same output as the reference design provided to JPL, has a tôtal package weight of 92 pounds with a 41 pound heat exchanger, including fins. This heat exchanger is designed to the ASME boiler codes rather than the shorter life automotive duty cycle.

2) JPL Rankine Engine Conservatism

The modern steam engine effort is now the least mature technology; the applied research phase. The Otto, Diesel and stratified charge engines are already in the product improvement phase. The gas turbine at this time has nearly completed at least one engineering development phase for trucks and is well into advanced development for cars. Chrysler is building its seventh generation gas turbine. The Stirling engine is more difficult to position on the R&D ladder, and is somewhere between exploratory and advanced development based on the R&D expenditures for a wide range of applications. Evaluation of the cost and performance potential for this group of engines, at vastly different development levels, should apply the most fundamental and wide ranging analysis to the least developed engine. JPL, however, conducted a cursory study of research steam engine cost reduction.

As is stated by JPL, to this day an enormous variety of approaches to the steam engine exist, again suggesting that a wide ranging analysis is in order. The only variation beyond the simple Rankine cycle mentioned by JPL was dismissed in one paragraph, without presenting any supporting analysis. See Section 3 that follows for this reheat cycle approach.

The short sighted attitude of the JPL steam engine cost analysis is evident in the following examples from JPL's results for the 150 horsepower mature engine.

Expander weight:

JPL estimated 225 pounds. A lower bound could have been derived by Otto engine practice at 1.5 pounds per cubic inch. For the Carter projected performance for the fixed admission expander, the 150 horsepower expander would have a displacement of 65 cubic inches and a lower bound weight of 98 pounds. The total engine ready-to-run weight might be 17 percent lighter.

Is this feasable? Not with today's research expanders. But consider that the Carter expander has no camshaft, cooling jackets, cooling water pump, valve train lubrication, and it runs at conventional piston speeds. It does run at higher specific output and higher pressures suggesting that a more realistic estimate of the weight might be 150 pounds. The detailed analysis apparent in other alternative engines was not applied to this significant disparity.

Expander Materials:

For the steam engine valves, springs and seats JPL assumed 10 pounds of superalloy. The steam environment is less severe for these components than the Otto cycle engine because gas temperatures are lower and it is not an oxydizing atmosphere. SES uses austeitic steel for valves and seats but has used Hastelloy X valve springs in research efforts primarily because of its proven characteristics. Conversion of this ten pounds of superalloys to a more realistic austenitic steel changes the total engine retail price by $59, or 3 percent.

JPL applied a total of 43 pounds of stainless steel to expander steam accumulators, cylinder liners, steam inlet lines, and piston crowns. SES currently operates at 1000 F with cast iron cylinder liners, cylinder heads, and piston crowns. SES has also run a ceramic thermal buffer on piston crowns to reduce thermal loss and piston temperature. The ceramic thermal buffer approach might be extended to the cylinder heads with a no-stress ceramic insulator in a cast iron pressure vessel. This approach is used by Chrysler in their automotive gas turbine. Assuming only half of the cost differential between cast iron and stainless steel nets another $20 in retail price.

Water Feed System:

JPL estimated 30 pounds for the mature steam engine feed and condenser pumps. SES currently uses a 14 pound variable flow control feed pump that has four times the flow capacity required for the JPL application. A small electric pump is used for subcooling. A reasonable production estimate for this package in the JPL mature engine is perhaps 8 pounds rather than 30 pounds.

Combined Results:

A true production estimate of the cost and weight for the JPL mature Rankine cycle is certainly open to wide speculation. Looking only at the specific cases sighted above and the vapor generator analysis of the previous section, as much as 185 pounds can be conservatively removed from the JPL projection (vapor generator 89, expander 75, water feed system 22). Scaling up the 90 horsepower Carter projection from 90 to 150 horsepower, using the JPL percentage weight increase for this power range, gives an even lower weight. A tabulation of these results will summarize JPL's weight conservatism for the 150 horsepower systems.

	JPL System Weight at 150 HP		
	JPL Projection	SES Specific Reductions	Carter Projection Scaled Up
Engine Weight, 150 hp ready to run	754 lbs	568 lbs	544 lbs
Relative Weights	100%	75%	72%

A realistic estimate of the JPL mature system costs can be derived as follows. A total of $239 in retail price reduction is identified for specific changes in the stainless steel and superalloy content at 150 horsepower. Scaling this to the 141 horsepower required to give comparable performance to the 150 horsepower standard Otto cycle engine yields a $225 retail price reduction. The net weight of stainless steel and superalloy at 141 horsepower becomes 31 pounds. The total engine weight at 141 horsepower will be approximately 527 pounds, with 496 pounds of other materials (non-stainless or super-alloy). At the JPL average cost for all other material, this yields a further retail price reduction of $213, based on materials variable costs only.

For the OEE equivalent 141 horsepower JPL mature engine, the following realistic weight and only materials variable costs changes result.

	JPL System Weight and Price at 141 HP		
	JPL Projection	SES Specific Reductions	Carter Projection Scaled Up
Engine Weight	702 lbs	527	505
Relative Weight	100%	75%	72%
Retail Price (Impact of Materials Variable Cost Only)	$1781	$1492	--
Relative Retail Price	100	84%	--

3) The Low Cost Reheat Cycle Steam Engine:

Three basic cost advantages result from the variable admission expander with reheat, as opposed to the variable pressure, simple cycle steam engine.

- Variable admission provides a torque speed curve similar to the Stirling cycle so that the maximum installed horsepower can be reduced.

- The reheat cycle redistributes the component sizes towards minimum heat exchanger size with an increase in expander size. The improvement in cycle efficiency directly reduces the boiler heat input and size and reduces condenser heat rejection. The expander is the lowest cost per pound engine component, approaching the specific cost of the Otto cycle "short block", as it is primarily a cast iron component.

The reheat cycle, combined with a variable admission expander, results in a very high efficiency and superior torque/speed characteristic, without resorting to very high peak system pressures. The lower peak pressure reduces the material's content by reducing the stress and loading on all of the high pressure components: pump, boiler, expander and high pressure plumbing.

A preliminary review of a reheat cycle, variable admission steam engine has been made for the JPL equivalent 150 horsepower Otto cycle engine (JPL Chapters 10 and 11). The materials and cost comments in the first two sections of this SES note apply in general. The total installed power is reduced from 141 to 119 horsepower as described in SES's Note 12.

The combined impact of reduced installed power and higher efficiency is a 39 percent reduction in condenser heat rejection and a 48 percent reduction in boiler heat input (or 48 percent lower maximum fuel flow). Lower maximum boiler pressure provides a 23 percent net decrease in boiler stainless steel, including the additional reheat boiler pass.

The expander cylinder head structure is the most critical, high temperature pressure vessel component in the expander. By applying a fixed pressure and temperature scheduling between stages, the expander as well as the boiler structure is considerably simplified. The state point tabulation below illustrates this advantage.

	JPL Fixed Admission Variable Pressure Mature Steam Engine		SES Variable Admission Reheat Fixed Pressure Mature Steam Engine	
	Max. Pressure	Temperature	Max. Pressure	Temperature
1st Stage	2500 psi	1400^0F	1500 psi	1250^0F
2nd Stage	---	---	400 psi	1500^0F

Following the cost methodology of JPL Chapter 11 and the SES design analysis, SES has approximated the cost factors for the reheat cycle, 119 horsepower engine as follows:

Variable Cost	$ 450
Material Overhead & Special Tooling	60
Factory Fixed Cost	236
Manufacturing Cost	836
Corporate Overhead	240
Return on Investment	139
Wholesale Price	1,127
Selling Price	1,465

Of the high fuel economy engines derived by JPL (Brayton single shaft and free turbine, and Stirling) only the JPL single shaft gas turbine is projected to have a lower selling price, disregarding the gas-turbine's potentially higher cost, continuously variable transmission.

Critique by

Steam Power Systems, Inc.
7617 Convoy Court
San Diego, CA 92111

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

10

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-212-10

June 29, 1977

Mr. Richard Burtz, Vice-President and
General Manager
Steam Power Systems
7617 Convoy Court
San Diego, California 92111

Dear Mr. Burtz:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

We are in receipt of your critique of the subject report including related material from Mr. Roy A. Renner and Mr. Jay Carter which was enclosed. Upon completion of the subject report our program was restructured under the sponsorship of the Energy Research and Development Administration (ERDA), Office of Highway Vehicle Systems, as summarized in the enclosure. This explains our response at this time, and includes a summary of our current work.

In the current program we are scheduled to address Rankine engines beginning in late 1977 and continuing for approximately one year. In conducting that work we will be most interested in technical discussions with companies actively engaged in the development of Rankine engine systems. We will address the points raised in your critique, along with those from all other respondees to the Rankine portion of the subject report.

We acknowledge the outstanding multifuel capability of the Rankine and its low emission characteristic. Regarding the several areas of disagreement expressed in the data you submitted, we had no intention of doing other than evaluating heat engines on a common basis. The usage of an "Otto equivalent engine" (OEE) concept was a convenient analytical tool, as was the Delphi concept in dealing with technical complexities that are amenable only to the approach of averaging the opinions of qualified technical experts. We regret that under the cost and time constraints that existed, we were unable to conduct a second iteration of engine development costs which perhaps would have reduced somewhat the cost estimate for Rankine engines. Nevertheless I think you will agree that this is not a pivotal issue in the context of the reference study.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

Steam Power Systems
- 7617 Convoy Court, San Diego, California 92111

NOVEMBER 1975

Comments by Steam Power Systems, Inc.
on the Jet Propulsion Laboratory report
"Should We Have a New Engine?"

The JPL report has been before the public for several months now. It is an impressive piece of work. Its main conclusion, that we do indeed need a new kind of automobile engine, is well substantiated. Volume I is small, light, and easy to read, and is enjoying a wide circulation. Volume II is big, heavy, and difficult to read, and unfortunately is the Volume that we will be dealing with today, because Volume I is more or less derived from Volume II.

The JPL report is receiving wide and expensive promotion. A team of JPL staffers is crisscrossing the country giving "presentations" before interested bodies. Mr. Rhoads Stephenson, the project director, appears on television from time to time, we are told.

We feel that it's time somebody blew the whistle on all this. We feel that it's time someone pointed out what a great many people already know: that the JPL report is, in some very important aspects, a sloppy and irresponsible piece of work. We believe - and we are not alone in this - that the JPL report, bought and paid for by the Ford Motor Company - is at least in part an exercise in special pleading on behalf of the Ford Motor Company specifically, and the Detroit automobile industry generally. We believe that it is part of an effort by the automobile manufacturers to soak up and pre-empt public research funds - which they don't need - primarily to keep such funds away from researchers who might actually produce results that could be disturbing to the auto industry.

Finally - and here again we are not alone - we believe that the prestigious name of the Jet Propulsion Laboratory is being employed in such a way as almost to constitute an abuse of public trust.

Now to get down to cases. There are two main points upon which the JPL report must be taken to task. First, the report makes firmly optimistic predictions about the

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glowing future of two engines, the Stirling and the Brayton; predictions that are unjustified, unfounded, and, in short, rather staggering. No one reading Volume I would ever suspect that these are simply wild guesses. And second, as a necessary part of these predictions, JPL makes a strenuous effort to deprecate and dismiss the Rankine engine, which otherwise is grudgingly admitted to share the low-pollution and fuel-versatility that are allegedly possessed by the Stirling and Brayton.

Specifically, by a series of what must be regarded as deliberate errors or omissions, JPL attempts to prove that the Rankine engine of the future must inevitably be too heavy, too costly, and too inefficient to be worth bothering with. They, in effect, declare that the "Mature" Rankine engines of 1985 or 1990 will be less advanced than the existing Rankine engines of 1975.

Before we turn to actual exhibits from Volume II, a few general remarks might be in order.

The Stirling engine was invented in 1816, and the Brayton, or gas turbine, in 1873. Their theoretical efficiencies - the word "theoretical" must be emphasized - have attracted heat engine researchers for a century. In the last thirty five years, hundreds of millions of dollars have been spent by large corporations attempting to develop these two engines, and yet, as automotive powerplants, they are still in their infancy. They are too heavy, too costly, and too inefficient.

The Rankine or steam engine was well-developed by the end of the 18th century and steam automobiles were running at the end of the 19th century, but modern development of it as an automobile engine dates back a mere ten years or so. Only a few million dollars have been spent on this effort, mostly by small companies, but progress has been steadily made. There is still a long way to go at the present level of expenditure.

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Incidentally, speaking of actual rather than theoretical efficiency, the most efficient heat engines in the world today are the steam engines that generate our electricity.

Now to our specific objections. Time will allow us to hit only the high spots.

1. (Exhibit 1)

These three figures and one table are all from Chapter 12, Volume II. Notice that JPL's own calculations, in the upper right, show that a mature prototype Rankine engine will be available in mid-1984, but that on Table 12-9, in the upper left, the date is mysteriously bumped to 1990. Look what that does to the Rankine development costs - those extra six years and even the costs are incorrectly multiplied. But that figure, $260 million, appears authoritatively in Volume I, where it is characterized as "reasonably accurate for the Mature configuration selected".

Notice also that the "Advanced" Brayton engine is predicted to be ready by 1985, at the same time as the "Mature" Brayton. JPL didn't quite get up the nerve to put this astounding prophecy in Volume I, and even the mature Brayton is called "essentially metalic" and it has a ceramic regenerator. To add insult to injury, JPL predicts in Chapter 7, Volume II, that the "Advanced" Rankine engine using ceramics, can probably never be achieved.

2. (Exhibits 2, 3 and 4)

Now we must unavoidably take a look at one of the so-called "research" methods used by JPL, the DELPHI iteration. This method asks a series of questions followed by a compilation of the answers which are returned to the experts and with the new knowledge, the answers are resubmitted, compiled, returned, etc. until a reasonably close agreement is achieved.

The nice neat graph at the bottom of Exhibit 2 shows the results, right or wrong, of a second iteration for the Brayton. The graph at the top of Exhibit 2, and all of the graphs on Exhibit 3, show the nonsense you can get on a mere questionnaire without the corrective influence of a subsequent iteration. Yet JPL refused to get any iteration, "due to time constraints", and solemnly printed this garbage as if it meant something. Exhibit 4 may shed some light on JPL's motives.

(Read Exhibit 4)

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3. (Exhibit 5)

Two tables are presented with all the engines analyzed by JPL which are astounding comparisons since in Table 10-3 it says that a Brayton in a heavier car can out-accelerate a Rankine with less horsepower. Table 11-16 says that for equivalent performance the 103 horsepower Brayton is equal to the 119 horsepower Stirling is equal to the 141 horsepower Rankine and so on. This is never really proven in the text and only alludes to some remarkable transmission technology as an excuse.

4. (Exhibits 6, 7 and 8)

This is a prime example of the less than careful treatment given the Rankine, and due to an error in the JPL figure 7-15 (original figure in black - corrections in red). The mature Rankine power system is 954 pounds according to JPL- slightly heavier than current technology in pounds per horsepower. But the current Carter point is missplotted! When corrected the current engine is 810 pounds @ 150 HP - lighter than the advanced JPL engine weight of 861 pounds. We estimate a mature power system weight of 635 pounds by 1980. Reference Carter letter (Exhibit).

Comparing the advanced technologies for weight reduction of the three JPL engine types - both Brayton and Stirling are orderly (e.g. (1) current weight/HP (2) Mature wt. improvement (3) advanced technology) - not so for Rankine the procedure is mature heaviest (2) advanced, next (3) and current technology (1) lightest!!

Table 7-5 from the JPL report is a weight breakdown for the Rankine engine which gains weight after 10 years? NOTE THAT THE CARTER ENGINE IS RATED AT 90 HP.

I could obviously give several more examples contained in the Exhibits but due to the limited time we have, I would like to finish my statement with this:

What JPL is suggesting is that you discard the one proven alternate that has demonstrated low emissions and multi fuel capability and which is on the verge of getting better mileage than the internal combustion engine and instead pursue two highly risky concepts that may be doomed to failure even though they have both received four times longer the attention of some of the most astute modern developers and 10 to 50 times more funding to date than the steam engine has.

Table 12-5. Estimated time and cost comparisons for prototype alternate heat engine development

Alternate engine	Year prototype development complete[a]	Maximum (minimum) effective expenditure rate, $million/year		Total direct cost to develop, $million[a]
Mature stirling	1983	16	(9)	< 130
Mature gas turbine[b]	1985	14	(6)	> 95
Advanced gas turbine	1985	14	(5)	> 130
Mature rankine	1990	15	(3)	< 260

[a] At E(P) = 0.75 (15 X 15 = 225)

[b] with ceramic regenerator

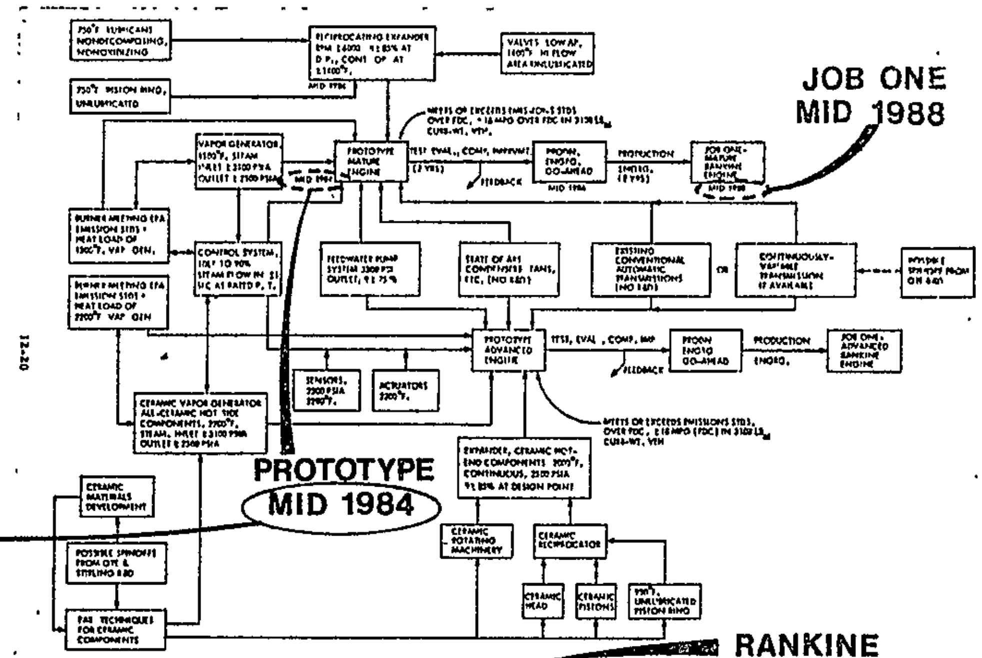


Fig. 12-9. Mature Rankine Engine R&D network

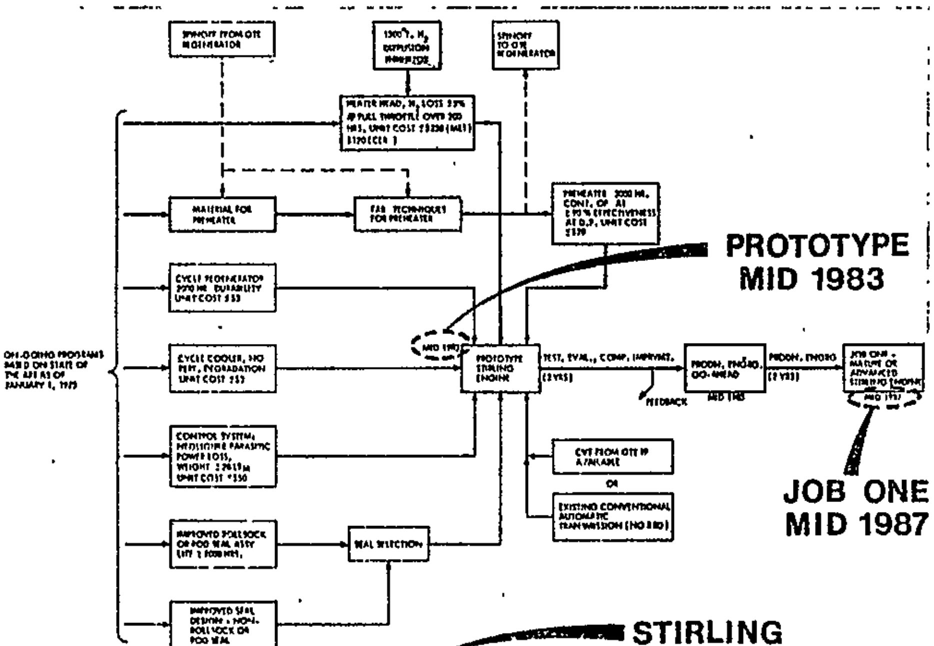


Fig. 12-1. Stirling Engine R&D network

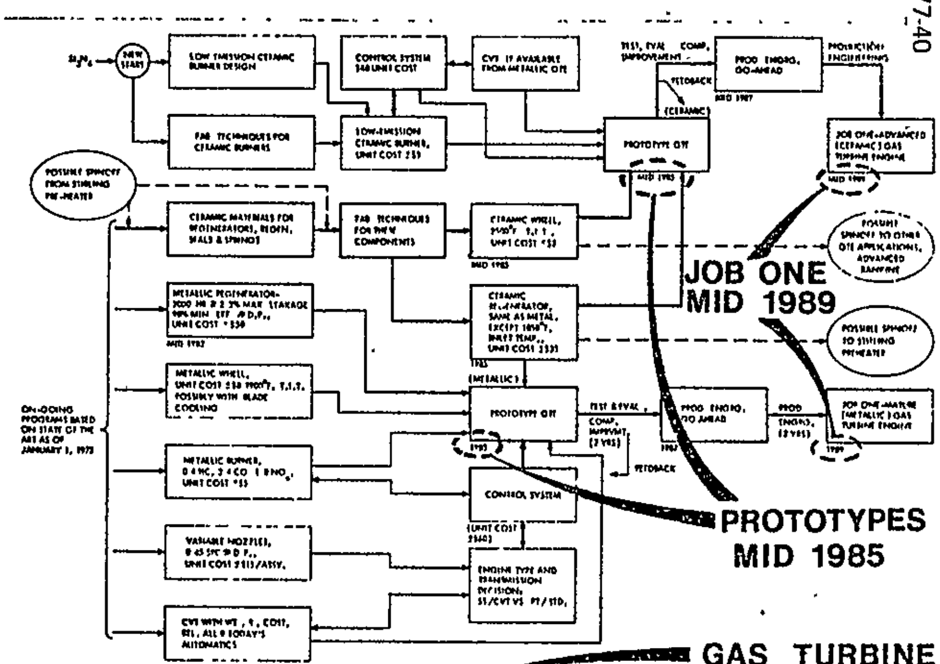
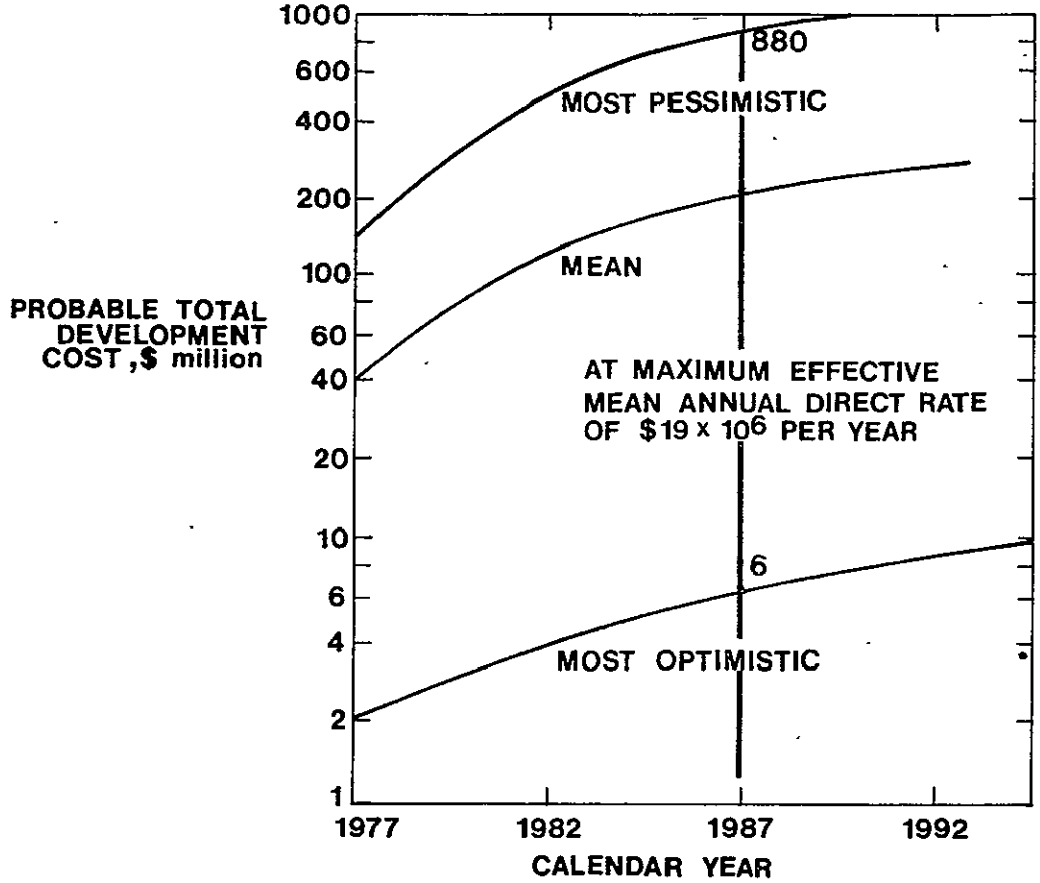
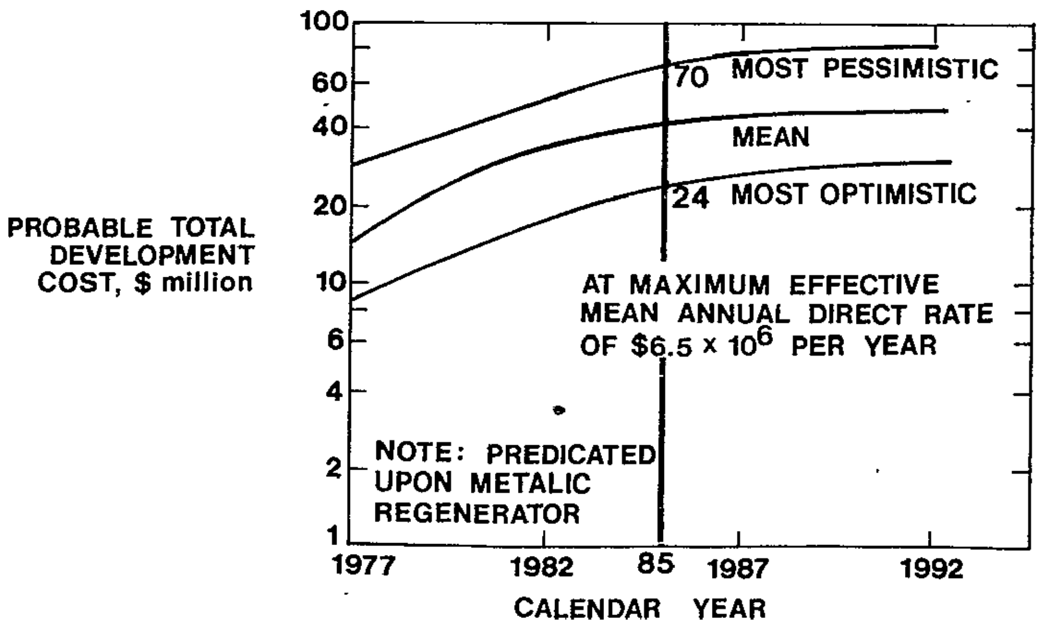


Fig. 12-5. Gas Turbine Engine R&D network



MATURE PROTOTYPE ENGINE

Estimated cumulative total direct costs for accomplishment of critical Gas Turbine Engine (Fig.12-8) and Rankine Engine (Fig.12-12) R&D tasks



MATURE PROTOTYPE ENGINE

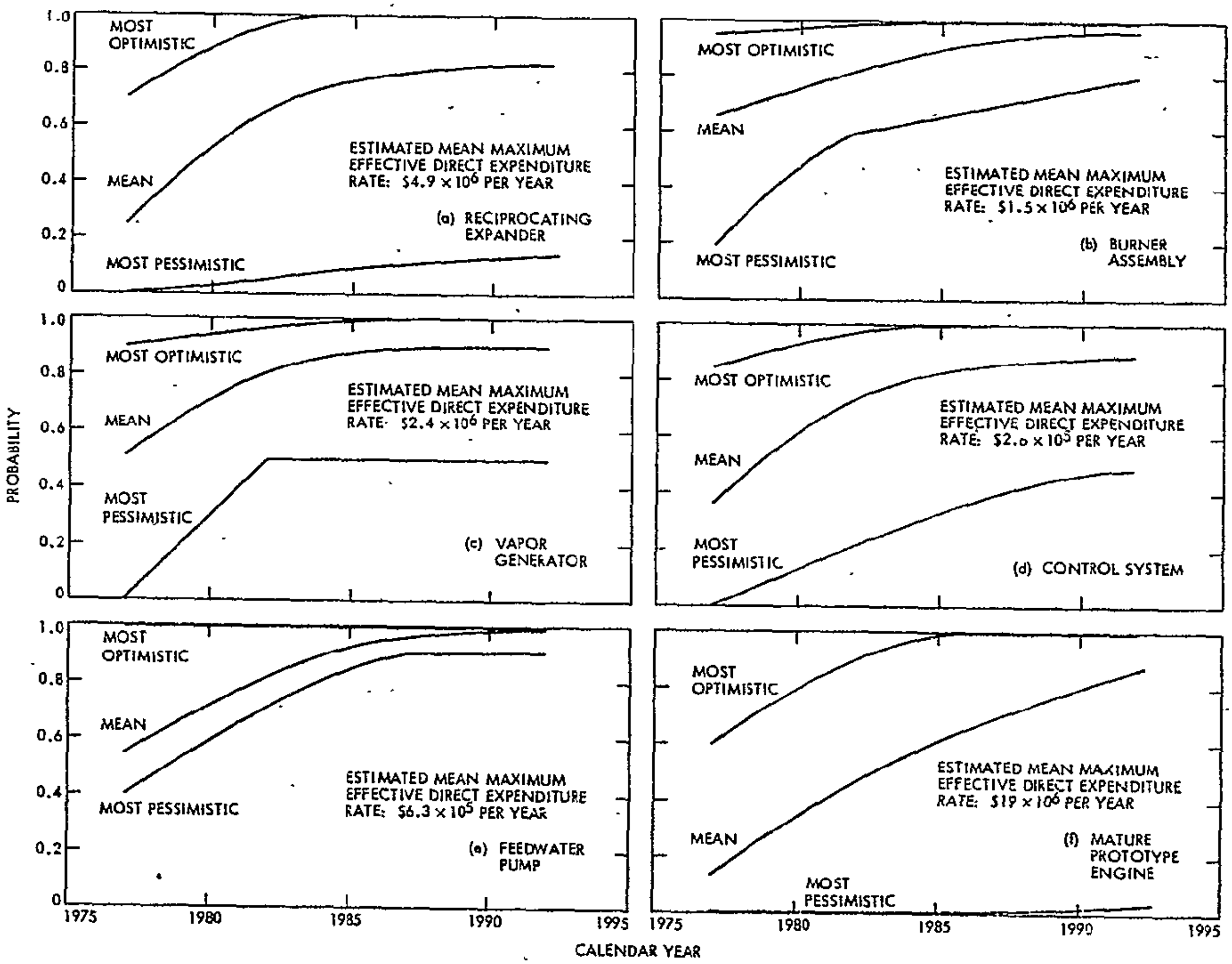


Fig. 12-11. Estimated probability of accomplishment of critical mature Rankine Engine R&D tasks at estimated maximum effective expenditure rates

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(4)

REPORT OF VENDOR TELEPHONE CONVERSATION

Caller: Roy Renner of Mechanical Engineer Consultant

Person called: R. Burtz of STEAM POWER SYSTEMS, INC.

Phone No. (415) 443-2992 Date Nov. 13, 1975 Time 3 P.M.

Subject: JPL Delphi Iteration Methods

Context: Roy returned my call inquiring about his statement that . . . "Subsequent to sending in his response (JPL Questionnaire), I learned through telephone conversations that plans for a second iteration had been dropped." My question was how did this occur? His response was as follows:

1. He had called about 2 months later, in February, 1975, on another matter, and asked when the 2nd iteration would be out. He had wanted another chance since he knew he had estimated on the high side.

2. The only reply he got then and later on a visit to JPL was that "plans for a second iteration were dropped due to a lack of time before publishing."

3. They never called him back or inquired about his guess even though Volume II of the report says ". . . expenditure rates were $3 and $19 million, respectively. However, the latter figure is so heavily biased by the astronomical cost estimate of one pessimist (Renner), that we have reduced it to $15 million by discounting the pessimist's estimate."

In cold fact, the report uses the $19 million figure, and does not reduce it to $15 million.

C-5

Table 11-16. Variable costs and selling price of 150-hp equivalent performance[a] engines

Engine	Variable cost, $	% OC	Selling price, $	% OC
UC Otto, oxidizing catalyst, 150 hp	346 ±35	-12	1255 ±120	-5
UC Otto, 3-way catalyst, 150 hp	394 ±35	DNA[b]	1320 ±120	DNA
SC Otto cycle, 3-valve 150 hp	395 ±35	—	1320 ±120	—
Diesel, 156 hp	505 ±50	28	1489 ±130	13
SC Otto, direct injection, 153 hp	418 ±45	6	1377 ±130	4
Brayton single shaft, 103 hp	385 ±70	-2	1392 ±140	5
Brayton free turbine, 107 hp	483 ±70	22	1604 ±140	22
Stirling 119 hp	524 ±75	33	1619 ±140	23
Rankine 141 hp	669 ±75	69	1781 ±140	35

[a]See Chapter 10 for definition of equivalent performance.

[b]DNA: does not apply.

[c]Requires a continuously variable transmission; at no cost increment over 3-speed automatic. (Refs. 11-8, 11-9).

Table 10-3. Weight and horsepower of OEE vehicles

Engine type	Vehicle class: Small — Curb weight, lb	Small — Design max. power, hp	Compact — Curb weight, lb	Compact — Design max. power, hp	Full-size — Curb weight, lb	Full-size — Design max. power, hp
UC Otto (baseline)	2100	70	3100	125	4000	175
SC Otto	2110	70	3150	127	4090	179
Diesel	2310	74	3340	131	4220	182
Brayton (single shaft)	1880	49	2660	86	3400	118
Brayton (free turbine)	1920	51	2710	89	3470	123
Stirling	2140	57	3050	99	3890	137
Rankine	2220	66	3200	119	4130	166

"COMPACT CAR 0 TO 60 IN 13.5 SECONDS"

"FULL SIZE CAR 0 TO 60 IN 11.5 SECONDS"

5

6

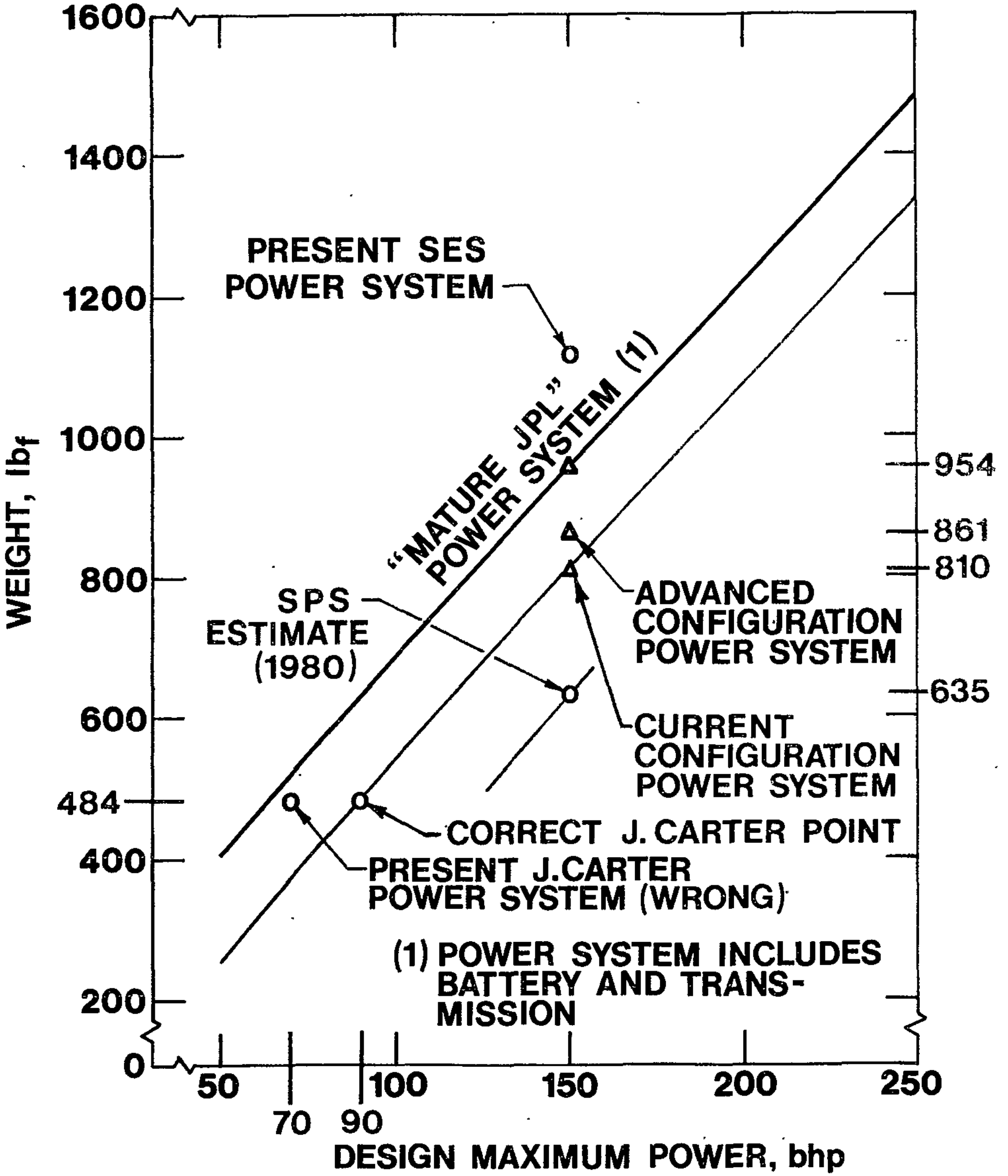


Fig. 7-15. Projected Rankine engine weights (Mature configuration)

7

COMPARISON OF ENGINE TECHNOLOGY PROGRESS (JPL)

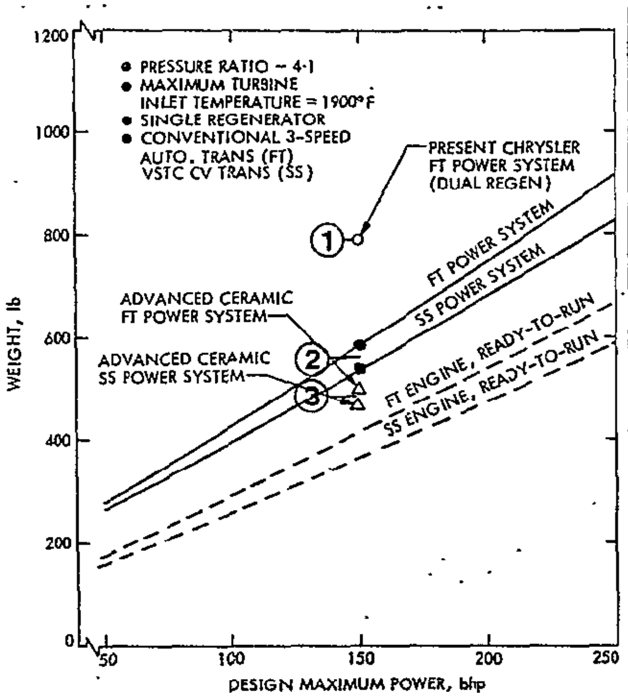


Fig. 5-12. Open-cycle Brayton engine weights (Mature configuration)

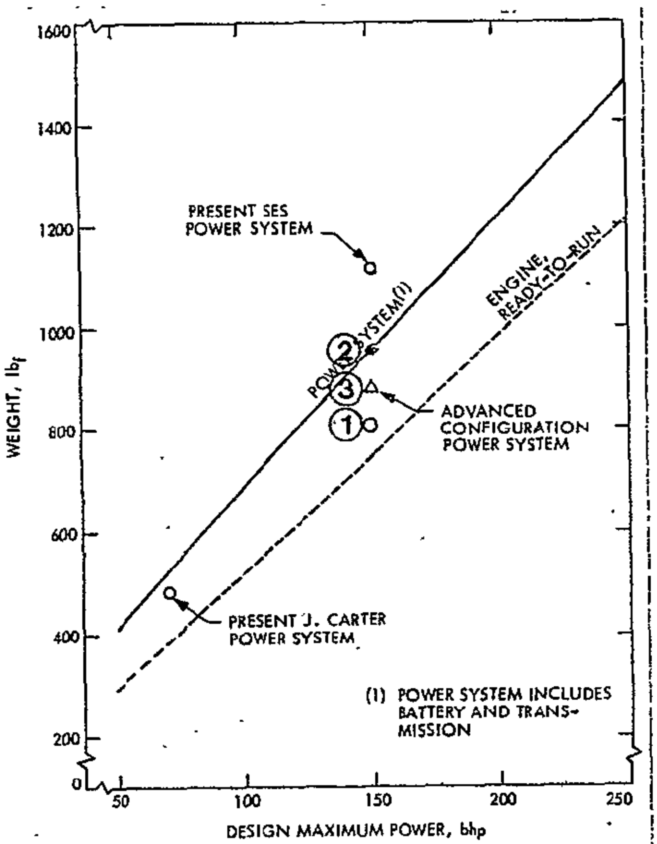


Fig. 7-15. Projected Rankine engine weights (Mature configuration)

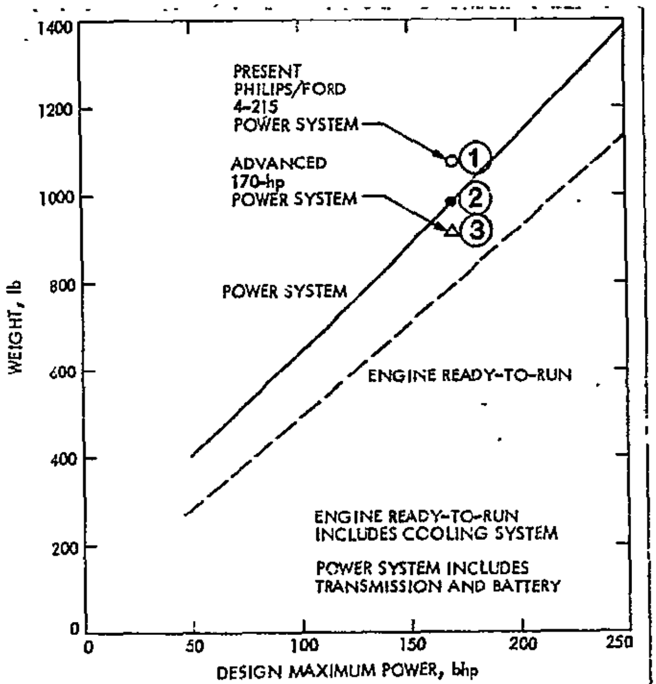


Fig 6-26. Stirling powerplant weight (Mature configuration)

(1) CURRENT TECHNOLOGY (1974)

(2) MATURE TECHNOLOGY (1985)

(3) ADVANCED TECHNOLOGY (1990+)

Table 7-5. Rankine engine parts breakdowns

Component or subassembly	Present configurations: J. Carter (90 hp) Weight, lb	Present configurations: SES (150 hp) Weight, lb	Mature configuration: Conjectural (150 hp) Weight, lb	Mtl.[a]	Proc.[b]	Advanced configuration: Conjectural (150 hp) Weight, lb	Mtl.[a]	Proc.[b]
Vapor generator assembly	(98)	(165)	(164)			(128)		
Preheater and evaporator tube fins			5 / 10	J / B	10	80	I	76
Vapor generator tubing			99	E	28			
Vapor generator housing			25	E	54	20	E	54
Insulation			3	Z	07	5	Z	07
Combustor atomizer			3	E	80	3	E	80
Combustor blower			2	J	01	2	J	01
Combustor liner			1	H	54	2	I	76
Ignition assembly			5	Z	00	5	Z	00
Air cleaner ducts, diffuser, etc.			11	Z	00	11	Z	00
Expander Assembly	(76)	(428)	(221)			(172)		
Cylinder block			68	A	61	65	A	61
Steam chest(s)			27	E	63	Manifold, steam chest and head integral with boiler subassembly		
"Head"/valve/valve seat/spring subassemblies			10	H	80	3	(?)	(?)
Cylinder liners			6	E	68	6	I	78
Vapor generator to expander, piping			8	E	28	--	--	--
Piston crowns			2	E	63	1	I	76
Skirts and rings			10	A	61	3 / 4	A / I	76 / 61
Connecting rod subassemblies			12	D	63	12	D	63
Crankcase			25	J	61	25	J	61
Bearings			5	D	07	5	D	07
Crankshaft			30	A	63	30	A	63
Lubricant pump and filter			11	Z	07	11	Z	07
Lubricant			7	Z	07	7	Z	07
Condenser Assembly	(41)	(113)	(88)			(88)		
Condensor			70	J	14	70	J	14
Fan and shrouds			18	Z	00	18	Z	00
Fuel control system	incl. in vapor generator	(12)	(12)	Z	00	(12)	Z	00
Power control system	(13)	(10)	(15)			(15)		
Throttle valve			5	Z	00	5	Z	00
Electronic components			10	Z	00	10	Z	00
Water feed system	(67)	(90)	(198)			(198)		
Feed and condenser pumps			30	Z	07	30	Z	07
Feedwater preheater	none	none	35	B	78	35	B	78

20-28 Series

STATE-OF-THE-ART FOR A 150 HORSEPOWER CVT TRANSMISSION

DESIGN PARAMETERS

SERIES 24	PUMP WT.	+	MOTOR WT.	+	CONTROL WT. (15%)	= TRANSMISSION WT.
	273	+	266	+	81	= 620 POUNDS

Continuous working pressure at rated speed . . . . 3000 psi
Heavy-duty capability. Normal relief valve setting . . . . 5000 psi
Shock load capability. Proof pressure rating . . . . 10,000 psi
Safety limit (actual test) . . . . 20,000 psi

SERIES AND SPECIFICATIONS

SERIES	MAX. DISP. IN.³	TORQUE PER* 1000 PSI FT.-LB.	HP PER 1000 PSI* @ 1800 RPM	HP PER 1000 PSI* @ 1200 RPM	MAX. SHAFT SPEED RPM
20	2.03	27.0	9.21	6.14	3800
21	3.15	41.8	14.30	9.53	3500
22	4.26	56.6	19.35	12.90	3200
23	5.43	72.0	24.67	16.45	2900
24	7.24	96.0	32.90 X 5 = 164.5 HP	21.90	2700
25	10.12	134.5	46.00	30.70	2400
26	13.87	184.0	63.00	42.00	2100
27	20.36	270.0	92.50	61.67	1900
28	34.08	453.0	154.84	103.20	1800

*Theoretical Values

VARIABLE DISPLACEMENT PUMP, VARIABLE DISPLACEMENT MOTOR DIMENSIONS (APPROX.)

SERIES	LENGTH*	WIDTH*	HEIGHT*	MOUNTING FLANGE SAE SIZE	DRIVESHAFT	(APPROXIMATE) P. V. WT.-LBS.	(APPROXIMATE) M. V. WT.-LBS.
20	14	8 3/4	10 9/16	C	14T-12/24 Pitch**	97	109
21	14 11/16	10	11 1/4	C	14T-12/24 Pitch**	118	129
22	15 3/16	10 1/2	11 1/2	C	14T-12/24 Pitch**	135	146
23	15 3/4	11 7/8	12 3/8	C	14T-12/24 Pitch**	173	184
24	19 13/16	13 3/8	13 5/8	D	13T- 8/16 Pitch**	273	266
25	22 1/16	14 1/4	15	E	13T- 8/16 Pitch**	359	370
26	23 7/8	14 1/4	16 3/8	E	13T- 8/16 Pitch**	515	539
27	24 7/8	16 7/8	17 1/2	F	15T- 8/16 Pitch**	592	602
28	26 7/8	18 9/16	17 31/32	—	23T- 8/16 Pitch**	1035	1045

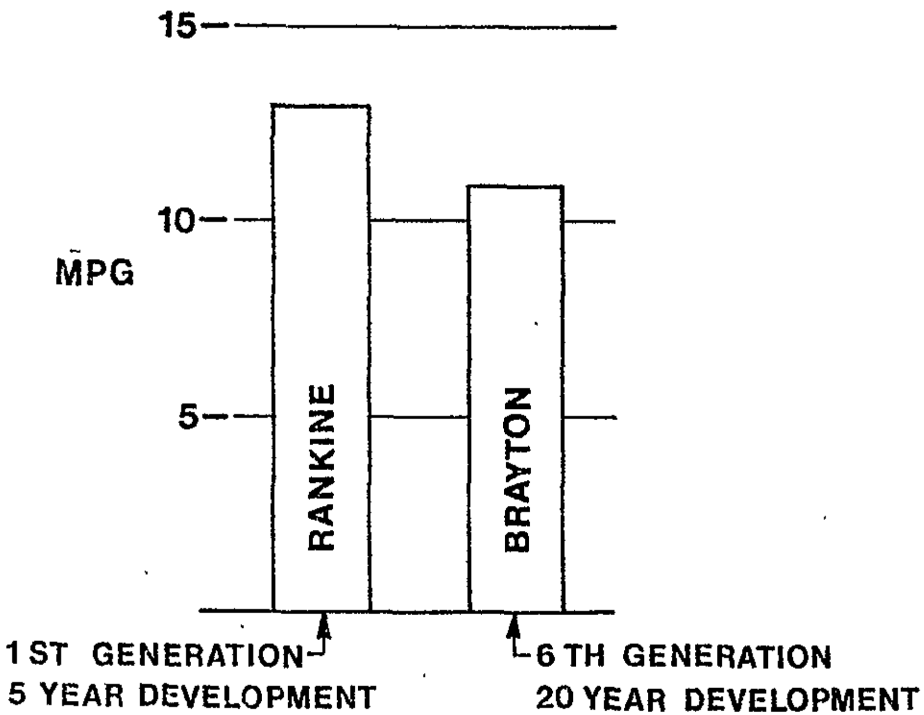
*Maximum Dimensions In Inches **SAE Taper And Other Shafts Available

FIXED DISPLACEMENT MOTOR DIMENSIONS (APPROX.)

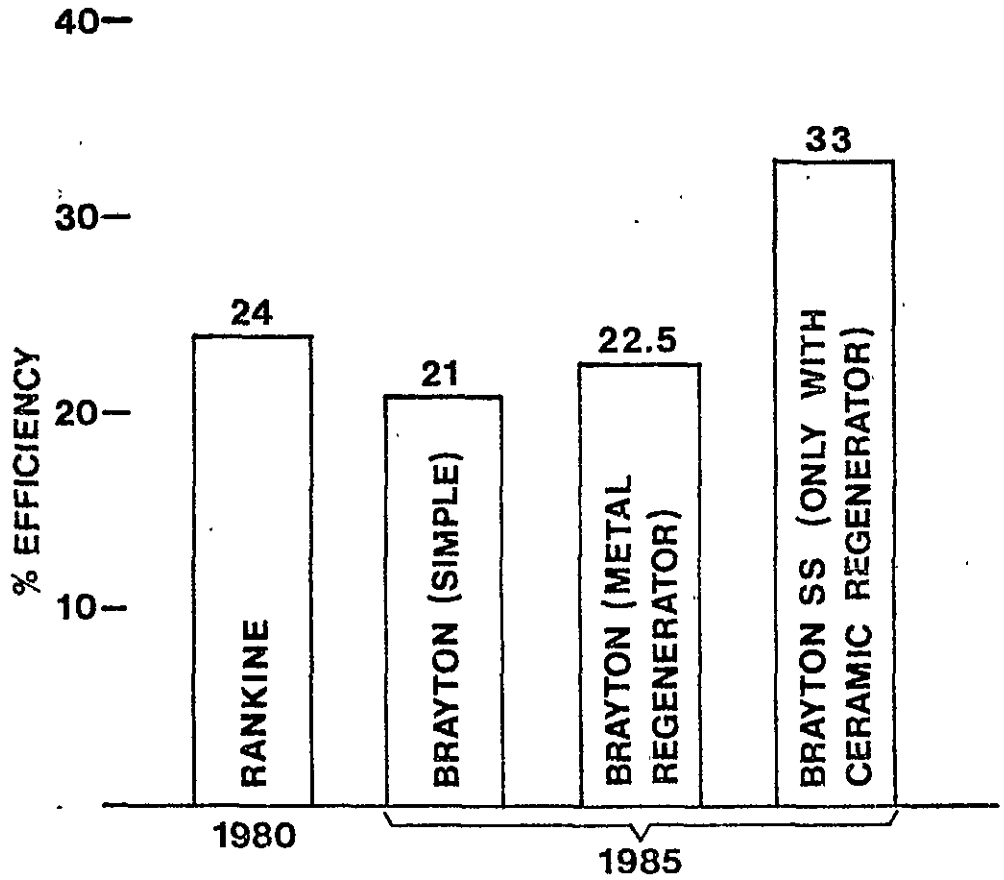
SERIES	LENGTH*	WIDTH*	HEIGHT*	MOUNTING FLANGE SAE SIZE	DRIVESHAFT	WT.-LBS.
20	13 9/16	6 1/2	6	C	14T-12/24 Pitch**	60
21	14 5/16	6 5/8	6 3/8	C	14T-12/24 Pitch**	76
22	15 1/16	6 7/8	7 1/2	C	14T-12/24 Pitch**	88
23	15 3/4	7 5/8	8 1/8	C	14T-12/24 Pitch**	104
24	17 5/8	8 1/2	8 1/8	D	13T- 8/16 Pitch**	154
25	18 13/16	10 3/8	10	E	13T- 8/16 Pitch**	175
26	22 13/32	14 1/4	16 5/8	E	13T- 8/16 Pitch**	230
27	21 5/16	12 5/8	11 3/4	F	15T- 8/16 Pitch**	338
28	19 1/16	18 9/16	17 31/32	—	23T- 8/16 Pitch**	685

*Maximum Dimensions In Inches **SAE Taper And Other Shafts Available

1974 TEST RESULTS FEDERAL URBAN DRIVING CYCLE 3000 LB INERTIA WT.



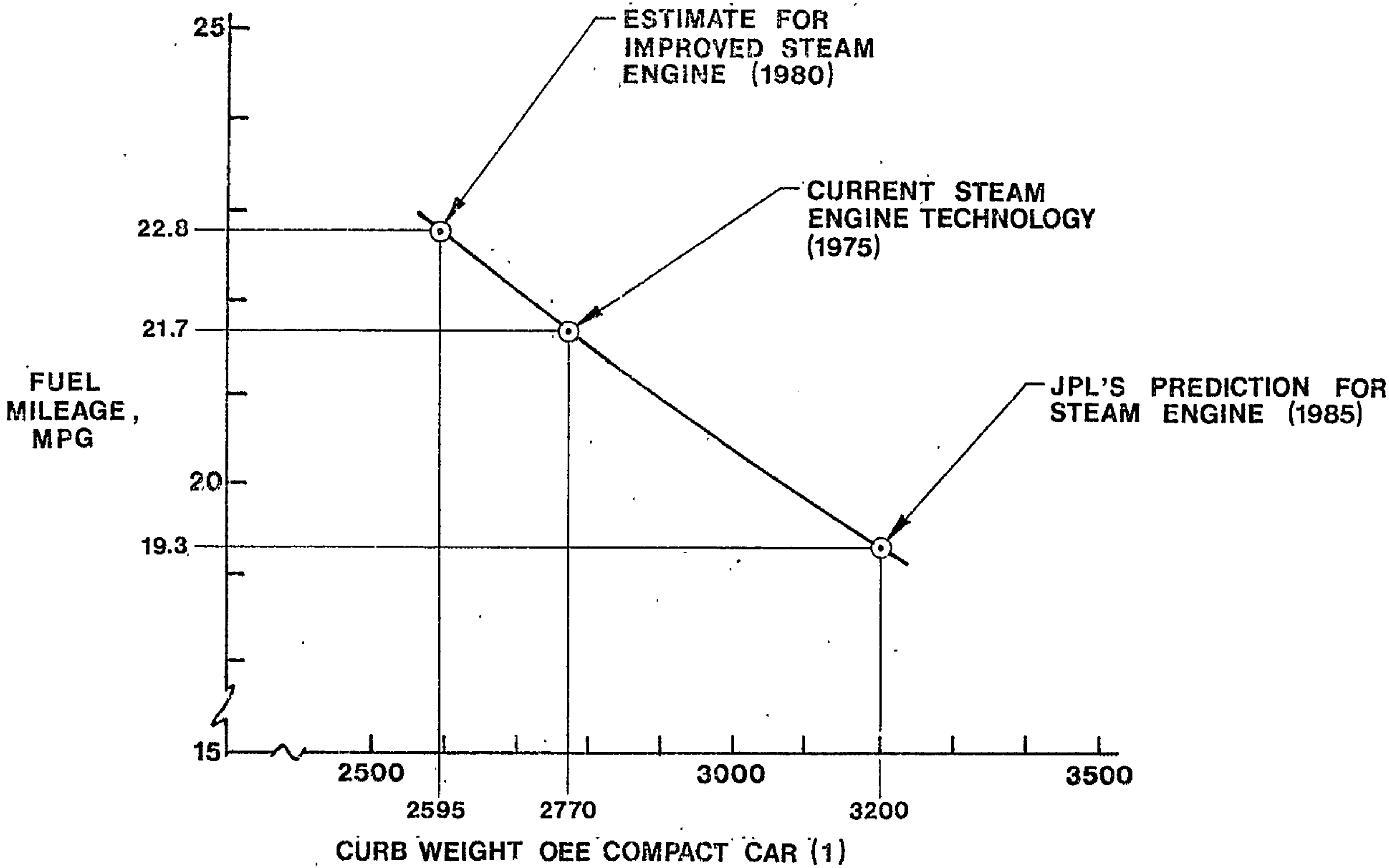
PREDICTED BRAKE THERMAL EFFICIENCIES



10-16

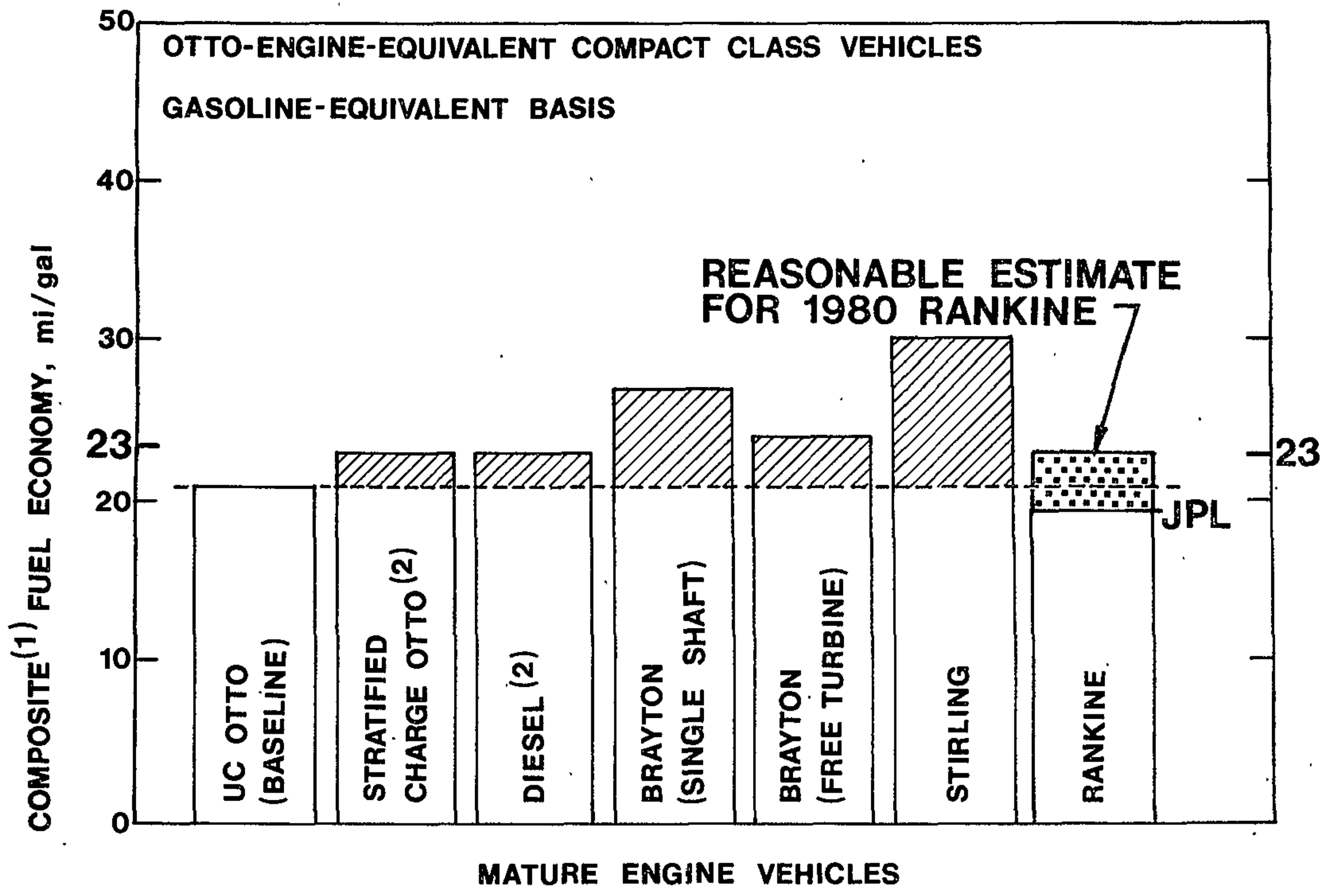
77-40

10



(1) IDENTICAL PASSENGER AND LUGGAGE CAPACITY, IDENTICAL ACCELERATION AND TOP SPEED.

EFFECT OF ENGINE WEIGHT ON VEHICLE MILEAGE



(1) RECIPROCALLY WEIGHTED MEAN OF URBAN (55%) AND HIGHWAY (45%) FUEL ECONOMIES.

(2) CALIBRATED TO MEET 2.0 g/mi NOx STANDARD.

Fig. 14. Fuel economy potential of Advanced configuration heat engines

Table 11-10. Variable costs of equivalent-performance alternate engines

	Stirling (119 hp)		Rankine (141 hp)		Brayton free turbine (107 hp)		3-way catalyst (0.41/3.4/0.4) Otto cycle (150 hp)		Oxidizing catalyst 0.41/3.4/2.0 Otto cycle (150 hp)	
Material type	Weight, lb	Cost, $	Weight, lb	Cost, $	Weight, lb	Cost, $	Weight, lb	Cost, $	Weight, lb	Cost, $
Cast iron	53	13	102	25	127	32	250	50	250	50
Carbon steel	104	31	76	21	—	—	250	75	250	75
Alloy steel	8	4	16	8	9	5	5	3	5	3
Austenitic stainless	58	43	160	120	15	11	—	—	—	—
Ferritic stainless	—	—	—	—	2	1	—	—	—	—
Precipitation hardening stainless	—	—	—	—	5	3	—	—	—	—
Superalloy	7	26	10	37	11	41	—	—	—	—
Ceramic	15	15	—	—	14	14	—	—	—	—
Aluminum alloy	126	70	96	53	1	1	20	11	20	11
Copper alloy	—	—	—	—	—	—	20	15	20	15
Miscellaneous[a]	183	247	249	307	109	300	120	143	125	102
Variable material[b]	554	449	709	571	293	408	695	319	700	278
Variable[c] labor (hrs)	10	75	13	98	10	75	10	75	9	68
Total variable cost		524		669		483		394		346

[a]Not broken down (conventional auto materials), non-homogeneous or miscellaneous and purchased parts. Includes power and fuel control, auxiliaries and emissions control, where applicable.

[b]No material or labor overhead.

[c]Includes foundry labor.

. . . normalization of the engine designs and costs to equivalent performance levels. This factor is of significant benefit to both the Stirling and Brayton engines. If these engines were costed on an equivalent horsepower basis rather than an equivalent vehicle performance basis, their costs would be significantly higher."

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Jay Carter Enterprises, Inc.

PHONE 817/569-0181

RESEARCH AND DEVELOPMENT ENGINEERS

P. O. BOX 684
BURKBURNETT, TEXAS 76354

October 9, 1975

Mr. Richard Burtz
Steam Power Systems
7617 Convoy Court
San Diego, California 92111

Dear Richard:

Thank you for calling and letting me know about the public release of the JPL report. Normally when we see a report that doesn't do justice to the potential of the steam engine we regard the authors of that report as either uninformed, misinformed, or biased. This should not have been the case concerning the JPL report, and this concerns us.

I made a special trip to see the authors in order to discuss some misconceptions they had on steam engines, and to explain the results of EPA's tests on our steam powered Volkswagen Squareback. I gave them the projected weights and efficiencies of our second generation steam car, which were based on results of the first steam car.

I was surprised to see that their projected weight of a 150 h.p. mature steam system was 754 lbs., since the total weight of our 90 h.p. system was only 335 lbs. Scaling our system up to 150 h.p. and neglecting any improvement in horsepower to weight ratio indicates a total power system weight of 558 lbs. (196 lbs. less than their projected 150 h.p. mature system).

We now have the steam system which will go into D.O.T.'s Paratransit Vehicle running, and the weights are actual. The horsepower has been increased from 90 to 100 h.p., and the weight reduced from 335 to 322 lbs. The horsepower to weight ratio of this system scales up to 483 lbs. for a 150 h.p. steam system, again neglecting improvement in horsepower to weight ratio. This is only 64% of the projected weight of the mature 150 h.p. steam system. Enclosed is a component weight breakdown

We were also surprised at the poor fuel economy projections of their mature 1400°F steam system. This is in error as much as their weight projection. Based on the engine map for the second generation system which is

Mr. Richard Burtz
October 9, 1975
Page 2

enclosed, the projected fuel economy over the urban driving cycle is 18.5 mpg at a vehicle test weight of 3500 lbs. and a steam temperature of 1050°F. This fuel economy is 10% better than their projection for a mature steam system operating at 1400°F.

JPL has more than just an obligation to fulfill its contract with Ford. Because many national long range decisions may be made from the results of their report, they have an obligation to be as fair and unbiased in their appraisal as possible. Their extreme conservative attitude toward the steam system and their unwarranted optimism with the gas turbine are a gross misuse of public trust. Even with all the money and time which has already been spent on the gas turbine, the best present gas turbine car cannot approach the fuel economy and emissions of our first prototype steam car. Turbine power enthusiasts are still dealing with projections from classical theory, and have no running vehicle that even closely supports their claims. Obviously, these enthusiasts must have some very powerful lobbyists.

Dick, I agree with you, nobody can afford to let this report go unquestioned. If I can help let me know.

Sincerely,

Jay Carter, Jr.

JC:jt

P.S. You have my permission to use this letter if it would help.

STEAM SYSTEM WEIGHT

Projected Second Generation		Actual Second Generation
76	Expander	79
98	Boiler; atomizer, blower, D-C motor, and controls	84
18	Feedwater pump, condensate pump, and oil return pump	10.2
29	Water tank and three gallon water	(29) est.
12	Centrifuge and accessory drive	12.5
3	Throttle valve	3
8	Accumulator	8
10	Relays, vibrators, coils and electronics	8
6	Condenser fan and clutch	13.5
25	Dual rotor alternator	19.5
--	Water preheater	5
35	Condenser	(35) est.
15	Starter	15.5
335#		322.2#

(16)

ROY A. RENNER
MECHANICAL ENGINEER
2020 RESEARCH DRIVE - LIVERMORE, CA 94550
(415) 443 2992

November 11, 1975

Mr. Richard Burtz, General Manager
Steam Power Systems, Inc.
7617 Convoy Court
San Diego, CA 92111

Dear Dick:

Enclosed is a statement explaining my response to JPL's DELPHI questionnaire regarding Rankine engine development costs. The statement also indicates that had a second iteration of the DELPHI process been carried out, my estimates would have been greatly modified.

As summarized on Page 12-8 of the JPL Report: Volume 2, there are two important ingredients in total engine development costs: the first is the expenditure rate per year, and the second factor is the number of years of development required. It should be noted that the estimated expenditure per year is about the same for all engines considered ($14 - 16 million/year.) The expenditure rate for Rankine is given at $15 million/yr, not including my "astronomical" estimate. So, JPL's high development cost for Rankine engines comes from the number of years and not the annual rate. According to Table 12-5, the Mature Rankine prototype would be available in 1990. This is based upon a 75% probability of achievement. You should be aware that my original time estimates gave E(p) as 0.50 for 1982 and 0.80 for 1987, which would work out to be E(p) = 0.75 in 1986. Someone must have been a lot more pessimistic than myself, if the mean value of the response came out to be 1990.

My "second iteration," which I offer to you here, would certainly include a shorter development time, taking note of the presently steep learning curve. It seems entirely reasonable that a "mature prototype" could be built in the seven year period 1975-1982. Using my revised $14 million/yr Rankine R & D expenditure rate, the total direct cost would be about 98 million. Since this is less than total R & D costs given for most of the other engines, there is no apparent reason to discriminate against the Rankine engine on this basis. (Note the odd arithmetic in Table 12-5, in which $14 million per year until 1985 yields a total of $95 million for the mature gas turbine).

I hope the enclosure is useful. If you have any questions, please call.

Sincerely,

Roy A. Renner

Roy A. Renner

ROY A. RENNER
MECHANICAL ENGINEER
2020 RESEARCH DRIVE · LIVERMORE, CA 94550
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November 11, 1975

STATEMENT BY ROY A. RENNER,
CONCERNING RESEARCH AND DEVELOPMENT
COSTS FOR STEAM AUTOMOBILE ENGINES

Introduction

The Jet Propulsion Laboratory recently released the results of a study entitled, "Should We Have a New Engine?" This study has stimulated a great deal of interest and comment in both engineering and non-technical circles.

One part of the JPL study was an estimate of possible future research and development costs for different alternative automobile engines. These estimates were a composite of opinions solicited from a number of experts outside of JPL. In gathering this information, JPL used a form of DELPHI technique, in which respondents have an opportunity to refine their estimates through a succession of questionnaires. There is normally an information feedback to the respondent after each questionnaire, so that the respondent has the benefit of at least some of the composite group thinking.

Although originally planned as a DELPHI process, JPL's inquiry on future steam engine development costs ended with a single questionnaire. I was one of the outsiders queried on this subject. After reviewing JPL's final report, I found that my cost estimates were considerably higher than those of the other respondents. While my first estimate is not necessarily erroneous, it is now evident to me that it was conceived in a context which was quite different than intended by JPL.

The purpose of this statement is to explain the context of my original response; and to offer a new estimate which may be of interest to readers of the study.

Original Estimates

I originally gave two R & D cost estimates: one was a minimum annual rate of expenditure, below which an insufficient progress would be made; the other was a maximum annual rate, beyond which additional expenditures would buy no further progress. These two estimates were $8 million/yr and $75 m/yr, respectively. The probability of achieving a mature steam engine prototype, ready for production go-ahead, assuming the maximum expenditure rate was estimated as 50% by 1982, 80% by 1987, and 95% by 1992.

I would now reduce both the dollar amounts and the time-to-accomplishment considerably, with the realization that the estimates were intended to fit a rather limited context.

Chronology of the DELPHI Study

The questionnaire was accompanied by a letter dated December 26, 1974. My response was returned to JPL December 31, 1974. The instructions indicated that the means and extremes of all responses would be made known to the participants in several weeks. Sometime subsequent to sending in my response, I learned through telephone conversations that plans for a second iteration had been dropped.

Rationale for My Original Assumptions, and Changes That Would be Made

1. An industry-wide plus government participation in R & D was assumed. A recent briefing by JPL on the study used a context of "single effort." On these grounds, I would reduce the maximum by at least a factor of 2.5.
2. I was influenced by a personal preoccupation with total costs. This was clearly my error, since the JPL instructions called for labor plus materials only, and without including overhead costs. Consequently, all of my indicated costs should be reduced further by a factor of about two.
3. "Production Readiness" was assumed. There is a vast difference in the engineering responsibility, cost, and time for readying a prototype for production, vs. only the demonstration of technical potential. Testimony of the Ford Motor company before the U.S. Senate in 1973 revealed plans to spend $117 million/yr for the development of emission controls for the internal combustion engine (Ref. 1). General Motors undoubtedly had figured on at least a comparable sum. In the light of these annual expenditures of hundreds of millions of dollars, I didn't think that $75 million per year to be spend on a promising alternative to the ICE was out of line at all. To expend very much less would signify play-acting, rather than a significant and serious national commitment.

   A curious fact has emerged regarding the term, "Production Readiness." In the questionnaire I received and responded to, the goal of the estimate was:

   "Mature reciprocating steam engine prototype, ready for production go-ahead, meeting or exceeding the above emission standards over FDC, with fuel economy $\geq$ 17 mpg over FDC in 3100 lb curb-weight vehicle."

The emphasis by underlining is mine. I emphasize this because this phrase was omitted from the statement of goals as published in the JPL final Report, Vol. II, Table 12-4.

If the R & D process were relieved of the enormous responsibility of pre-production engineering, then I could with a clear conscience reduce the time to achieve the desired result. A small reduction in the annual rate of expenditure over that period might also be warranted. If a serious commitment to work toward production readiness were to emerge, however, the responsibilities and costs would rise.

4. Interperetation of "Maximum Effective Total Expenditure Rate." Perhaps I took too literally the statement in the questionnaire, "--beyond which any additional expenditures buy no further progress--." Respondents were asked for maximum and minimum rates of expenditure, but not recommended rate. Perhaps recommended and maximum were synonymous in the minds of some.

5. Other Considerations

Subjectively, I now need to evaluate the impact of other considerations. Two examples will be given:

A. The time to develop a "Mature Prototype" meeting the JPL technical specifications (Ref. 2) may be shorter than for other competing engines. Recent developments at a number of steam research organizations indicate to me that many of the technical goals for performance, fuel economy, configuration, and system weight can be met in less than five years. Some of these goals will be met without "maximum effective R & D expenditures.

B. Balancing the above optimistic outlook is the considerable effort that might be required to develop low-cost, price competitive hardware. Since this was included as a consideration in the JPL inquiry, R & D cost and time must be added back into the estimate.

New Estimates

In the light of the above considerations, my drastically revised estimates are given below. Again I wish to emphasize that the original figures were not necessarily incorrect in the assumed context. The new figures are adjusted for the purpose of more closely matching the intent of the JPL study as now perceived in hindsight.

1. Maximum Effective Total Expenditure Rate, for a mature Steam Engine Prototype (Not for production readiness). Direct Cost only, not including overhead, for a "single-effort" : (See Ref. 2)

   $14 million/year

2. Minimum Effective Total Expenditure Rate, below which insufficient progress is made: (See Ref. 2)

   $4 million/year

3. Development Period to achieve a high probability* of meeting all requirements for a mature prototype (not production readiness): (See Ref. 2)

   7 years, 1975-1982

   (* Probability of greater than 75%)

Total Direct Cost, 1974 dollars, not including overhead, for a seven-year development program at the maximum rate:

$98 million

Comments

The remarkable similarity of the $14 million annual rate to the mean estimates for other engines, given in JPL-Vol. II - Table 12-5 should not be regarded as coincidental or deliberate. There are, in fact, many similitudes in the problems to be solved in each of these constant-combustion engines. Emphasizing once more, my view is that these figures for all competing engines may be low if a true and serious national commitment is intended. However, with this revision we have at least on a common base for consideration.

References and Notes

1. "Automotive Research and Development and Fuel Economy," Hearings before the Committee on Commerce, U.S. Senate, May-June 1973, U.S. Government Printing Office, Serial No. 93-41.

2. See explanation of R & D goals in Chapter 12, "Should We Have A New Engine?" Vol. II, Jet Propulsion Laboratory, Aug. 1975.

3. As an indication of alternative engine R & D costs, it is understood that the Philips Laboratories have spent approximately $80 million (1970's equivalent dollars?) on the development of Stirling engines. Good results are being obtained, but much more will need to be spent before the engine is considered suitable for automobiles. Gas turbines, on the other hand, have already been the beneficiary of world-wide developments since the 1930's, undoubtedly representing some billions of dollars. This included the knowledge and technology that has been built up in jet engine development and manufacture.

Roy A. Renner
Mechanical Engineer

RAR:tt

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Evaluation of the JPL Report presented at the 1975 Society of Automotive Engineers Detroit Automotive Engineering meeting in rebuttal to the JPL presentation of "Should We Have a New Engine" October 16, 1975, by Richard D. Burtz, Steam Power Systems, Inc.

The conclusion that engines of the future will have to be non-polluting and have a broader fuel base than the I.C.E. is encouraging to those of us involved in the research and development of alternate engines. It is also heartening to see that of the three basic types of engines which fulfill these requirements, the belief exists that they can eventually exceed or equal the fuel efficiency of internal combustion engine types.

We do not understand, however, the disparity in the degree of optimism with which these various engines are viewed. The Brayton Cycle or gas turbine has received every benefit of doubt and what we consider to be an extremely optimistic evaluation while the Rankine Cycle or steam engine is the object of an overly pessimistic review. Let me cite some examples.

The Brayton Cycle

In order to achieve roughly a 100% increase in vehicle fuel mileage over current Brayton engines, the mature gas turbine engine is reduced 32% in weight, gains 50% in cycle efficiency and utilizes a continuously variable transmission and ceramic regenerator. This engine is predicted to have a lower initial cost than any form of internal or external combustion engine and provide a savings in cost of ownership of as much as $850 over its 100,000 mile life on an Otto engine equivalent basis.

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I am certainly not in a position to say that this is unlikely since I do not pretend to be an expert on gas turbine design and manufacture. I have, however, consulted a recognized expert in this field, Mr. Homer J. Wood, President of PowerDynetics, Inc., Sherman Oaks, California. Mr. Wood has been active in the engineering design and manufacture of turbomachinery (gas turbine engines and diesel turbochargers) since graduating with a masters degree in automotive engineering from M.I.T. in 1940. He was assistant chief engineer and Head of turbomachinery group at Airesearch Manufacturing Company from 1947 to 1953. He is currently operating his own design engineering service with such clients as Avco Lycoming, Pratt and Whitney, United Aircraft, Cummins, John Deere, Onan and Continental Aviation. He has published fifteen papers on turbomachinery, has been a member of ASME and SAE Gas Turbine Powerplant Committees and holds 36 patents in this field. He has provided me with a statement which I will excerpt here and make available to Mr. Stephenson:

"Chapter 5 of Vol. II, contains the technical arguments leading to a conclusion that Brayton engines are one of the two leading candidates for a strongly-motivated replacement of Otto-cycle engines. It is not possible to prove that conclusion to be in error, but it certainly can be questioned as to its dependence on manufacturing technologies for which there is no proof of practicality. In this context, the most doubtful element is the ceramic disc regenerator."

"Using (SAE Paper 690036, "Influences of Gas Turbine Cycle Parameters on Regenerator Geometry") techniques, we have repeatedly demonstrated to skeptical clients that a pressure ratio of 4:1 is not optimum for vehicular service. The arguments are complex, but relate to part-load and idling fuel economy integrated over a rational driving cycle as well as reduction in recuperator/regenerator manufacturing costs per horsepower. We have applied these methods to "mature" and "advanced" Brayton Engines described in (the report), and conclude that neither is rationally optimized for its claimed state-of-the-art status. However, neither involves thermodynamic impossibilities - - - just inherent

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configurations that are not compatible with claims of low production cost. (This program also) demonstrates that (regenerator) effectiveness (assumed by JPL at a flat 0.90 at maximum power) is not a valid parameter for heat exchanger optimization."

"I see the major obstacle to both mature and advanced Brayton engines to be lack of a viable recuperator or regenerator. In spite of over 15 years of serious development, a ceramic disc regenerator with durable seals is not available. Furthermore, it may never be available because of inherent problems involved in forcing a matrix to function as a sealing element and a pressure vessel as well as performing a heat transfer function."

"To commit substantial development funds to Brayton engines without an assured economic solution for this essential component would be folly. There are other possibilities than the ceramic disc, but our studies indicate little hope for their manufacturing cost being reduced to levels acceptable for automobiles."

"JPL seems to have accepted claims of ceramics enthusiasts to the point that they suggest that both "mature" and "advanced" Brayton engines could be available by 1985. That is absurdity, and no responsible gas turbine engineer I know has any such confidence that known ceramic problems and commensurate manufacturing cost difficulties will be solved in any such time span. I am strongly of the opinion that a viable ceramic rotor (axial or radial) for a gas turbine is hopelessly impractical unless a non-brittle ceramic is discovered. Furthermore, a viable radial turbine is even less likely than an axial."

"Another blind spot in (the) JPL view of Brayton engines is their lack of adequate variations of cost/HP with engine size. I have been working with miniaturized turbomachinery since 1945, and a lot has to be learned (if it can be learned at all!) before Brayton engines could be cheap enough for "Mini" and "Small" automobiles."

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"Part of the apparent merits of Brayton engines as seen by JPL is their consistent introduction of lower installed power for the same performance. This can be shown to be related to an inconsistent policy with respect to introduction of advanced transmission concepts. From my viewpoint, the only factor significantly affecting installed power for a given automobile class is weight/HP of engine plus transmission."

The Rankine Cycle

The steam engine seems to be the victim of abject pessimism to the point that it was treated as a hopeless stepchild at the outset of the survey. Beginning in the introduction it is used as an example of poor theoretical efficiency and in the Chapter devoted to the Rankine Cycle the mature steam engine is characterized as controversial, costly, and not recommended for further development. There are, however, some fundamental errors in the Rankine Cycle analysis. I refer you to Figure 7-15 where engine weight vs Horsepower yields a mature engine weight of 954 lbs @150 HP (shown slightly heavier than the present Carter engine in weight/HP). The Carter point however is misplotted at 70 HP instead of the rated 90. When extrapolated to 150 HP the Advanced engine (861 lbs) is now heavier than the current Carter engine (810 lbs @ 150 HP). Our estimate for a Mature 150 HP engine is 635 pounds; considerably lighter. What is baffling about this weight estimating is that after 15 to 25 years of development the steam engine gains 51 pounds over current configurations. This deficit is due to weight estimates which are heavier than current technology for mature engines (15 years away) and advanced engines (10 years after that?).

A good example of this is the water feed system which gains 108 pounds over a current 90 pound system for a total of 198 pounds. The Steam engine pays heavily for this extra weight in having to propel a 30% heavier Otto Engine Equivalent vehicle with 50% more horsepower than the single shaft Brayton.

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The unfair treatment of the Steam engine continues in the chapters on cost. A basic problem in the cost equation would seem to be the materials involved in the makeup of the steam engine vs the mature turbine. There is 6 times more stainless steel and superalloy projected in the JPL Rankine engine than in an equivalent Brayton running at temperatures of 450° F to 500° F hotter. We have data that indicates that all this expensive material could be replaced in the steam engine by iron aluminum alloys now being developed for powerplant and/or fuel conversion use. The development of this material is now well under way at the Solar Division of International Harvester.

The cost analysis itself is in serious question even though Volume I represents the numbers as "reasonably accurate for the Mature configurations selected". I call your attention to the fact that while other engines were subjected to a Delphi iteration method, the Rankine engine was relegated to a questionnaire answered by 5 persons associated in a wide variety of ways with Rankine Cycle engines. This set of data was used to determine development time and cost for the steam engine. Some examples are shown in figures 12-11 and 12-12. One respondent was so pessimistic about the development of the mature steam engine that it had a tremendous lopsided effect on the entire estimate. The difference between optimistic and pessimistic cost estimates for the mature Rankine engine differ by 2-1/2 orders of magnitude (e.g. for a 1987 engine the cost spread is $6 million to $880 million)! These kind of figures seem to represent little more than an uninformed guess.

We are not asking that the Rankine automotive engine be the only engine to be developed for the future needs of the country, but that it be considered on a fair basis of comparison with other alternates including advanced internal combustion and some other compound cycles (which were a glaring omission in the report). The steam engine has earned this right in light of the fact that it is at this time the <u>only</u> engine to have officially demonstrated the ability to run on alternate fuels <u>and</u> meet the most stringent emissions standards in an actual operating automobile.

(18)

SCIENTIFIC ENERGY SYSTEMS CORPORATION
570 Pleasant Street, Watertown, Mass. 02172 (617) 924-1420

INTRODUCTION

SES has been engaged in automotive steam engine development for seven years. For the past four years SES has been conducting this work under EPA/ERDA contract. A part of this work has been applied to the future potential of the automotive steam engine. With this background, SES has prepared a critique of the Jet Propulsion Laboratory report "Should We Have a New Engine, An Automobile Power System Evaluation, 1975." This critique is primarily focused on the Rankine or steam engine evaluation.

SUMMARY

Six fundamental oversights by JPL invalidate their steam engine analysis:

1. A thermodynamic error in positive displacement expander efficiency analysis results in a significant underestimate of the steam engine's efficiency.
2. The expander analysis error also incorrectly eliminates the variable admission expander. The variable admission expander would have a dramatic impact on cost and fuel economy through a reduction in maximum power required, improved part load efficiency and lower system pressures.

3. Misinterpretation and modification of SES vapor generator data erroneously resulted in a major cost penalty to the steam engine. A state-of-the-art vapor generator design analysis by SES for the JPL mature steam engine results in a 66% lower vapor generator materials cost.

4. JPL, in essence, conducted a cursory cost reduction study of the first modern generation of research steam engines. The necessarily conservative concepts of these research engines were not treated to the same scrutiny and cost conscious projections afforded the other unconventional engines.

5. JPL dismissed without apparent analysis a very cost-effective steam engine design submitted by SES. This reheat cycle, variable admission system is second only to the JPL Stirling engine in efficiency and it is cost competitive. The fuel economy and cost projections by SES for the steam engine are ranked below with the JPL alternatives.

6. JPL was unjustifiably pessimistic in their development prognosis for the steam engine. The "reheat cycle" concept provided by SES requires only two technical advances: the durability demonstration of a reheat expander and the development of the reheat boiler control strategy.

To achieve the projected efficiency no improvement is required in: component efficiencies, materials, heat exchanger effectiveness, emissions, nor system dynamics.

(19)

PROFESSIONAL BIOGRAPHY

HOMER J. WOOD

Registered Professional Engineer #2824

Birth Date: [redacted]

Birthplace: [redacted]

Marital Status: Divorced; Two Children

Residence: 14285 Valley Vista Boulevard
Sherman Oaks, California 91403
Telephone (213) 783-8162

ACADEMIC BACKGROUND:

B.S. Degree (with honor), California Institute of Technology, 1938. Mechanical Engineering.

M.S. Degree, Massachusetts Institute of Technology, 1940. Mechanical-Automotive Engineering. Held full tuition scholarship 1938-1939. Offered but declined Sloan Fellowship for 1939 - 1940. Degree delayed to 1940 because of completion of thesis after entering industry.

INDUSTRIAL EXPERIENCE:

July 1939 - September 1941

Menasco Mfg. Co., Burbank, California.
Project-Engineer, February 1940 - September 1941.
Aircooled in-line piston engines for aircraft, design, development, and experimental production.

October 1941 - February 1942

Lockheed Aircraft Corp., Burbank, California.
Senior Research Engineer.
Pressurization compressor development.

February 1942 - July 1943

Kinner Motors, Inc., Glendale, California.
Project Engineer.
Design and supervision of tank and aircraft engine test facilities. Design and development of improved tank engines and installations in vehicle.

August 1943 - October 1953

AiResearch Mfg. Co., Los Angeles, California.
Project Engineer, July 1944 - January 1947.
Design, development, and experimental production of air cycle refrigeration turbines and pressurization compressors. Designed and developed the first air cycle refrigeration turbine to be put into production for jet aircraft (1), and the first combined turbine refrigeration and pressurization compressor systems for propeller-driven aircraft (2).

(1) Patent 2,492,672
(2) Patent 2,502,194

Assistant Chief Engineer, January 1947 - October 1953.
Department Head of Turbomachinery Group, covering air cycle turbines, pressurization compressors, air turbine motors, air turbine starters, gas turbine motors, gas turbine compressors, gas turbine engines, exhaust turbosuperchargers, and fans. Department included 175 people (which did not include laboratory personnel). Yearly expenditure by this group approximately $4,500,000. Designed and personally responsible for the development of the first two gas turbine engines of less than 500 HP to meet Government qualification requirements (3). They were also the first small gas turbines to be put into profitable production. Designed and developed the first air turbine starters for large jet engines (4) and these also were the first of their class to be put into production. Later designed improved gas turbine which is still in production and represents majority of gas turbine production of engines under 500 HP (5).

(3) Patents 2,648,491; 2,792,197; 2,850,876
(4) Patent 2,625,047
(5) Patents 2,760,719; 3,014,694

CLIENT LIST (Past and Present):

Continental Aviation & Engineering Corp.
Detroit, Michigan

Pratt & Whitney Aircraft Division
United Aircraft Corporation
East Hartford, Connecticut

Hamilton Standard Division
United Aircraft Corporation
Windsor Locks, Connecticut

Hydro-Aire, Inc.(Subsidiary of Crane Co)
Burbank, California

United Aircraft Corp.(Corporate Staff)
East Hartford, Connecticut

The Cosmodyne Corporation
Hawthorne, California

Kongsberg Vapenfabrikk
Kongsberg, Norway

Onan Corporation
Minneapolis, Minnesota

Vickers Incorporated
Torrance, California

Jet Division
Thompson Products, Inc.
Cleveland, Ohio

Foote Bros. Gear and
Machine Corporation
Chicago, Illinois

Summers Gyroscope Co.
Santa Monica, California

Deere & Company
Moline, Illinois

John Deere Tractor Works
Waterloo, Iowa

Avco Lycoming Division
Williamsport, Pennsylvania

Cummins Engine Company
Columbus, Indiana

PUBLICATIONS.

"Air Conditioning of Turbine-Propelled Military Aircraft," Aviation, February, 1947; SAE Journal, February, 1947.

"Auxiliary Gas Turbines for Pneumatic Power in Aircraft Applications," SAE Quarterly Transactions, April, 1950.
Awarded SAE Wright Brothers Medal.

"Hydraulic Differential Drive," Machine Design, April, 1950.

"Characteristics of Expansion Turbines for Auxiliary Power," SAE Quarterly Transactions, July, 1952.

"Has the Teapot Tempest Come of Age?" SAE Journal, July, 1954; SAE Preprint #157 - 1953.

"Comparative Rating of Positive-Displacement Engines and Turbines for Cryogenic Power Systems," Progress in Astronautics and Rocketry, Vol. 3: Energy Conversion for Space Power. Nathan W. Snyder, ed., Academic Press, New York, pp. 565-592; ARS Preprint 1317- 1960.

"Chemical Power Systems for Missiles and Space Vehicles," SAE Preprint 469A; (SAE Automotive Engineering Congress, Detroit, Michigan, January 1962).

"Current Technology of Radial-Inflow Turbines for Compressible Fluids," Journal of Engineering for Power, ASME Transactions, Vol. 85, 1963; ASME Preprint 62-GTP-9.

"Applications and Performance Levels of Radial Inflow Turbines," SAE Preprint 653D; (SAE National Meeting, Detroit, Michigan, January 1963).

"Gas Turbines in Future Industrial Vehicles," (SAE Mid-Year Meeting, Chicago, Illinois, May 1965).

"A Polytropic Technique for Gas Turbine Performance Prediction and Evaluation,"(SAE Automotive Engineering Congress, Detroit, Michigan, January 1966); SAE Paper 660161.

"Nonlinear Vibration Damping Functions for Fluid Film Bearings," (SAE Automotive Engineering Congress, Detroit, Michigan, January 1967); SAE Paper 670061.

"Influence of Gas Turbine Cycle Parameters on Regenerator Geometry," (International Automotive Engineering Congress-SAE-Detroit, Michigan, January 1969); SAE Paper 690036.

"Automobile Gas Turbines - A Quantum Jump Pending?" Gas Turbine International, March-April, 1972.

"Performance Potential of Single-Stage Gas Turbine Engines," SAE 739135, IECEC Meeting, August, 1973.

Steam Power Systems
7617 Convoy Court, San Diego, California 92111

December 2, 1975

The Honorable Walter M. Ingalls, Chairman
Assembly Committee on Transportation
Room 2091, State Capitol
Sacramento, California 95814

Attention: John White, Associate Consultant, Committee Staff

Dear Sir:

Please find attached the list of questions, submitted in response to your request, to be forwarded to Mr. R. Rhoades Stephenson of JPL. Also included are exhibits numbered 1 through 12 which are coordinated with and necessary to each question.

Once answered by JPL, we hope there will be no doubt that the Rankine Cycle engine should be included in plans for the development of alternate engines of the future.

We again thank you for including us in your agenda for the hearing on alternate engine technologies on November 18th in San Diego and your assistance in clearing up what we believe to be serious errors in the JPL Report "Should We Have a New Engine?".

Best regards,

Richard Burtz
General Manager/Vice President

RB:jt

Enclosures

Critique by

University of California, San Diego
Department of Applied Mechanics and
Engineering Sciences
La Jolla, CA 92093

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

11

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-168-11

June 29, 1977

Prof. Alan M. Schneider
Department of Engineering Sciences
University of California at San Diego
La Jolla, CA 92093

Dear Professor Schneider:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

Thank you for your letter to Dr. R. Stephenson of 9/5/75 regarding the flywheel car as proposed by Dr. Post. As you can appreciate, we received many letters regarding the subject report, and a critique response plan was included in a subsequent restructuring of the program as explained in the attachment.

Our work to date has been limited to automotive highway transportation using alternate heat engines, but follow-on efforts in other transportation areas are anticipated, but are not currently approved. Vehicles incorporating mechanical energy storage systems, especially buses, will probably find their greatest utility in the urban transportation field. The first extension of the work as authorized by our sponsor might be in the areas of electric and hybrid vehicles, and we expect to address buses later on.

At such time as we may address propulsion systems which are exclusively or partially based on flywheel energy storage, we will be most interested in further discussions with you in person.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:cr

Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

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DEPARTMENT OF APPLIED MECHANICS
AND ENGINEERING SCIENCES

~~POST OFFICE BOX 109~~ AMES B-010
LA JOLLA, CALIFORNIA ~~92037~~ 92093

September 5, 1975

Mr. R. Rhoads Stephenson
Principal Investigator
Automobile Power Systems Evaluation Study
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Stephenson:

Imagine my delight and surprise, after reading about JPL's engine recommendations on the front page of the L. A. Times on Thursday, to receive a full copy of your report on Friday.

Since you asked for comments I do feel compelled to make the following: I regret that you did not include in your analysis a study of the flywheel driven car as proposed by Dr. Richard Post of the Lawrence Livermore Laboratories (see the attached).

Your results are important. I sincerely hope that you will persevere to see that a research and development program of the type you recommend does, in fact, come about.

Sincerely,

Alan M. Schneider
Professor of Engineering Sciences

AMS:dho
Enclosure

October 1974 Vol. 4, No. 10

A WORLD OF ENERGY: ANOTHER VIEW

ALAN M. SCHNEIDER
Professor of Engineering Science, University of California, San Diego

* * * * * * *

Editor's Note: In the November 1973 issue of this Newsletter (page 3:11:1) we editorialized on this same subject, and under a similar title. This month we bring you Dr. Schneider's mental model of the energy problem as he believes it can be solved. The following article is based on a report, Alternatives to the Energy Crisis, *prepared by Professor Schneider following the conference which he organized, and to which he refers.*
--JM

* * * * * * *

Most proposals heard today for alleviating the U.S. energy crisis emphasize one or more of the following: coal, oil, shale, tar sands, strip mining, off-shore drilling, supertankers, and nuclear energy. These imply significant environmental degradation and/or depletion of irreplaceable resources. It is pertinent, therefore, to consider the extent to which the combination of solar, wind, wave motion, and other REnewable Non-pollUting (RENU) sources of energy can supply our future needs.

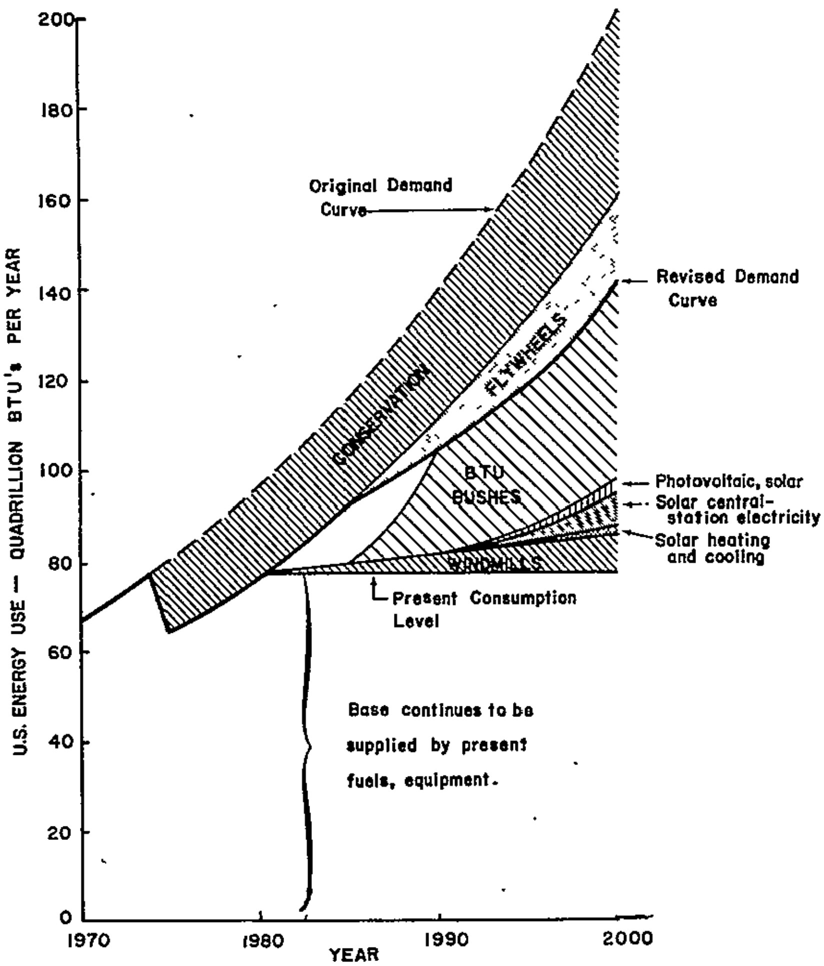
A two-day conference was held recently in La Jolla at the University of California/ San Diego (UCSD) to explore this question. After considering both technological and economic factors, it was concluded that indeed it would be possible to make up the entire gap between the present consumption level and our future needs without increasing our dependency on either fossil or nuclear sources.

A hypothetical future energy demand curve can be drawn based on a 3 3/4% annual rate of growth. This rate is lower than the 4 3/4% growth rate of the sixties, but higher than the 3 1/3% rate which prevailed from 1950 to 1970, and the 2 3/4% growth rate characteristic of the last 120 years. This does not imply that a 3 3/4% rate should be accepted as inevitable, but only serves as a starting point for the remainder of this discussion.

The horizontal line originating at our present annual consumption in the following figure is projected forward in time, on the assumption we will continue to supply the current energy level by present fuels, methods, and equipment. This assumption leaves the gap between this line and projected demand curve to be made up by the new sources which we will discuss.

CONSERVATION

The first step in filling this gap, said Dr. Lester Lees, founder and former Director of the Environmental Quality Laboratory at the California Institute of Technology, is conservation. The people of the United States have shown during the past winter that we can easily attain a 20% reduction in energy use, with negligible effect on our standard of living, primarily by cutting obvious waste. For planning purposes, let us assume a 20% reduction in use starting immediately, as shown in the figure.



FLYWHEEL AUTOMOBILES

Dr. Richard Post, Lawrence Livermore Laboratories, suggested that another 10% reduction in overall consumption would result from the energy savings obtained by using flywheels instead of gasoline engines to power our cars. The flywheels would be spun up at night (off-peak demand)[in the garage], or in five minutes at re-equipped gas stations, using electrical energy. They would provide cars, trucks, and buses with range, speed, and acceleration capability not much different from that provided by gasoline engines. Their superior efficiency would allow a two-thirds' reduction in energy use by transportation, with no reduction in passenger- or ton-miles. Dr. Post recommends that serious development and testing be undertaken at once, and the units introduced as standard equipment by 1985.

Conservation and flywheels lead to the revised demand curve shown as the heavy line.

WIND POWER

By 1980 we could be a position to begin mass-production of windmill designs now being developed under NASA sponsorship, said Dr. Homer J. Stewart, Professor of Aeronautics, California Institute of Technology. He envisions one-megawatt peak power (250 kw average power) windmills, located along power lines throughout the Great Plains, generating electricity and feeding directly into the existing electrical grid.

He projects a figure of $600 per kw for the capital cost of the windmills, site, and grid connection. This cost does not compare unfavorably with present fossil fuel electrical plant costs of $200-$400 per kw, when one recognizes there would be no fuel cost. We would install 23,000 units yearly at a capital cost of $3.4B, or $68B total by 2000, at which time windmills would be supplying 20% of the projected 570 X 10^6 kw average electricity use rate.

Note the contribution of windmills shown in the figure. Windmills could supply even more than this, but at a higher cost of $900 per kw; the additional cost will be needed to cover the energy storage equipment which would be required.

The concept of neighbors banding together to form a windmill district, like a present-day water district, to share the cost and benefits of a large common windmill, was also suggested.

SOLAR ENERGY

We have the knowledge now to heat and cool buildings, and to heat water, using solar energy. If there is just a slight additional increase in fossil fuel prices, solar heating and cooling of buildings (SHACOB) will become economically competitive, states Dr. Benjamin Berkowitz of the General Electric TEMPO Center for Advanced Studies. However, the fact that SHACOB growth is closely tied to the rate of new construction, as well as costs and institutional factors affecting its acceptance by the construction industry (U.S. consumers being accustomed to thinking primarily of first cost and only secondly, if at all, of recurring costs) places a rather stringent limit on what can be accomplished by the end of this century.

If SHACOB were adopted for all new construction after 1980, 4.5 X 10^{15} LTU's per year can be achieved by the year 2000. But this level is a theoretical upper limit. More realistically, Dr. Berkowitz predicts a small start by 1990, growing to 1.9 X 10^{15} BTU's per year by 2000, as shown in the figure. SHACOB's major impact will be seen two or three decades into the 21st century.

Solar swimming pool heaters are available now in San Diego which, at current fuel prices, will pay for themselves in 4-5 years. Solar hot water heaters can be installed in existing homes with cost recovery in 10 years. If retrofit of existing homes caught on, the solar heating contribution shown would begin earlier and rise faster.

Dr. John Russell, Manager of Special Projects at General Atomic Company in San Diego, pointed out that the technology exists for large-scale generation of electricity in central stations by solar heating ("solar-thermal"), but that it is currently too expensive by a factor of three to four. New ideas and developments will be required if this form of solar energy is to become competitive. He cited a recent National Science Foundation study which indicated that if the technology did evolve, solar-thermal could play a part beginning in 1990, growing in importance to an ultimate level much larger than that shown in the figure for the year 2000.

A technological breakthrough in manufacturing costs is required before solar cells ("photovoltaics") will be economically viable. Dr. Richard Stirn of the Jet Propulsion Laboratory, California Institute of Technology, predicts that, with adequate research funding, this should be attained by 1980, resulting in substantial growth of this technology beginning, as shown, by 1990. The ultimate contribution of this technology, as well as SHACOB, will be much larger as we move into the 21st century.

THE BURNING BUSH

The balance of our energy needs can be made up by BTU bushes, says Dr. George Szego, President of Intertechnology Corporation, Warrenton, Virginia. BTU bushes are plants grown to be burned, and the heat is used to generate electricity. If we prepare now, he says, we can begin to realize sizable energy production in 1985 and close the gap by 1990. Dr. Szego estimates that the capital outlay for such photosynthetic materials is $130, "other" costs are $50, and the on-site power station will cost $200 per kw for a total of $380 per kw of electrical energy. Assuming a 0.7% solar energy conversion, it will take 0.6 acres of plant life per kw. We can then grow crops and generate energy forever at a current cost of $1.50 per million BTU, which is substantially less than the current cost of oil at $2.50 per million BTU.

The small gap between 1980 and 1990 will have to be filled by stricter conservation.

WAVE POWER

Not included among the energy sources shown in the figure, because of uncertainties in the schedule and cost, is a new technology suggested by Professor John Isaacs, Director, Institute of Marine Resources, Scripps Institution of Oceanography, La Jolla, California, for generating electricity from the up-and-down motion of the ocean waves.

WASTE MATERIALS

Recovery of energy from these was omitted only for lack of conference time.

SO . . .

The keynote speaker, Dr. Kenneth Watt, Professor of Ecology, University of California at Davis, believes that Project Independence, as enunciated by former President Nixon, has failed. Dr. Watt warned that we cannot bear the cost of importing energy to sustain projected levels of use without losing control over the country's finances. Our greatest export ace, food, is insufficient in volume to balance the cost of oil imports. Symptomatic of the shortage, the domestic price of food has already sharply risen in response to heavy purchases from abroad. Only through energy conservation can we retain control of the economy.

If the future depicted in the figure is to become reality, it was stressed by all speakers that strong action must be taken now. In particular, research, development, pilot plants, and demonstration models will have to be funded.

Congressman George Brown of Riverside, California stated that the scientific community and the public must convince their elected representatives that a change must be made from the current policy, which promotes nuclear and fossil fuel development while relegating the RENU sources to low-burner level, to strong support for the RENU sources.

The theme of the conference was conceived by the author [Professor Schneider], who served as conference coordinator. Sponsored by UCSD's Third College (Dr. Joseph Watson, Provost), it was well attended by over 800 students, environmentalists, and concerned citizens. Following the

Critique by

Kinetics Corporation
1121 Lewis Avenue
Sarasota, FL 33577

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

12

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

June 29, 1977

Refer to: 34LPE-222-12

Mr. Wallace L. Minto, President
Kinetics Corporation
1121 Lewis Avenue
Sarasota, Florida 33577

Dear Mr. Minto:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

This is to acknowledge your letter and the engineering data enclosed with it concerning the fluorocarbon Rankine engine. Our response at this time is explained in the enclosure, which also includes a summary of our redirected program.

We found your evaluation of fluorocarbon versus steam working fluids to be quite complete except for the economics of the former and for possible health questions arising from leakage of fluorocarbon vapor or handling of the liquid. We have made no study of these factors, but we feel that they should be addressed. Certainly the engineering advantages of fluorocarbons over steam are more than sufficient to qualify them as candidates, especially where lower system temperatures are required or are inherent such as, for example, a diesel bottoming cycle.

Regarding the higher density of organics, we feel that this is not always an overriding advantage. Consider the TECO bottoming cycle for diesel engines, which uses an organic working fluid. A problem exists due to the small size of the expander and the concomitant difficulty in obtaining acceptable efficiencies. For some components, efficiency and reliability considerations may outweigh size.

Regarding your comparison of engine size among the candidate Rankine configurations, the small size of the fluorocarbon version is being challenged by steam systems operating at temperatures of the order of 1000°F and boiler

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JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

pressures up to 2500 psig. We agree that the Rankine system should not be judged solely on the basis of work per unit mass of working fluid, and that an organic may be preferred to steam. The considerations which you presented will be taken up during the Rankine work discussed in the enclosure.

We look forward to further discussions with you at the time the Rankine Technical Task Summary is being prepared, and we thank you for your informative letter.

Sincerely,

H. E. Cotrill

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

KINETICS CORP.
1121 LEWIS AVENUE
SARASOTA, FLORIDA 33577
PHONE: 813-366-3050

September 3, 1975

R. Rhodes Stephenson, Principal Investigator
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Dear Dr. Stephenson:

Thank you for the copy of the Caltech report on alternative automotive engines.

My chief comment concerns the analysis presented on Rankine engines. The authors have examined the question of working fluid only superficially and drop into the usual erroneous pitfall concerning organic working fluids. On page 7-3 of Vol. II, it is stated, "Second, the available work per unit mass of working fluid is significantly lower than for water." (My emphasis added), and thereafter the analysis of a Rankine engine is confined to water as the working fluid.

At this early fork in analysis, they take the wrong road. In any expansion engine, and particularly a positive displacement engine, the overriding consideration is the available energy per unit volume of working vapor. This determines the displacement of the engine for a given power output, which in turn determines the engine's weight, size and cost.

Enclosed herewith is a Kinetics memo dated 6, November, 1973 which treats this subject more fully.

Secondly, our extensive experience caused us to discard the piston engine very early, since it usually has low mechanical efficiency and excessive weight per unit of displacement. We developed the variable expansion ratio Gerotor rotary expander, which is valveless, internally reversible, small, with pure uniflow breathing, light in weight and very cheap to mass produce.

I agree that the analysis given of Rankine engines is appropriate for a 1925 Stanley Steamer, but it completely ignores the developments resulting from in-depth analysis of the parameters most crucial to a viable Rankine automobile : efficiency, component weight and cost.

Thank you for the opportunity to examine the study.

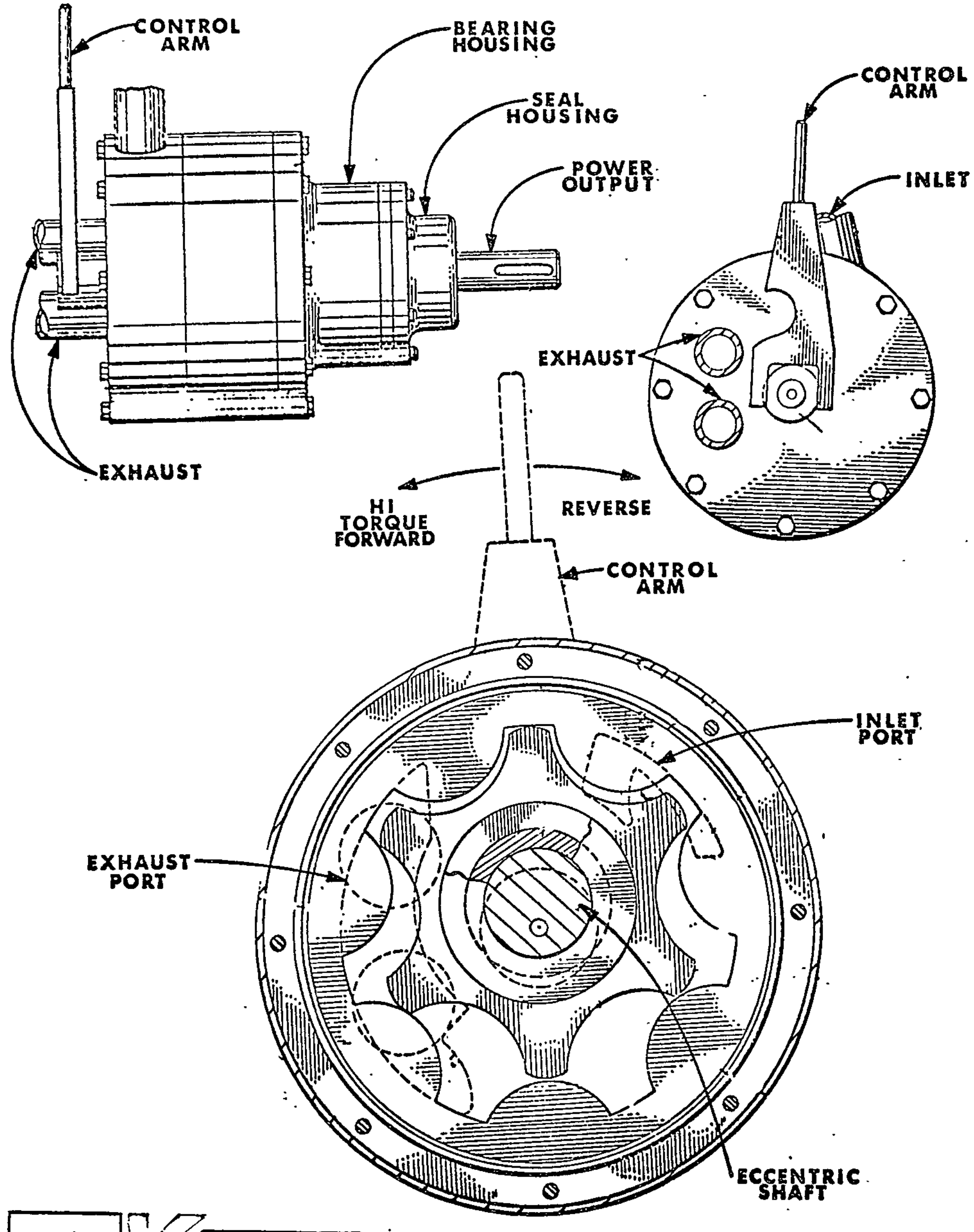
Very truly yours,

W. L. Minto

Wallace L. Minto
President

WLM/llf
Enclosures:

KINETICS ROTARY ENGINE



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COMPARISON OF FLUOROCARBON AND STEAM RANKINE CYCLE EFFICIENCIES

It has been stated that fluorocarbon Rankine cycles must operate at lower temperatures than steam cycles, which limits their achieveable theoretical Carnot efficiency. However, it must be realized that fluorocarbon Rankine cycles can achieve a far greater percentage of theoretical Carnot efficiency than steam can in an automotive vehicle, where there are other temperature limits in addition to that of the working fluid. When these other constraints are imposed, fluorocarbons are capable of higher cycle efficiency than steam in a practical machine.

Practical parameters:

Let us review the parameters which govern a practical Rankine automotive drive:

1. It must be a fully-closed system to prevent the inconvience or cost of replenishing the supply of working fluid at frequent intervals.

2. For maximal overall efficiency at all speeds and accelerations, it should use a positive displacement expander of reasonable size and weight.

3. For maximum volumetric expander efficiency at varying speeds, a positive displacement expander with small clearances is essential.

4. Any cooling of the operating parts of a vapor expansion engine markedly reduces it efficiency.

5. A positive displacement engine must be lubricated for efficiency and long life.

6. The lubricant used in a sealed system must be stable indefinitely to at least the maximum engine inlet temperature. With known lubricants, this imposes a practical upper temperature of 600°F in a sealed system.

7. For a reasonable size of condenser, a substantial temperature differential to ambient air must be maintained. The temperature of the condenser is suitably 200°F.

8. Any substantial condensation of the working fluid within the positive displacement expander under operating conditions will be harmful to its mechanical integrity.

Discussion

Figure I shows the net theoretical Rankine cycle efficiencies of two fluorocarbon fluids versus steam and the theoretical Carnot potential. It is evident that the maximum theoretical efficiency of steam at 600°F is less than that of R-113 at 400°F, in spite of the lower Carnot potential at the lower temperature.

Figure II shows in more detail the relatively poor performance of steam vs. Carnot potential, even at maximum cycle efficiency conditions when the exhaust is 200°F and dry saturated vapor, as required by the expander.

In addition to higher cycle efficiency than steam, another important practical parameter in an automotive vehicle is the size and weight and cost of the expansion engine. A superficial examination of the thermodynamic data indicates that steam has much greater available expansion energy than fluorocarbon, but this is per pound of vapor. An engine's size is primarily determined by its displacement volume per revolution, so the most important consideration in an expansion engine is the available energy per unit volume of inlet vapor. Because fluorocarbon vapors are extremely dense, they contain far more available energy per unit volume than steam. Thus, a flouorocarbon vapor expansion engine operating at maximum cycle efficiency is only a small fraction of the size and weight of a steam engine of the same horsepower also operating at maximum efficiency. This comparison is shown graphically in Figure III. At a given temperature, say 400°F, the low Carnot efficiency and the low vapor density of steam act together so that a steam engine would have to have more than 36 times greater displacement than an R-113 engine of the same horsepower output, when each is operating at maximum cycle efficiency for that temperature.

Of course, a steam engine may be made smaller by raising the steam pressure, and hence its density, for any given temperature. This is done in practice, to keep the expansion engine within a reasonable size. But always at the expense of cycle efficiency. Figure IV shows the effect of higher pressures at the 600°F lubrication limit on cycle efficiencies.

When steam pressure is increased to save expander size and weight, the lowering of cycle efficiency becomes the consideration of greatest importance in maximum horsepower output per unit engine size.

Thus, if we were to operate a steam engine at substantially higher temperature and pressure, it would still have to be larger than an R-113 engine to develop the same horsepower. Considering the available energy of expansion per cubic foot, an engine operating on steam at 600^{o}F and 1,000 psia inlet, with dry saturated exhaust, would have to be 70% larger than an engine developing the same horsepower with R-113 at 375^{o}F and 350 psia inlet.

<u>Other advantages of R-113 over steam in an automotive engine system.</u>

1. The high relative density of fluorocarbon vapor is a significant advantage in diminishing the size of pipes, valves and the required volume of the condenser. At 200^{o}F condenser temperature and corresponding pressures, R-113 vapor has more than fifty times the density of steam.

2. For the same engine horsepower, steam exhaust piping and conduits must have 350% of the cross-sectional area of R-113 exhaust piping to achieve the same low vapor velocity.

3. For the same engine horsepower, steam valves and piping from the boiler to the engine must have 700% greater cross sectional area than for R-113 when both are at maximum cycle efficiency conditions, for the same vapor velocity.

4. The smaller size of piping, valves and engine result in lighter weight, greater hoop strength and lower cost.

5. Water expands upon freezing, whereas R-113 shrinks upon freezing. Therefore, no damage would result to the R-113 system upon freezing. Of course, the freezing point of R-113 is much lower than that of water, so no special precautions or preventives are necessary under normal ambient conditions with R-113. Steam systems are very susceptible to freezing damage.

6. Much quicker start up is achieved with R-113 than steam. R-113 has a much smaller specific heat than water, achieves a higher pressure at a lower temperature and has a much smaller heat of vaporization. For a given burner and boiler, R-113 achieves the same operating pressure as steam in less than one tenth the time.

7. Steel achieves its maximum strength at about 400^{o}F, the operating temperature of R-113. Steel's strength

decreases rapidly at the higher temperatures needed for efficiency with steam.

8. Lower internal boiler temperatures with R-113 result in greater temperature differentials to combustion gases and lower exit gas temperatures in a practical size. This results in higher thermal efficiency of the burner-boiler combination.

W. L. Minto

November 6, 1973

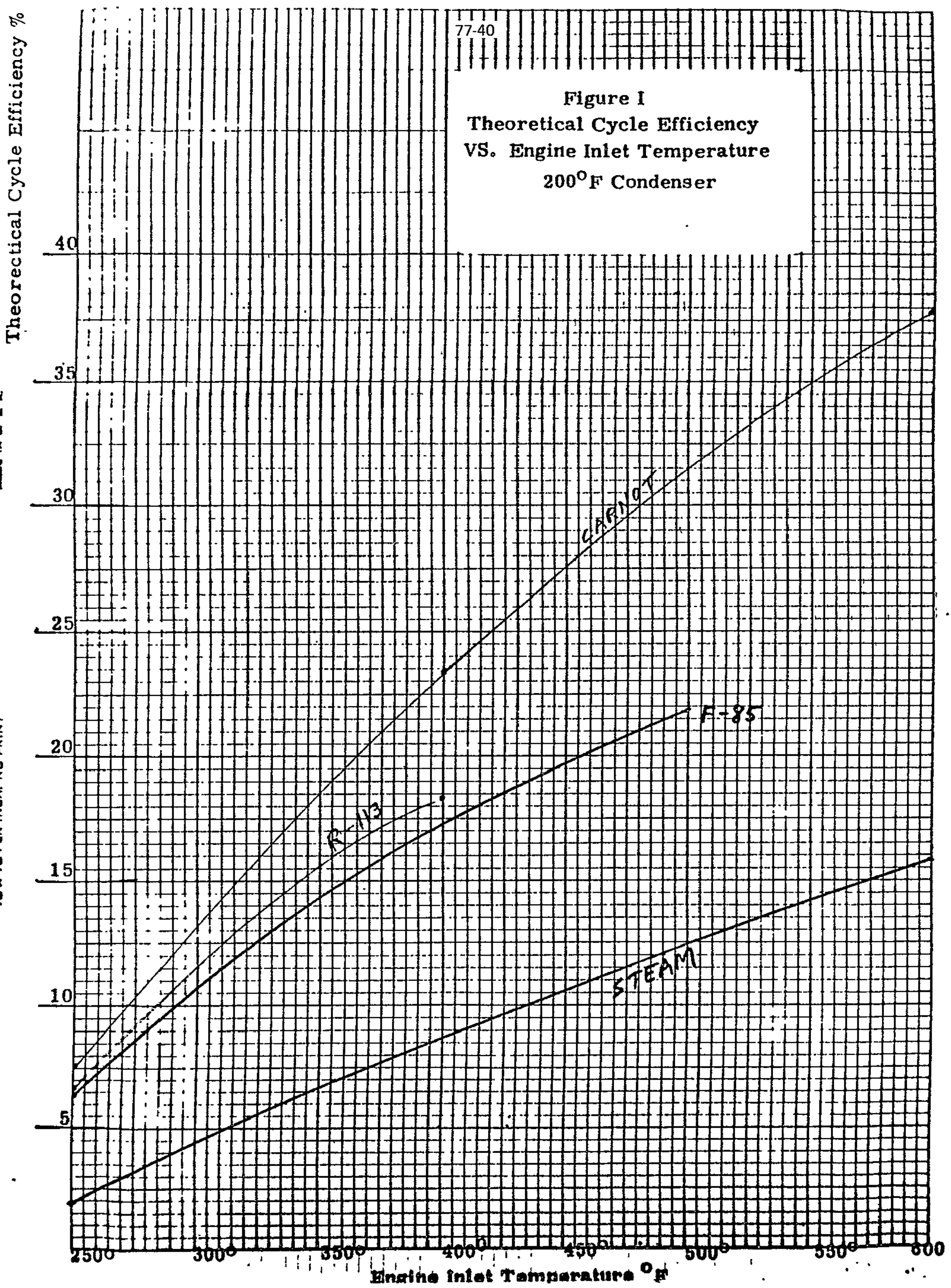


Figure I
Theoretical Cycle Efficiency VS. Engine Inlet Temperature 200°F Condenser

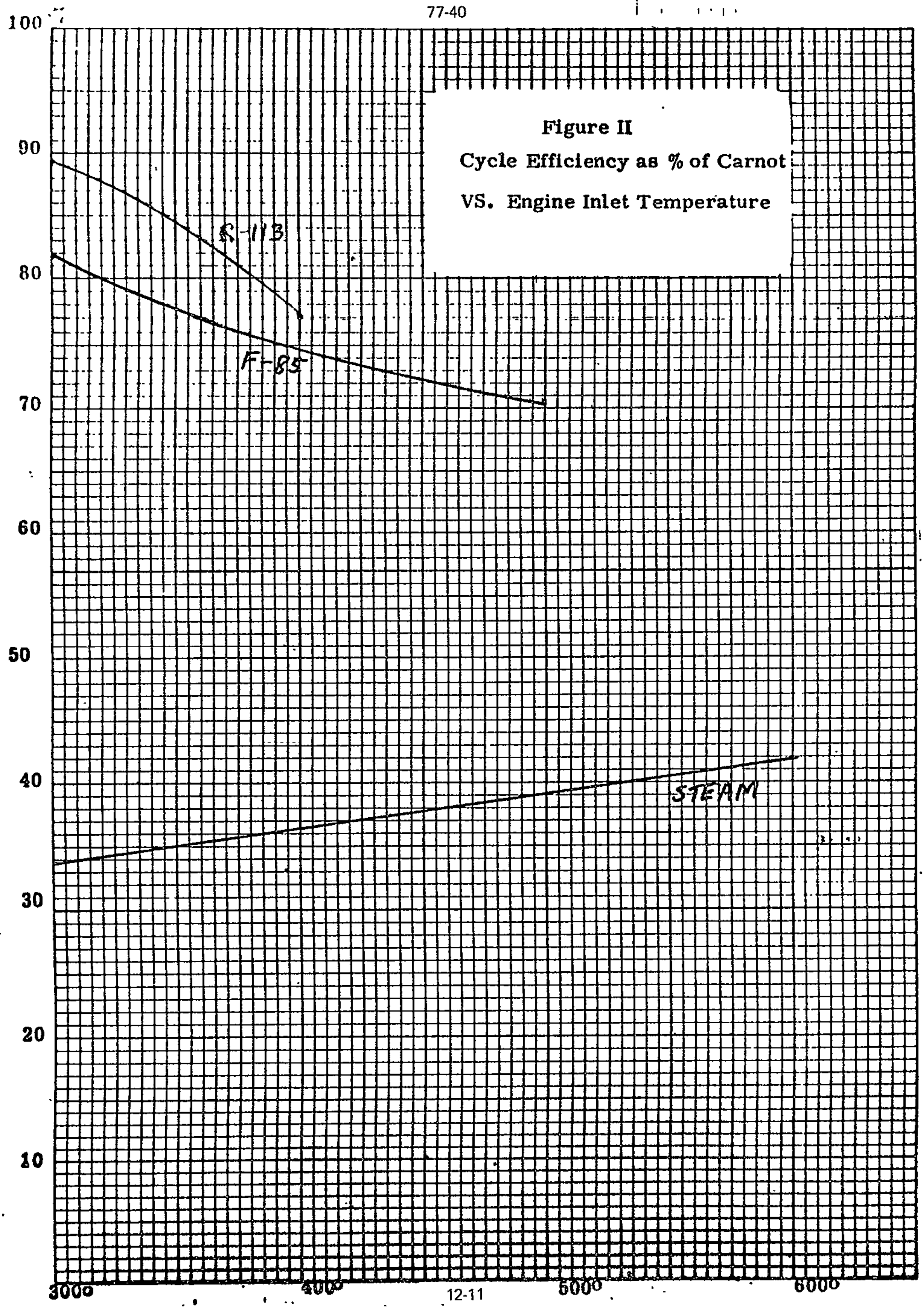


Figure II
Cycle Efficiency as % of Carnot
VS. Engine Inlet Temperature

10 X 10 PER INCH. NO PRINT

MADE IN U. S. A.

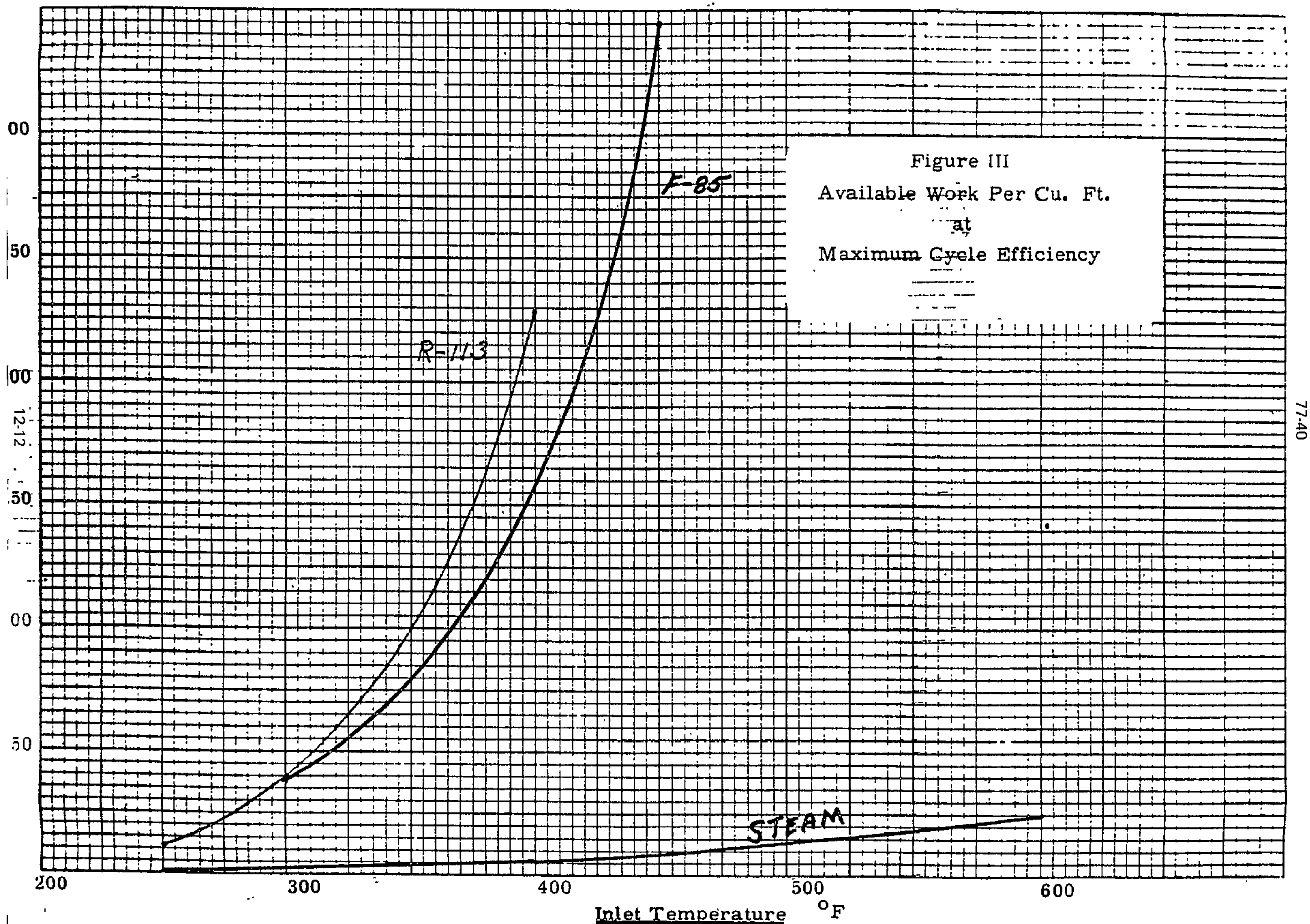


Figure III
Available Work Per Cu. Ft.
at
Maximum Cycle Efficiency

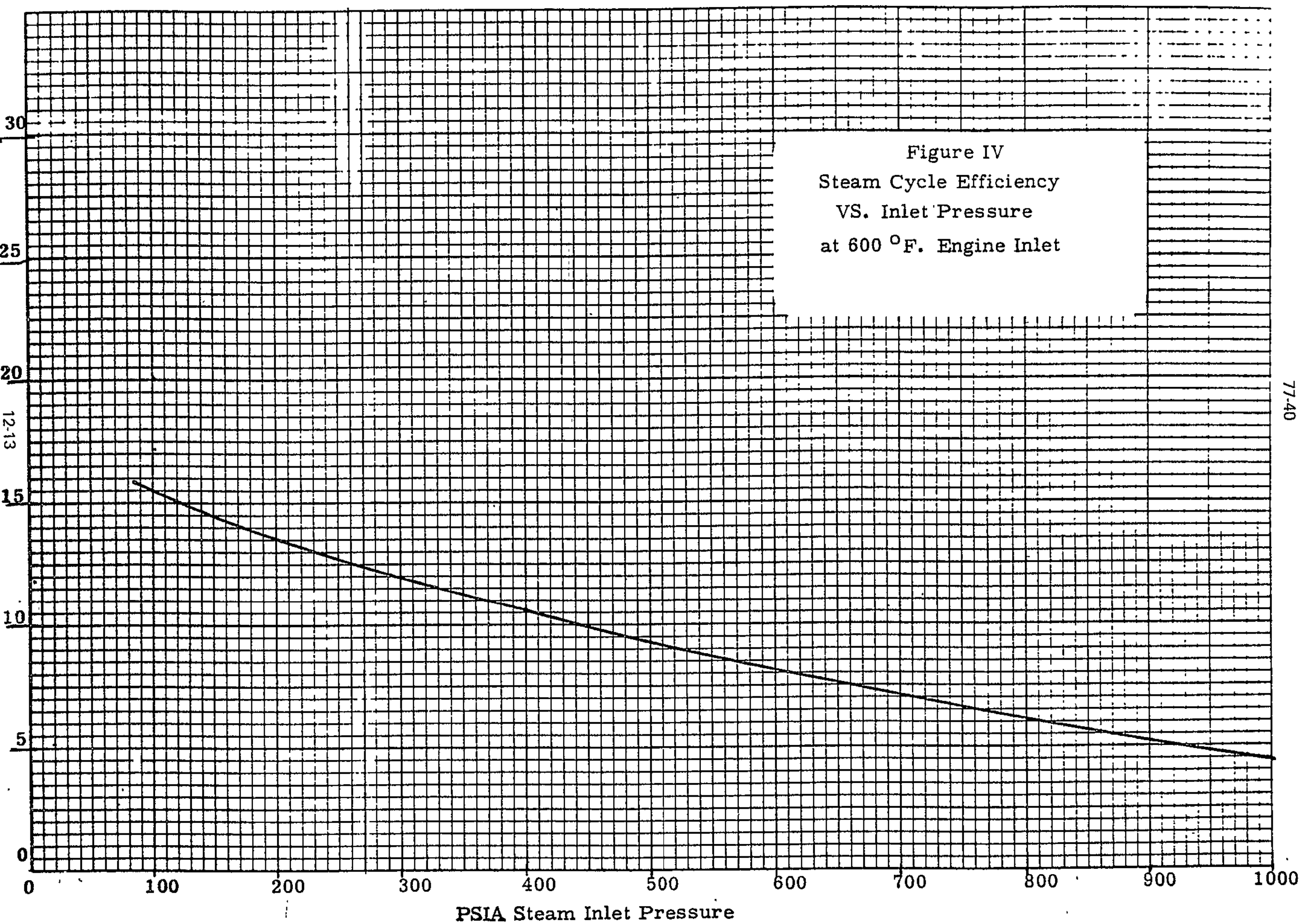


Figure IV
Steam Cycle Efficiency
VS. Inlet Pressure
at 600 °F. Engine Inlet
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
1000
PSIA Steam Inlet Pressure

12-13

77-40

	INLET TEMP °F	INLET PRESSURE PSIA	INLET ENTHALPY BTU/LB	INLET SP. VOL CU.FT/LB	INLET ENTROPY	EXHAUST ENTROPY	EXHAUST TEMP °F	EXHAUST ENTHALPY BTU/LB	ΔT EXHAUST-CONDENSER	ΔH EXHAUST-COND.	AVAIL. ENERGY BTU/LB	AVAIL. ENERGY BTU/FT³	% CYCLE EFFIC NO REGEN	% CYCLE EFFIC. REGEN.	NET % CYCLE EFFIC. AFTER PUMPING	% OF THEORETICAL CARNOT
R-113 [illegible]	250	101.63	115.597	0.33642	0.18779	0.18779		111.61		3.298	3.987	11.849	6.41	6.77	6.60	87.15
	300	173.2	122.36	.19108	0.19244	.19244		114.78		6.468	7.583	39.682	11.00	12.14	11.73	89.16
CONDENSER	350	278.38	128.07	.10960	.19613	.19613		117.37		9.058	10.699	97.607	14.33	16.31	15.58	84.16
200°F 54 PSIA	376	349.4	130.14	.08020	.19715	.19715		118.08		9.768	12.062	150.389	15.72	18.02	17.08	81.11
	400	427.2	130.68	.05678	.19664	.19664		117.73		9.418	12.951	228.09	16.76	19.09	17.92	77.05
STEAM	250	16	1170.4	26.23	1.7762	1.7762	200	1145.9	ZERO	ZERO	24.5	0.934			2.44	32.26
CONDENSER	300	21	1191.4	21.29	1.7762	"	200	1145.9	"	"	45.5	2.137			4.49	33.78
200°F 11.53PSIA	400	35	1237.2	14.457	1.7762	"	200	"	"	"	91.3	6.315			8.54	36.72
H_G = 1145.9 BTU/LB	500	56	1283.3	10.084	1.7762	"	200	"	"	"	137.4	13.625			12.32	39.42
H_{FG} = 977.9 "	600	85	1330.1	7.332	1.7762	"	200	"	"	"	184.2	25.123			15.85	42.00
	600	350	1310.9	1.704	1.6070	1.6070	324	1186.2	124	40.3	124.7	73.20	10.91	11.31	11.31	28.97
	600	500	1298.6	1.159	1.5588	1.5588	368.4	1196.0	168	50.1	102.6	88.52	9.07	9.50	9.50	25.16
	600	600	1289.9	0.9463	1.5323	1.5323	395	1200.3	195	54.4	89.6	94.68	7.99	8.39	8.39	22.24
	600	1000	1248.8	0.5140	1.4450	1.4450	485	1203.3	285	57.4	45.5	88.50	4.21	4.44	4.44	11.78
F-85																
CONDENSER	300	150	247	0.500	0.36	0.36	200	226	ZERO	ZERO	21.0	41.43			10.78	81.93
200°F 30PSIA	400	400	263	0.20	0.36	0.36	200	226	"	"	37.0	160.6			17.37	74.69
H_G = 226 BTU/LB	500	1000	277	0.08	0.36	0.36	200	226	"	"	57.0	608.7			21.94	70.21
H_{FG} = 171.																

Critique by

Robert Brooks
1342 N. Jackson Street
Waukegan, IL 60085

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-166-13

June 29, 1977

Mr. Robert Brooks
1342 North Jackson
Waukegan, Illinois 60085

Dear Mr. Brooks:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Regarding the subject report, we have received many critiques of enormous diversity, and acknowledge your letter of 9/5/75. One of the two enclosures explains the reason for our response at this time, and summarizes the changes in our automotive propulsion program structure that have occurred following completion of SP43-17. Although the Wankel engine is not excluded from our current program, little further work is anticipated.

In response to the question raised in your letter with regard to rotor seal leakage and housing distortion problems in Wankel engines, we have enclosed a list of reference documents. The references recognize the existence of these problems, but they do not necessarily represent the most recent information because we are not actively studying IC rotary engines.

If the opportunity should arise in the future for us to do so, we will review the status of these problems and incorporate the data in our annual report to ERDA. In the meantime we trust that the reports listed may contain some of the information that you were seeking.

Sincerely,

H E Cotrill

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections Project

HEC:cr

Enclosure (2)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

ENCLOSURE

1. "Progress of Rotary Engines:, Dr. Ing. Albrecht Hartman, presented at the 2nd NATO/CCMS Symposium, Düsseldorf, November, 1974.

2. "Update on the Rotary Engine", David E. Cole, University of Michigan, Ann Arbor, Michigan, October 1973.

3. "The Wankel Engine", David E. Cole, Scientific American, August 1972.

4. John Hartley, The Engineer, pp. 44-49, December 6, 1973.

5. D. N. Williams, Iron Age, pp. 57-59, February 25, 1971.

Robert Brooks 9/4/75

Dr. R. Rhoads Stephenson:

Dear Dr. Stephenson:

Thank you very much for sending Volumes I & II of your study "Should We Have A New Engine". Your report provides a mountain of valuable information.

Regarding the Wankel engine, I note on page 3-15 you say it has "current rotor-seal and housing distortion problems". I would appreciate it if you would led me know the source of this information and the make of production rotary engine car that has these problems.

Cordially,

1342 N. Jackson, Waukegan, IL 60085 312-336-8256

Critique by

Queen Elizabeth The Queen Mother
Birkhall, Ballater
England

14

Ballater 228

BIRKHALL, BALLATER

11th September 1975

Dear Mr Stephenson

Queen Elizabeth The Queen Mother bids me write and thank you for your letter and for the copy of your Engine Report which Her Majesty is looking forward to studying.

The Queen Mother remembers well meeting you in July 1974 when you were presented by the Chef. Queen Elizabeth understands that Mr. Sealey is now visiting California and hopes very much that his holiday will be most enjoyable.

Her Majesty sends you personally her warmest good wishes for the future.

Yours sincerely, Alastair Aird

Comptroller to
Queen Elizabeth The Queen Mother

Mr. R. Rhoads Stephenson.

Critique by

Hon. Pete V. Domenici
of New Mexico
United States Senate
Committee on Public Works
Washington, DC 20510

15

United States Senate

COMMITTEE ON PUBLIC WORKS
WASHINGTON, D.C. 20510

September 16, 1975

The President
The White House
Washington, D.C. 20500

Dear Mr. President:

I am writing to urge you to embark on one of the most important domestic initiatives of the decade: the development of a fuel efficient, virtually pollution-free automobile engine.

As you have repeatedly noted, the tighter emission standards required of the internal combustion engine to protect the public health have come into conflict with our national energy policy of maximizing automotive fuel economy. In fact, difficulty in controlling automotive pollution has led many to consider permanently abandoning the nitrogen of oxides standard presently called for in the Clean Air Act. Such difficulties have even led some to despair whether we can achieve clean air in our cities anytime in the twentieth century.

It has been obvious to those of us working in this area that the ideal solution to our problems lies in developing a new pollution-free engine capable of greater fuel economy. Proposals for such a development, however, have consistently elicited a skeptical response from professionals both within industry and the federal government, on the theory that a quantum breakthrough is required to produce a significantly cleaner engine which uses less fuel.

There is now evidence that such professional skepticism may have been overly pessimistic. A recent report from the California Institute of Technology's respected Jet Propulsion Laboratory indicates that a fuel efficient engine capable of emissions well below the statutory standards is within reach.

The report I refer to is entitled, "Should We Have A New Engine?: An Automobile Power Systems Evaluation." It was produced as the result of a grant from Ford Motor Co., and presents an independent assessment of the longer term powerplant options available in this highly complex and controversial area of overriding national importance.

The President
September 16, 1975
Page Two

I have studied the report and I am convinced that its conclusions fully justify a careful examination of the course of our present efforts to deal with automobile pollution and fuel conservation. I say this because, after carefully sifting through available technical data, the report identifies two engines, the Stirling and Brayton, that possess exciting potential as alternative engines superior to the present internal combustion engine.

The primary recommendation of the report, as I see it, is contained in the following statement taken from page 3:

> "Begin immediately the rapid implementation of design changes to the car itself which can significantly reduce fuel consumption, independent of the kind of engine uses. Concurrently, accelerate and direct the development of two particularly promising alternate engines - the Brayton and Stirling engines - until one or both can be mass-produced, with introduction in the improved cars targeted for 1985 or sooner. In the interim, press the development of the conventional Otto engine to its limits."

The developmental price tag for such an alternative engine is estimated to be approximately $1 billion over the next decade; a small price for public health, energy independence, and a livable urban environment. When the potential benefits of the use of one or both of these engines is considered, that developmental cost is put more into its proper perspective. For instance, the report, on page 82, indicates that "introduction of the Stirling engine alone, at a net cost of about $8 billion, will save over 2 million bbl/day by the end of the century. A comparable increase of petroleum supply would require a capital investment of at least $20 billion." As the report further points out on page 86:

> "Expenditure of $150 million per year for 5 to 10 years is well within the historical R&D funding capability of the industry (albeit with some changes in priority) and very small compared to contemplated budgets for developing some new sources of energy. It is also a small total price to pay, compared to an annual petroleum cost saving on the order of $10 billion (at $11 per barrel) which would result after total conversion to the alternate engine. The industry could pay for this development program and, from an analysis of the potential for increased profits, this level of expenditure seems warranted. However, it is not at all

obvious that they will do so--given sales slumps, reduced budgets, and their historical interest in short-term-payoff R&D. It is in the national interest that these alternate engine development programs be successfully completed. Thus, government should provide incentives and/or share in the funding to ensure that this program will be accomplished. Ongoing automotive programs, sponsored by DOT and ERDA, provide ample precedent for governmental involvement. An appropriate government laboratory should monitor progress and participate in program direction at key decision points."

The other obvious offset against developmental costs is the real possibility that, as indicated by the report on page 59, these engines "would relegate the automobile to a secondary place in the list of major polluters." Given the immense social and environmental dividends that such a happy circumstance would bring to a wide range of air pollution related problems, we cannot fail to evaluate, carefully and thoroughly, the opportunities suggested by this report.

For these reasons, and others, Mr. President, I strongly urge you to take the lead and marshall the full resources of the federal government and, acting in concert with private industry, to initiate a sustained effort to develop a new automobile engine. I have communicated these same thoughts to Senator Muskie as Chairman of the Subcommittee on Environmental Pollution of the Senate Public Works Committee in the hope that effective and coordinated Congressional action can be taken.

I recognize that fiscal restraint is essential in face of the innumerable competing demands made on the federal budget. Nevertheless, I can imagine few national initiatives which promise greater social, energy, and environmental dividends than the development of a truly fuel efficient, low pollution automobile. I would respectfully urge your immediate and favorable consideration of such an initiative.

Sincerely,

Pete V. Domenici
United States Senator

United States Senate

COMMITTEE ON PUBLIC WORKS
WASHINGTON, D.C. 20510

September 16, 1975

Honorable Edmund S. Muskie
Chairman
Committee on Public Works
United States Senate
Washington, D. C.

Dear Mr. Chairman:

A recent report from the California Institute of Technology's Jet Propulsion Laboratory entitled "Should We Have a New Engine" has identified the Stirling and Brayton engines as having the potential of being truly fuel efficient, virtually pollution-free engines.

The importance of such a development can hardly be overestimated. At every turn, our attempts through the Clean Air Act to protect the public health in urban areas have been stymied by the inherent difficulties of cleaning up the internal combustion engine. Attempts to control pollution from the internal combustion engine by catalysis have only spawned a new round of pollutants. Delays granted the automakers have in turn meant the imposition of more draconian transportation control strategies on communities to achieve the public health-related requirements of the Clean Air Act. All the while, continued reliance on the internal combustion engine only serves to exacerbate both the energy crisis and our dependence on foreign oil supplies.

Given the immense social dividends that a new engine would bring, and their integral relationship to our present effort to amend the Clean Air Act, I would urge that you contact the committee's leadership and the subcommittee's ranking minority member about the possibility of holding subcommittee hearings in the near future on this critical topic. In fact, given the broad implications of the report, I suggest that following the subcommittee hearings you may want to ask the Senate leadership to request an in-depth review of the nation's efforts in this area, including the initiation of joint hearings by the Public Works, Commerce, and Interior Committees. I would hope that perhaps such hearings could be scheduled prior to our reassessing the automobile emission standards in full committee markup.

Honorable Edmund S. Muskie
September 16, 1975
Page Two

I know you are as intrigued as I am by the Jet Propulsion Laboratory's suggestion that about $1 billion invested in the Brayton and Stirling engines now could result in an annual petroleum cost savings of $10 billion in the future. That, plus the ecological benefits outlined in this report, offers a superb opportunity for timely legislative action.

If there is anything I can do to be of assistance, please do not hesitate to call upon me. Kindest personal regards.

Sincerely,

Pete V. Domenici

PVD/lrkd

September 16, 1975

release — Contact: Steve Bell

U. S. Senator
pete v. domenici
new mexico
1251 Dirksen Building
Washington, D. C. 20510
202—224-5521

WASHINGTON, D.C.--U.S. Sen. Pete Domenici (R-NM), a member of the Senate's Environmental Pollution Subcommittee, has asked for special joint hearings of three Senate Committees "as soon as possible" to consider a recent report that suggests a non-polluting auto engine is possible within a decade.

The report, "Should We Have a New Engine?," was issued last week by the Jet Propulsion Laboratory of the California Institute of Tehcnology, with funding by Ford Motor Co.

Domenici said that "my study of this report indicates that the technology may be available for a watershed breakthrough in our efforts to control auto pollution and to reduce gasoline consumption dramatically. The auto companies have been sluggish in their research and costs will require federal involvement."

In his letter to Environmental Pollution Subcommittee Chairman Sen. Edmund Muskie, Domenici said that "at every turn our attempts through the Clean Air Act to protect the public health in urban areas have been stymied by the inherent difficulties of cleaning up the internal combustion engine. Attempts to control pollution from the internal combustion engine by catalysts have only spawned a new round of pollutants."

Domenici called for joint hearings of the Senate Public Works, Commerce, and Interior Committees, prior to full Public Works Committee consideration of amendments to the Clean Air Act. The Environmental Pollution Subcommittee has been attempting to draft amendments to that act for more than three months.

The JPL study of new potential engines identified both the Brayton and the Stirling engines as technologically feasible alternatives to the present Otto (internal combustion) engine. Both engines, the report says, could be developed with an estimated investment in research and development of around $150 million annually over five to eight years. Savings in fuel economy, alone, from the new engines would be an estimated $10 billion annually (at an $11 per barrel petroleum cost).

Critique by

Jerry A. Peoples
2419 Greenhill Drive NW
Huntsville, AL 35810

16

Jerry A. Peoples
2419 Greenhill Dr. N. W.
Huntsville, Alabama 35810

September 17, 1975

Mr. R. Rhoads Stephenson
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Dear Dr. Stephenson

I want to thank you for sending me a copy of "An Automobile Power System Evaluation." I congratulate you and your staff for the professional characteristics of the report. The depth and variety of concept ~~was~~ is impressive. You certainly have made a contribution to those arguements regarding the nature of the future automobile.

Best Regards

Jerry A. Peoples

Jerry A. Peoples

17

Critique by

Curtiss-Wright Corporation
One Rotary Drive
Wood Ridge, NJ 07075

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-184-17

June 29, 1977

Mr. Charles Jones
Director of Engineering, Rotary Combustion Engines
Curtiss-Wright Corporation
One Rotary Drive
Wood-Ridge, New Jersey 07075

Dear Mr. Jones:

Subject: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

This letter is in response to your letters to Mr. R.A. Mercure of the ERDA and Dr. R.R. Stephenson of JPL. In the time period since your communication with Dr. Stephenson, JPL automotive assessment studies have been restructured. The current work and the critique response plan are summarized in the attachment.

Regarding your comment on our minimal recognition in Volume I Summary of Advanced Otto and Otto Stratified Charge engines, your point is well taken although you can appreciate the problem of condensing a large amount of technical data into a summary format. Although Volume I lacks discussion of these engines, the data presented in Figure 14, which compares the projected fuel economy potential of advanced configuration heat engines, does include both the Uniform Charge (UC) Otto and Stratified Charge engines.

Regarding your comments on terminology in respect to classifying heat engine technology as "Present," "Mature" or "Advanced," such ratings, of course, are subjective and suffer from the lack of industry-wide concensus. A consistent assumption we made for all "Advanced" configurations is that their high temperature components would be manufactured from ceramic materials in order to take advantage of increases in thermal efficiency. This assumption is consistent, for example, with the Advanced Brayton engine since it is the only configuration containing ceramic gasifier and power turbine wheels. Accordingly, the earlier versions of the Brayton engine are considered less "Advanced" even though they may have the benefit of a considerable amount of technological development. In this regard, the classification of the rotary engine as an Advanced UC or Stratified Charged Otto configuration may be somewhat misleading. The intent was to show the engine as "Advanced" relative to the progression of more conventional Otto cycle engines, i.e., reciprocating. The rating does not necessarily relate to the developmental status of rotary engines, per se.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

The latest Curtiss-Wright data published for the Stratified Charge Rotary engine is impressive relative to other engines. Using the methodology of the APSES report, the limited amount of such data unfortunately does not permit the extrapolation of these test results to corresponding Federal Urban Driving Cycle projections. We are of the opinion that this must be accomplished before meaningful comparisons can be made with other heat engines. In this regard, we would be interested in further conversations with you in advancement of our follow-on automotive study effort.

It is general knowledge, of course, that earlier versions of the rotary engine have met with less than complete success. As you know, the single auto manufacturer using the engine has experienced marketing problems with the rotary equipped vehicles. In addition, the decision of a major domestic automotive company to postpone introduction of the rotary engine because of high base level HC emissions and relatively poor fuel economy has not furthered the case. If your own recent developments with the Stratified Charge engine indicate that these trends can be reversed we would be pleased to discuss them with you.

In regard to our restricting complete vehicle comparisons in the Summary to only compact cars, we felt that the compact car would be the most meaningful example. In order to minimize duplication of data from Volume II, the fuel economy results in Volume I are presented for comparative purposes using a compact vehicle throughout. The approach provides a meaningful and consistent comparison of fuel consumption results for the "Present," "Mature," and "Advanced" engines for one class of automobile. But as you suggest, the trends inherently may not be parallel between different classes due to different power-to-weight ratios of particular engines.

We appreciate the effort you have taken to review the subject report, and found your critiques to be most stimulating. We are looking forward to a continuing interechange of information.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

CURTISS-WRIGHT CORPORATION

ONE ROTARY DRIVE . WOOD-RIDGE, NEW JERSEY 07075

September 22, 1975

Dr. R. Rhoads Stephenson
Jet Propulsion Laboratories
4800 Oak Grove Drive
Pasadena, California 91104

Dear Dr. Stephenson:

I wish to thank you for my copy of the CalTech JPL report "Should We Have A New Engine?".

I have not reviewed the entire report in detail, but have studied Chapters 2, 3 and 4 of Volume II, which cover areas related to my experience with Rotary Engines, at some length and wish to congratulate all involved with these sections on having done an excellent job.

My strongest concern, however, is that the Summary Volume I does not represent Chapters 3 and 4 of Volume II by either content or conclusions. The advanced Otto or Otto Stratified Charge concepts are not mentioned and their relative position never discussed. Furthermore, the audience to whom Volume I is addressed is completely different than those for whom Volume II was written and, therefore, Volume I must either put the entire picture in perspective or else clearly state that detailed study of the second volume is essential to cover those aspects not treated.

I do have some reservations about Volume II as well, but I consider them less serious because the informed reader is given sufficient facts to establish a more balanced overview. Specifically, the definition of "Mature" and "Advanced" is not consistent from Otto to the Brayton and Stirling cycles. "Mature" is represented as current state-of-the-art as demonstrated experimentally, partially in some cases, with existing technology. Yet the standard for "Present" Brayton engines is defined as the level of pre-prototypes which have seen exploratory field testing or test bed trials, whereas the "Mature" Braytons represent a fairly substantial step forward to reduce weight and cost as well as combined component efficiencies and complex transmission changes to solve existing operational problems.

The experimental rotary engines which have run at Curtiss-Wright and elsewhere not only represent a lesser technical advance, but at demonstrated fuel economies, size and weight can realize substantial passenger car fuel consumption improvements without requiring any further developments. For example, the 1963 vintage Otto cycle carbureted "pre-prototype " rotary at Curtiss-Wright, as documented, would probably register the 15% "Advanced" status system (OEE) improvement you attribute to "propagated vehicle weight reduction" on page 4-32, without requiring the addition of charge stratification and ceramic-technology reduced heat losses, by virtue of weight and size advantages coupled witha basic engine (SFC) fuel consumption equal or better than the "Present" Otto cycle engines. Furthermore, the Stratified Charge Rotaries have, in our publications you reference, already demonstrated the approximately 15% engine fuel economy gain over conventional piston Otto engines on a Specific Fuel Consumption basis alone. Any further gains on your OEE basis would be additive, reducing system fuel consumption accordingly. Application of similar standards of classification as used for the continuous combustion cycles would group these engines as "Mature", recognizing that the technology for low fuel consumption Rotary Engines as well as technology for Rotary Engine emission control is currently available.

This issue is particularly grave because classification of either of these rotaries, with the desirable but not essential (as discussed above) addition of ceramic-technology, as "Advanced" automatically removed the engine from any further mention in Volume I. This, for the vast majority of readers, removed the engine from any further consideration whatever.

Finally, restriction of complete vehicle comparisons to only the compact car size, ignores the irreversible trend towards even smaller and lighter vehicles and, for that reason, may be seriously misleading. As stated above, we believe that not only will the Rotary Stratified Charge engine be closely competitive with the Brayton and Stirling cycle engines in the compact to large size automobiles but, more importantly, will outstrip both of these larger and heavier powerplants in the small and mini-sized vehicles. Putting both engine types on what we regard as more comparable maturity planes would further accentuate the advantages we anticipate.

Charles Jones
Director of Engineering
Rotary Combustion Engines

CJ:dd

CURTISS-WRIGHT CORPORATION

ONE ROTARY DRIVE • WOOD-RIDGE, NEW JERSEY 07075

March 31, 1976

Mr. R. Mercure
U. S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Dear Mr. Mercure:

In response to your "Announcement" distributed at the SAE International Congress in Detroit last February, a copy of the JPL critique sent to Dr. Stephenson last September and current test data is enclosed.

The main objection raised in the September 22nd, 1975 letter can be summarized as an inconsistent engine "maturity" classification. The recent stratified charge data being transmitted with this letter supports the position that stratified charge rotary engines currently on our test stands have demonstrated, with significantly improved size and weight characteristics, specific fuel consumptions in the principal road-load operating range superior to the present automotive diesel engines. Development of these engines is an active program at Curtiss-Wright and will, we believe, lead to further improvements in the near future.

Figure 1 compares our experimental stratified charge rotary engine data, at a representative 2000 RPM, with the Ricardo Mark V Diesel, (ref. 1) which we believe to be representative of present automotive diesel engines, many of which were directly derived from either the Mark V or prior Mark IV. Figures 2 and 3 compare "raw" emission results to published (ref. 2) results for the Texaco TCCS reciprocating stratified charge engine. We expect further improvement in HC, but what is particularly noteworthy is the low NO_x values, which are a strong plus for the rotary. In addition, both the Texaco engine which has shown good fuel economy and good emission control in vehicles, and our direct injected rotaries, are multi-fuel engines, offering a significant national resources advantage through their capability to burn a wide range of fuels. The gain in BTU per barrel of crude through use of a middle-distillate fuel has been developed in detail by Texaco in their recent publications (Ref. 3). We, of course, welcome further inquiries and would encourage a running dialogue, including visits to our facility, with your investigators.

The last point in my letter to JPL raises the issue of a stronger advantage for rotary engines in the smaller cars, where the weight is even more important. This point should be confirmed by extrapolating the JPL calculations to the smaller vehicle end and publishing the results.

In addition to our data, you should also solicit information from Toyo-Kogyo. The 1976 Mazda's, as you are probably aware, have demonstrated significant fuel consumption improvements over earlier models and are competitive with other high performance vehicles. If their performance is properly scaled to an "Otto Engine Equivalent" (OEE) basis, the comparative rating should prove favorable. We have also taken the liberty of enclosing pertinent SAE papers.

Very truly yours,

Charles Jones
Director of Engineering
Rotary Combustion Engines

CJ:dd

cc: Dr. K. Yamamoto (Toyo-Kogyo) - Japan

Enclosures:

1 - Letter C. Jones to Dr. R. Rhoads Stephenson dated 9/22/75 re JPL Report
2 - Ref. 1 - EPA-460/3-74-011A Report Dated October 1975 entitled "A Study of Stratified Charge for Light Duty Power Plants", Vol. 1
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105
3 - Ref. 2 - Report - "The Texaco Controlled-Combustion System - A Stratified Charge Engine Concept - Review and Current Status by W. T. Tierney, E. Mitchell and M. Alperstein
Presented at The Institution of Mechanical Engineers - "Power Plants and Future Fuels" Conference - London, England - January 1975
4 - Ref. 3 - Article - "Fuels for Transportation" - Published in Automotive Engineering, January 1976
5 - Fig. 1 - Comparison of Stratified Charge Data with Ricardo Mark V Diesel
6 - Figs. 2 & 3 - Compare "raw" Emission Results to Published Results for Texaco TCCS Reciprocating Stratified Charge Engine
7 - SAE Reports #650723, #720468 and #741206

CURTISS-WRIGHT
ROTARY COMBUSTION ENGINES
PART LOAD FUEL CONSUMPTION

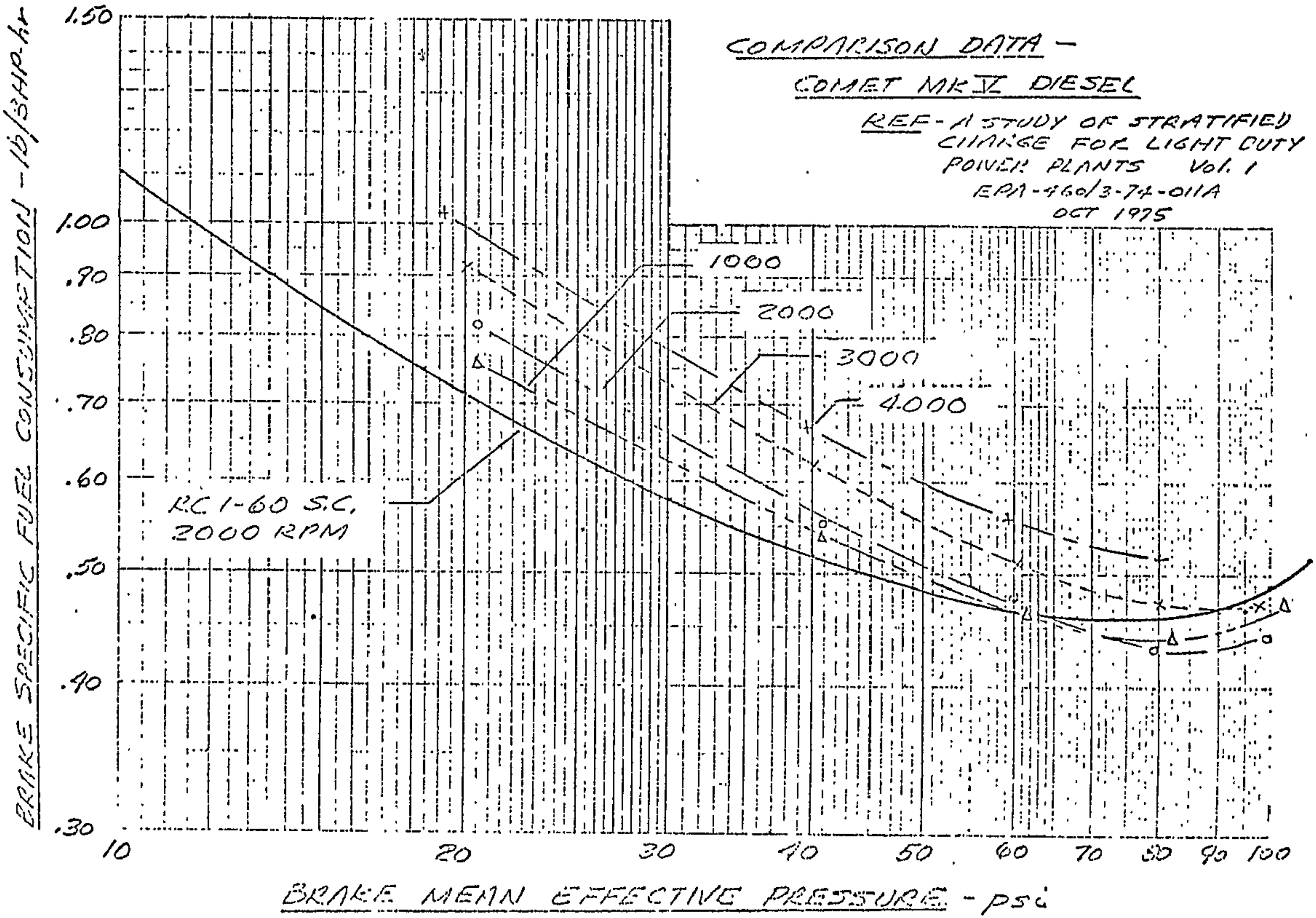
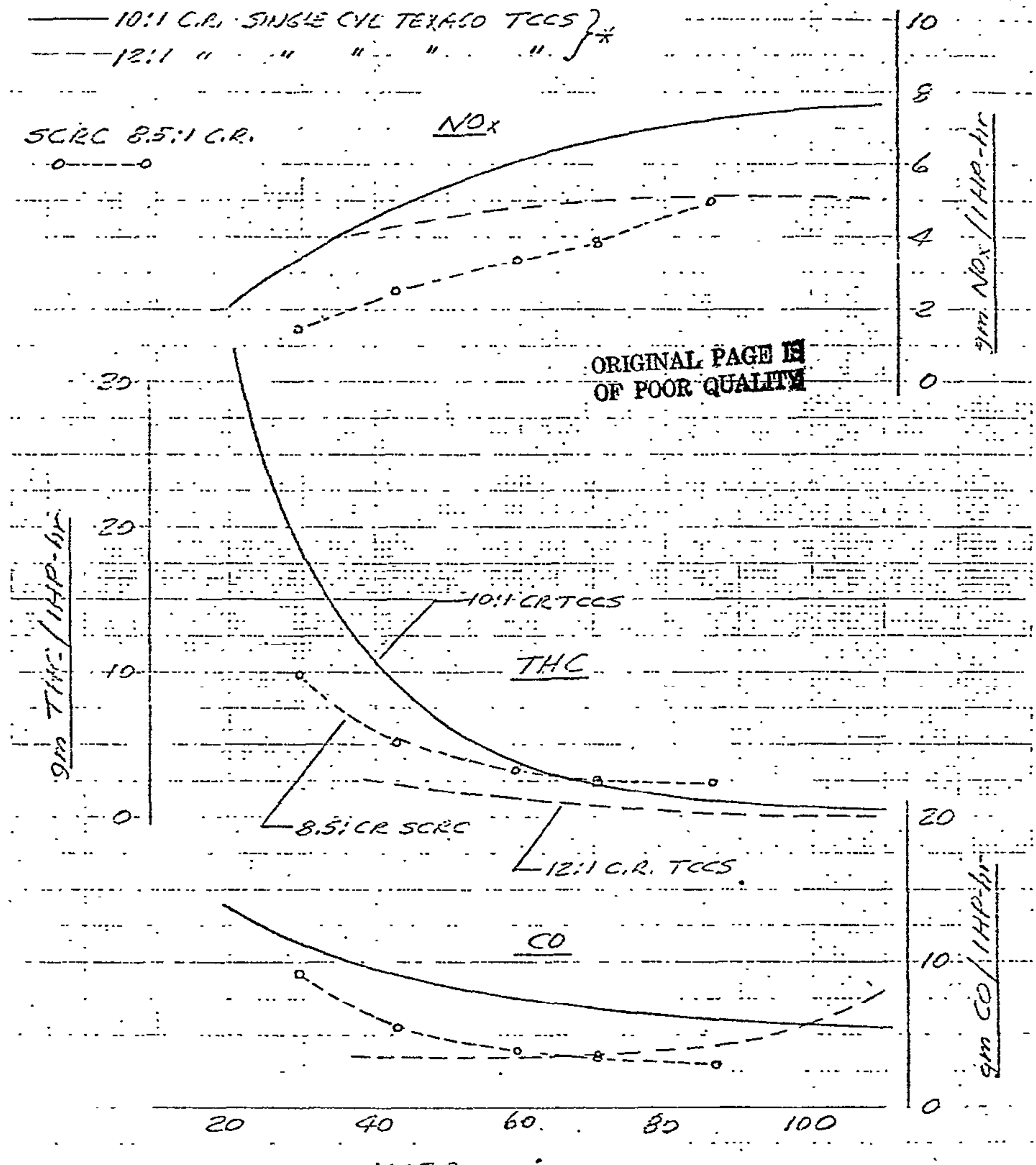


FIG. 1

CURTISS-WRIGHT
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
2000 RPM
INDICATED SPECIFIC EMISSIONS
GASOLINE FUEL



* REF. - THE TEXACO CONTROLLED-COMBUSTION SYSTEM A STRATIFIED CHARGE ENGINE CONCEPT REVIEW & STATUS PRESENTED AT THE INST. OF MECH. ENGRS. LONDON - JAN 1975 -

FIG. 2

CURTISS-WRIGHT
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
2000 RPM
PART LOAD FUEL CONSUMPTION

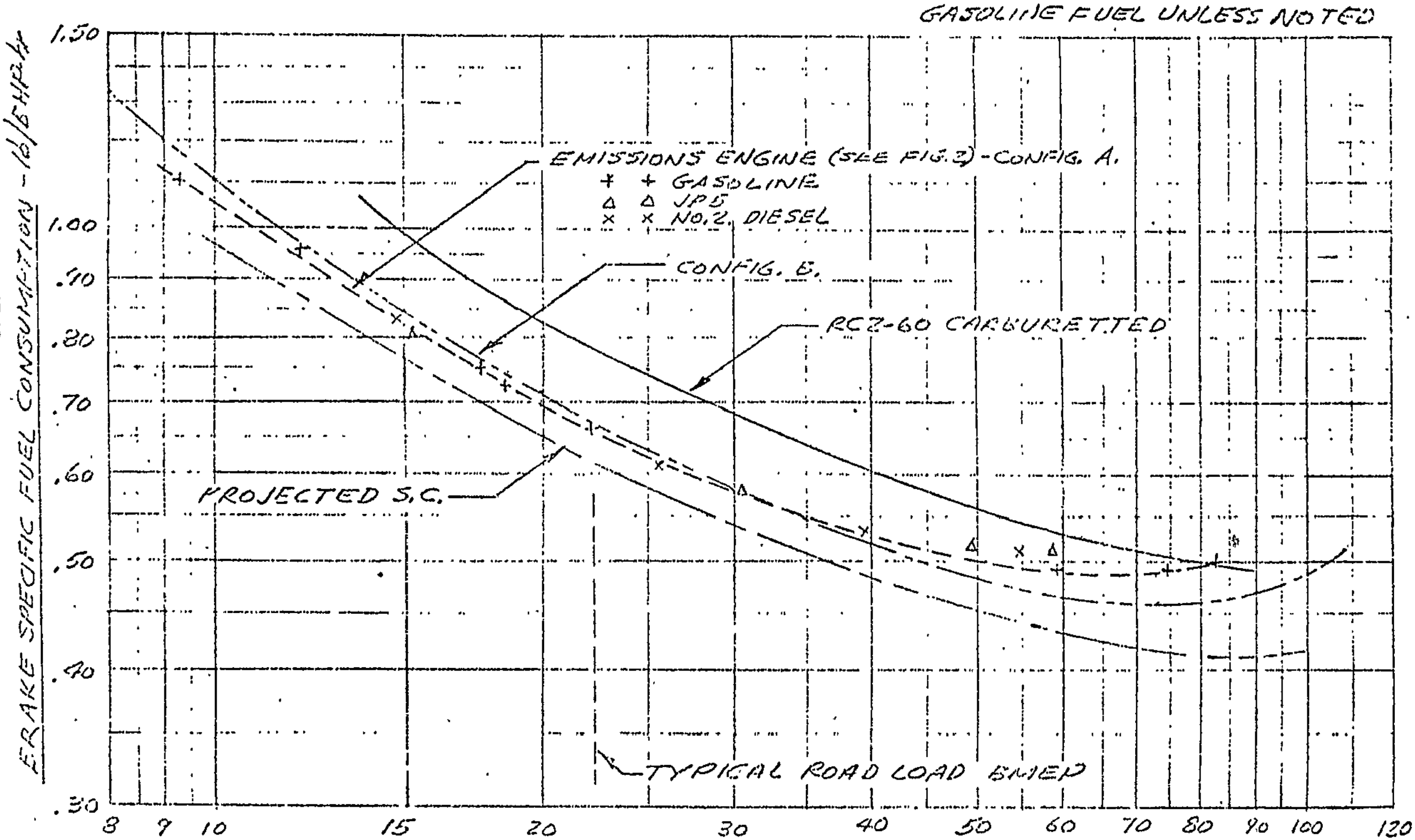


FIG. 9.

Critique by

Daimler-Benz Aktiengesellschaft
7 Stuttgart 60 (Unterturkheim)
West Germany

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

18

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-177-18

June 29, 1977

Professor Dr. -Ing. Hans Joachim Förster, Direktor
Daimler-Benz Aktiengesellschaft
Stuttgart-Untertuerkheim
7 Stuttgart 60 Postfach 202
West Germany

Dear Professor Forster:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded your letter to us for reply. Our automotive engine studies were subsequently restructured, and a summary of the current program is enclosed. Our response to the subject critiques is a part of the program.

The scope of the current effort does not include new technical work in direct response to specific points of each critique. Our approach is to note in detail the composite concerns expressed by the writers and make them part of the future work in several task areas of the ATSP project. Thus, our responses to the critiques will be implicit in the future work, rather than explicitly stated point by point in each letter.

We would like to offer some general comments, however, regarding the questions raised in your letter which concern various aspects of the Otto-engine equivalent (OEE) horsepower of Brayton-engined cars. Based on results of computations using our vehicle simulation computer program (VEEP), we find that acceleration performance with a hydromechanical continuously variable transmission (CVT) is, in fact, noticably faster than with the conventional hydrokinetic transmission. Thisis supported by a separate simulation cited in SAE Paper #740308, by E. Orshansky, et al; and thus a lower engine horsepower is required for the same performance level. The 50 to 80 mph DOT passing criterion, where the two transmission may yield more similar results, was not imposed in our study as a requirement for Otto equivalency. Since highway passing performance is an important safety consideration, we will review the impact of this crierion in future work.

As to your second question regarding comparisons among different engine-transmission combinations, the single-shaft Brayton engine was assigned a CVT because it needs one in order to make it feasible, due to its unfavorable torque-speed curve. The torque characteristic of the two-shaft Brayton, however, allows it to be coupled to a typical three-speed automatic transmission. The type of CVT required for the single-shaft Brayton (see pp. 5-25, Vol. II) can be simpler than a general-purpose CVT for other engine types. Because of the long and generally unsuccessful development history of CVT's up to 1974, we concluded at that time that a

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JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

general-purpose CVT might not be attainable by the early 1980's. This entire area, and the question of which transmission types to include in the "Mature" baseline, deserves serious attention in our future study efforts.

In response to your third question, regarding power augmentation, no aids were assumed for the Brayton engine. In this respect, the comparison of the engines was made in a comparable manner. We hope to make a similar comparison with both engines having power augmentation including, as you suggested, the diesel with the turbo-charger.

We appreciate your efforts in reviewing the subject report and look forward to a continued interchange of information. Your penetrating questions will be addressed more fully in our follow-on studies.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections Project

HEC:gpa

Enclosure

DAIMLER-BENZ AKTIENGESELLSCHAFT
STUTTGART-UNTERTÜRKHEIM

Daimler-Benz Aktiengesellschaft · 7000 Stuttgart 60 · Postfach 202

U.S. Energy Research and Development
Administration
Attn.: R. Mercure
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachussetts Avenue, N.W.
Washington D.C. 20 545

Ihre Zeichen	Ihre Nachricht vom	Unsere Zeichen	Telefon-Durchwahl (0711)	Datum
		E6SB Dr. Co/p Dr. Conrad Bei Antwort bitte angeben	302 7825	23.08.1976

A remarkable result of the JPL-report is the statement, that a 118 HP-single-shaft gasturbine and a 175 HP-Otto-engine in a car of the same type give the same acceleration from start. How is this possible?

One reason given in the JPL-report is, that the turbine driven car is lighter because of the lower weight of the turbine, the lower power and the resulting " weight propagation ". However this explains only a difference in power of about 30 HP and not of 57. There must be therefore additional reasons, one of them could be the type of transmission used. (On page 5-25/26 of the report it is mentioned for example that the hydromechanical transmission is a mean to improve the acceleration).

On page 3.15-3.16 the compared Otto-engine is said to be equipped with a conventional automatic transmission, that will say, it is assumed, that a single-shaft Gasturbine with hydromechanical transmission accelerates better than a SI-engine with the same power and with an automatic transmission or otherwise expressed: the hydromechanical transmission converts the same power much better than the conventional automatic transmission. But according to our calculations, at least for the SI-engine this is not the case. For example the hydromechanical transmission decreases the time for accelaeration to 60 mph only by less than 1/2 sec, the lead after 4 sec is one car length, after 10 sec about 2 car lengths, and the DOT-passing distance for 50/80 mph is practically the same for both transmissions.

We have therefore the following three questions:

First question: Is it your opinion that the acceleration from start with a hydromechanical transmission instead of a conventional automotive transmission with torque convertor is so much better, that one needs by about 20 HP less for the same acceleration?

Second question: Supposed the hydromechanical transmission is better than the conventional, why is than the gasturbine + hydromechanical transmission compared to an Otto-engine + conventional transmission (pages 3-15 and 16) and not to an Otto-engine + hydromechanical transmission ?

Third question: Are there any other facts (in addition to the above mentioned weight-effect) which are typical for the gasturbine and not for the Otto-engine and which allow to decrease the gasturbine design power by about 20-25 HP without a decrease in acceleration, for example is there a kind of power augmentation (waterinjection etc.) ?

We would be glad to receive a detailed list of the facts which cause the 57 HP-difference between the Otto-engine and the equivalent single-shaft gasturbine.

Yours sincerely
Daimler-Benz Aktiengesellschaft

Prof. Förster Tiefenbacher

Copy: Mr. Gregory J. Nunz, Manager
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91 103

Prof. Dr.-Ing. HANS JOACHIM FÖRSTER
Direktor
i. Hs. DAIMLER-BENZ AKTIENGESELLSCHAFT

7 STUTTGART 60 (Untertürkheim)
☎ 3 02 22 84

October 7, 1975

Mr. R. Rhoads Stephenson

Jet Propulsion Laboratory
California Institute of
Technology

48oo Oak Drive, Pasadena

California 91103

Dear Mr. Stephenson,

Thank you very much for the copy of the Caltech JPL report entitled "Should we have a new engine? An Automobile Power Systems Evalution". We are studying this report in detail with interest. A first survey give rise to the question whether the performance of cars with Brayton or Stirling engines might not have been over-evaluated by the fact that the maximum power needed for a comparable performance with the Otto-Engine has been reduced to much. Another point is whether the efficiency of smaller engines will go down too, since the low maximum power of cars fitted with the Brayton or Stirling engine is one of the main reasons in favour of the two systems. The evaluation of the overall performance of cars fitted with different engines can be a very important subject.
The not so favourable results referring to the Diesel-Engine do not agree with our own experiences, especially when you take turbo charged versions into account.

Of course these are only preliminary remarcks which may lose there substance when we will have got a better understanding by a thorough study of the report.

Yours sincerely,

Critique by

Brendan Trainor
2041 Holly Drive
Hollywood, CA 90028

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

19

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-165-19

June 29, 1977

Mr. Brendan Trainor
2041 Holly Dr.
Hollywood, California 90028

Dear Mr. Trainor:

Subject: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

We appreciate the interest that you expressed in your letter regarding the subject report. Because of the strong interest of the U.S. Energy Research and Development Administration in transportation energy conservation they have sponsored at JPL a follow-on effort in automotive technology assessment. The restructured program is summarized in the enclosure.

In our follow-on study we will address most of the issues you identified, and in concurrence with your suggestion we intend to interview Richard Smith on the subject of Rankine engines including comparative assessments relative to other classes of automotive engines. His contemporary experience in Rankine cycle engines should enhance his contribution to the overall evaluation of alternative automotive engines. Thank you for bringing this to our attention.

Sincerely,

H E Cotrill

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

Brendan Trainor

P.O. Box 351

Hollywood,90028

R. Rhoads Stephensen

Principal Investigator

Automobile Power Systems Evaluation Study

Mr. Stephensen:

I am thankful to you for mailing me a copy of your meticulous report on steam, gas turbine and Stirling heat engines. Remembering that I am a journalist interested in alternative engineering, I respect the amount of work that has gone into your report. It is a carefully considered, well argumented piece that should be of invaluable reference to concerned citizens. Your Chapter 12 in Volume 2 is especialy invaluable.

However, as one who has been interested in the Rankine engine, I would like to point out some glaring errors, and also some underestimates of performance regarding the Rankine engine, both historically and as represented in the work of Richard Smith, who, it should be remembered, has over fourteen years direct experience in the field, and is the only steam manufacturer who builds road vehicles for Paying customers.

First, in 7.1.1., you describe steamers as losing out in competition to Otto engines because of " high weight, limited range, high manufacturing cost, and overall low economy of operation." I must admit that I cannot find any reputable automotive historian to corroborate that. With a few exceptions, steam cars (as opposed to steam traction farm plows and steam rollers) are consistently recorded as much smaller and lighter than their I.C. rivals. The Stanley racers were the first wind tunnel tested racing cars and weighed 1800 lbs., the White racers were also extra light in comparison to the Mercedes, Napiers, Fords and Chryslers they raced, and usually bested. The racing cars had oversized boilers in comparison to the production cars which were also generally lighter than their I.C. counterparts. The Dobles were luxury limousins but their engine compartments were still somewhat smaller and lighter as a system than their counterpart Rolls Royce. It should be pointed out that we compare complete engine systems. That is, I.C. engines, auxiliaries, transmissions and differential vs. steam generators, engines and coupling gears. No steam engine worth its name should have to have a transmission. It is simply unheard of until modern times to require a transmission.

As to limited range, steamers were the first cars to go from Boston to Philly, to cross the Alps in Europe, and scored high or won every endurance race run while the they were allowed to compete. It is true that the Stanleys did not use condensors until 1916, giving them 40-50 mile filling ranges. However, it did not take long to refill the tanks. The Whites during that time had excellent range, the Dobles improved still further. It must be remembered that in those days I.C. cars were notorious for breaking down and ranges were competive.

As to high manufacturing cost, I.C. manufacturers, of course, did not invent the assembly line. Although a steamer would cost you ten times as much as a model T, it could last you ten times longer, provide a noiseless, pleasant, safe ride, and would not pollute the air. And as the articles I mailed you testify, people in those days noticed that.

Nowhere can I find that steamers had higher maintenance costs. This statement certainly suprises me. So does sections 7.6.1. and 7.6.2. How Rankine maintenance compares to gas turbine or Stirling I don't know, but I'm sure it is superior to Otto engines with catalytic convertors. The absence of moving parts, clutch and transmission attest to that.

In 7.1.4 I take exception to your assumption that variable pressure steam generators and fixed-admission P.D. expanders are the best steam design. Richard calls fixed cut-off a "disaster" in steam engineering. Although his engine, custom designed, is expensive, he feels his design could be massed produced easily and cheaply.

Perhaps the question of weight and cost is heavily dependent on the amount of stainless steel used in the generator. The Dobles were all stainless steel, and expensive, but indestructible, requiring very little manintenance. Smith does not use much stainless steel in his design, gets good endurance, and acceptably low maintenance.

In short, I think that steam is mature now, and could be mass produced now. It offers several advantages over the turbine: better torque at part load, lower production costs (I believe that), and better fuel economy in urban and suburban driving cycles. I think that the Smith engine could be on the road in three years, saving millions of barrels of oil in lubrication and real fuel consumption (as opposed to pheney dynanometer EPA tests) . I take exception to chart 7-11; a Smith engine uses one quart of oil every 2,000 miles, no oil change necessary.

Changeover from Smith engine to hydrogen Stirling engine could be easily accomplished. Steam's superior torque to hydrogen may find some applications where it will always be superior.

Fuel consumption by Mature and advanced Stirling, if it is as you projected, may very well be superior to Rankine. However, even in the future smaller vehicles, used primarily in urban cycle, may be better off with steam.

But if Rankine is not ultimate answer to fuel consumption, I still regret that Smith was not interviewed, since he has the most experience and knowledge of anyone in the field. The results for the money spent gotten by Lear and S.P.S. and Aerojet Rocket are ridiculously poor compared to Smith and the historical steamers.

Thank you again,

Brendan Trainor

Critique by

PowerDynetics, Incorporated
PO Box 5710
Sherman Oaks, CA 91413

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

20

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-179-20

June 29, 1977

Mr. Homer J. Wood, President
Power Dynetics, Inc.
P.O. Box 5710
Sherman Oaks, CA 91413

Dear Mr. Wood:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. Robert A. Mercure of the U.S. Energy Research and Development Administration (ERDA) has forwarded to us your letter along with its Reference 2 (your letter to Mr. Richard D. Burtz of Steam Power Systems). Subsequent to receipt of your correspondence, our automotive studies were restructured and a critique response plan developed as summarized in the enclosure.

Your letter to Mr. Burtz contains a number of statements on thermodynamic cycles, availability of viable ceramics, lack of recuperator or regenerator, and scaling to small sizes of the Brayton engines that disagree with statements in the subject report. We acknowledge your well delineated points and feel that it is important that such significant differences of opinion be fully understood and resolved. The several points you brought up together with related ones from other critiques will be addressed in the on-going study.

We appreciate your interest in the study, and your thoughtful critique of the report will be valuable in our follow-on work. In those areas where we are not in total agreement future dialogues should prove to be quite productive. We would welcome an opportunity to visit with you at the time the Rankine engine work is updated.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

PowerDynetics, Incorporated | *PDI*

Post Office Box 5710 • Sherman Oaks, California 91413 • Phone (213) 783-8162

12 April, 1976
Ref. No. 10422

U.S. Energy Research & Development Administration
Division of Transportation Energy Conservation
20 Massachusetts Avenue, NorthWest
Washington, D. C. 20545

Attention: Mr. Robert A. Mercure
Heat Engine Systems Branch

Reference:
1) Your letter dated April 6, 1976.
2) Letter Wood to Burtz (SPS) 10 October 1975, Ref. No. 10224A.

Dear Mr. Mercure:

In reply to your request contained in reference 1, I am enclosing a copy of reference 2, which was released publically at a California legislative committee meeting on 18 November 1975. After discussion of this matter with our current clientele, I have decided to make reference 2 my only response.

To provide an adequate and properly documented critique of the JPL report would require time that we do not have available and funding of the magnitude of $100,000 or more. Use of my name, PowerDynetics, Incorporated, or H. J. Wood and Associates in a manner that would imply approval of the JPL report or any revision thereof is specifically not authorized.

I regret that we are unable to accommodate you in this matter.

Yours very truly,

POWERDYNETICS, INCORPORATED

Homer J. Wood

Homer J. Wood, President

HJW/bj
encl.

cc: W. A. Bass

PowerDynetics, Incorporated | ***PDI*** COPY

Post Office Box 5710 • Sherman Oaks, California 91413 • Phone (213) 783-8162

10 October, 1975
Reference #10224

STEAM POWER SYSTEMS
7617 Convoy Court
San Diego, Calif., 92111

cc: E. Cox
W. Bass

Attention: Mr. Richard D. Burtz
General Manager

Subject: AUTOMOBILE POWER PLANTS

Reference:

1) "Should We Have a New Engine?" Vol. I and II, August 1975. Jet Propulsion Lab., California Institute of Technology.
2) SAE 660161, "A Polytropic Technique for Gas Turbine Performance Prediction and Evaluation," January, 1966. Homer J. Wood.
3) SAE 690036, "Influence of Gas Turbine Cycle Parameters on Regenerator Geometry," January 1969. Homer J. Wood and William A. Bass III.
4) SAE 739135, "Performance Potential of Single-Stage Gas Turbine Engines," IECEC Meeting Paper, August, 1973. Homer J. Wood.
5) NTIS #PB-202-251, "Manufacturing Cost Study of Selected Gas Turbine Automobile Engine Concepts," August 1971. E. S. Wright, et al/United Aircraft Research Labs.
6) Gas Turbine World, pages 38 and 40. September 1975.

Gentlemen:

This is to present my comments on reference 1 in confirmation of opinions expressed at our conference of 8 September. As agreed then, my main focus will be on JPL treatment of the Brayton Cycle engine. Copies of references 2, 3, 4, and 5 were handed to you at that time. A copy of reference 6 is part of each copy of this letter.

Chapter 5 of Vol. II, reference 1, contains the technical arguments leading to a conclusion that Brayton engines are one of the two leading candidates for a strongly-motivated replacement of Otto-cycle engines. It is not possible to prove that conclusion to be in error, but it certainly can be questioned as to its dependence on manufacturing technologies for which there is no proof of practicality. In this context, the most doubtful element is the ceramic disc regenerator.

PDI has been intensively involved in design and manufacturing cost studies regarding gas turbines vs. diesels for industrial vehicles since 1964. This work has been for Deere, Cummins, United Aircraft, and Teledyne, and involved manufacturing cost studies and iterative design activities. Furthermore, "RSS-7" of reference 5 was designed by PDI as an automobile engine, and introduced a tunnel-sealed all-metal regenerator as an alternate to disc types.

PDI did not participate directly in the cost analyses of reference 5; although these estimates have been challenged, they represent far more depth than reference 1. Behind them lie several years of joint Deere, UAC, and PDI studies of similar engines in lower production quantities commensurate with an industrial market.* (Incidentally, the footnote on page 133 of reference 5 is in error. More recent analyses have shown that titanium is not necessary. Furthermore, no engine proposed therein except "RFT-4" used an aluminum rotor.) "RFT-4" is directly comparable to the "mature" Brayton engine of reference 1, and will be discussed later. Figure 51 shows RFT-4 to have highest manufacturing costs in spite of a compromise in BSFC to reduce those costs. Table XXVI and Figure 52 show RSS-7 to have lowest "cost-of-ownership," and this difference was based on much lower fuel costs than are now projected. Note m.p.g. figures in Table XXVI.

References 2 and 3 present analytical methods specifically evolved to cope with difficulties PDI encountered in evaluating vehicular gas turbines, and their validity has been verified by UAC (recently changed to "UTC") and other clients. Reference 3 is particularly important in providing a methodology for minimizing bulk and cost of recuperators or regenerators. All realistic production cost analyses of which we are aware have shown that such minimization is essential to bringing gas turbine costs to competitive levels. Reference 3 demonstrates that effectiveness (assumed by JPL at a flat 0.90 at maximum power) is not a valid parameter for heat exchanger optimization.

Using Reference 3 techniques, we have repeatedly demonstrated to skeptical clients that a pressure ratio of 4:1 is not optimum for vehicular service. The arguments are complex, but relate to part-load and idling fuel economy integrated over a rational driving load cycle as well as reduction in recuperator/regenerator manufacturing costs per horsepower. We have applied these methods to "mature" and "advanced" Brayton engines described in reference 1, and conclude that neither is rationally optimized for its claimed state-of-the-art status. However, neither involves thermodynamic impossibilities —— just inherent configurations that are not compatible with claims of low production cost.**

I see the major obstacle to both mature and advanced Brayton engines to be lack of a viable recuperator or regenerator. In spite of over 15 years of serious development, a ceramic disc regenerator with durable seals is not available. Furthermore, it may never be available because of inherent problems involved in forcing a matrix to function as a sealing element and a pressure vessel as well as performing a heat transfer function. To commit substantial development funds to Brayton engines without an assured economic solution for this essential component would be folly. There are other possibilities than the ceramic disc, but our studies indicate little hope for their manufacturing cost being reduced to levels acceptable for automobiles (as distinct from diesel-competitive truck and bus service). Reference 6 is an important and realistic appraisal.

*PDI was very active in this background.

**RFT-4 in reference 5 would have a much larger and more expensive regenerator to match RSS-7 fuel consumption.

Steam Power Systems
San Diego, Calif., 92111
Mr. Richard D. Burtz

10 October, 1975
Reference #10224
Page three of four

JPL seems to have accepted claims of ceramics enthusiasts to the point that they suggest that both "mature" and "advanced" Brayton engines could be available by 1985.* That is absurdity, and no responsible gas turbine engineer I know has any such confidence that known ceramic problems and commensurate manufacturing cost difficulties will be solved in any such time span. I am strongly of the opinion that a viable ceramic rotor (axial or radial) for a gas turbine is hopelessly impractical unless a non-brittle ceramic is discovered. Furthermore, a viable radial turbine is even less likely than an axial.

Another blind spot in JPL view of Brayton engines is their lack of adequate variations of cost/HP with engine size. I have been working with miniaturized turbomachinery since 1945, and a lot has been learned about cutting costs in small components. However, a lot more must be learned (if it can be learned at all!) before Brayton engines could be cheap enough for "Mini" and "Small" automobiles.

JPL's enthusiasm for Stirling engines seems remarkable naive in view of the fact (I have checked this rather carefully) that only one road vehicle in the world is running with such a power plant (the GM Stirling-battery hybrid is not significant). It is a bus operated in Europe by Phillips, and it is far from demonstrating practical road performance competitive with either gas turbines or diesels. Our clients that have made serious cost studies of Stirling, Brayton and Diesel engines are firmly convinced that manufacturing costs are prohibitive for Stirlings based on probable evolution from present technology. This contrasts with a JPL conviction that no "breakthroughs" are necessary.

I emphasize the lack of vehicular experience, since this is an aspect in which Brayton engines are not deficient, there being a 25-year background in a wide variety of vehicles. A great deal has been learned from those field tests. To give Stirling engines a top rating from their present field evaluation status is very naive. In other words, Stirlings are far behind Braytons in current evolutionary status as to knowledge of what are practical and durable mechanisms.** Known problem areas are rollsock seals and cylinder heads (including heat exchangers).

Although not very important to SPS, JPL is obviously unaware of recent advancements in diesel technology. Probably their "fact finders" ran into unwillingness to reveal performances and technologies currently regarded as highly proprietary. In any event, the advanced diesel is much more attractive than they indicate.

Part of the apparent merits of Brayton engines as seen by JPL is their consistent introduction of lower installed power for the same performance. This can be shown to be related to an inconsistent policy with respect to introduction of advanced transmission concepts. From my viewpoint, the only factor significantly affecting installed power for a given automobile class is weight/HP of engine plus transmission.

*See Table 12-5, Vol. II, which also shows the absurdity that development costs would be equal.

**Table 12-5, Vol. II actually places a "mature" Stirling two years ahead of a "mature" Brayton! Another absurdity!

Steam Power Systems
San Diego, Calif., 92111
Mr. Richard D. Burtz

10 October, 1975
Reference #10224

Automotive steam engines are not within my experience, and I remain skeptical of their ultimate viability in competition with Otto and Diesel engines. Regardless of that, they certainly have plenty of practical vehicular experience with obvious evolutionary effects (as contrasted with Stirling engines).

I found section 2.5.2 of reference 1, Vol. II to be a particularly bad treatise on thermodynamics, which managed to draw a ridiculous conclusion that engines having condensable working fluids have inherent inefficiencies that cannot be avoided. This is not even true of water as the working fluid unless the choice of cycles is limited to those discussed by JPL. Modern steam central power stations operate at thermal efficiencies above 40% even when they are rated on H.H.V. instead of L.H.V. fuel standards. Thus, in a generalized thermodynamic review (which 2.5.2 pretends to be), those condensable-fluid power plants are as efficient as diesels, and it takes binary or cascaded cycles to beat them. Nonetheless JPL uses 2.5.2 arguments even in press releases to degrade Rankine engines.

Of course the various cycles used in large steam power plants involve lots of strategies (such as wet condenser towers) that are not available to automobiles. Just how much this inhibits practical Rankine engines is unclear to me, my opinion being somewhat prejudiced by overblown claims of Lear and others of his ilk. Accordingly, I must leave it to SPS to critique JPL in their evaluations of practical Rankine automobile engines.

Obviously there is much more fault that could be found with JPL's exercise in academic effrontery, but this is already a long letter. I hope it will be of some assistance to you. Just remember that my own opinion is favorable to advanced gas turbines in trucks and buses (but those engines are obviously not visible to JPL). As to automobiles, I continue to think they will be Otto or Diesel engines, with a piston Brayton engine having a much better chance than JPL indicates.

Yours very truly,

POWERDYNETICS, INCORPORATED

Homer J. Wood

Homer J. Wood, President

HJW/bj
encls.

Engineering news and trends

Westinghouse Canada plans for 35,000-hp 2-shaft machine

Westinghouse Canada is beginning to publicly release information on its new industrial 2-shaft gas turbine which is ISO rated at about 35,000 hp. Designated the W-352 — intended for pipeline and process applications.

Two-shaft design developed by Westinghouse Canada's engineering department is said to be basically derived from service-proven W-251 technology. Technical paper on the W-352's design features and performance will be presented at the 4th annual Turbomachinery Symposium being held at Texas A&M University in College Station, Texas, October 14 through 16.

Attendance limited to first 700 who sign up — requires registering in advance. Costs $130. For more information we suggest you call the symposium chairman, Dr. Boyce, at (713) 845-2924.

Allison sales up 45 per cent in past five years

Detroit Diesel Allison sales of industrial and aircraft gas turbines have increased 45% from 1970 through 1974, says general manager, Jim Knott. Diesel sales climbed 43% for the same period while power transmission products sales jumped 77%. For past two years the Division's annual gross has exceeded $1 billion.

Industrial gas turbine portion of the business is still relatively small — when compared with aircraft sales. Built mainly around the 3000 to 4500-hp models of the 501K derivative of the T56 turboprop engine.

Predicts 0.44 sfc truck turbine engine by end of 1975

Knott claims GT-404-3 truck turbine rated at 360 hp should be operating with a fuel efficiency of 0.44 lbs per bhp-hr by the end of the year — with a 3,000-hr life. Says turbine will be competitive with diesel engines when the SFC gets down to 0.42 even though diesels now getting 0.38.

Could go into production with 0.42 SFC engine

General Motor's been holding to that 0.42 SFC figure for several years now as requirement for practical gas turbine fuel consumption — for trucks. Assuming goal has not changed it's reasonable to expect some sort of limited production once that figure is hit.

GT-404 or 505 will be offered as top of the line engine — with reduced maintenance, longer time between overhauls, less oil consumption (diesels burn quart of oil every 300 miles), and lack of vibration as main operating advantages — and selling points.

Company in no hurry to start production

Knott acknowledges that company can take its time with introduction of the truck-bus turbine engines now that there's no competition. Blames failures at Ford and others on ceramic regenerator. GM has stuck with stainless steel and says it has payed off in reliability.

Big question is, how much of the diesel market will gas turbines take? And since GM has biggest piece of the truck diesel market, how much is it willing to pass over to turbines — presumably at a lower profit margin?

Knott is looking for enough turbine volume to justify $175 million investment which he says is what it will take to produce 50,000 units a year.

Turbine engines will cost more than diesels

Marketing people figure the turbine engine for truck, bus, and boat markets will probably sell for 10% to 15% premium over diesels. But this will certainly change once the turbine is in production for a few years — and design modified to reduce manufacturing costs.

General manager Knott says focus of gas turbine engineering work has now changed from emphasis on performance improvement to reduction in manufacturing cost. Expect engineering to be completed some time next year so that first drawings can be sent out to manufacturing for cost analysis.

Defense cutbacks may jeopardize industrial 701

Long-rumored industrial version of Allison's 8,000-hp class XT-701 turboshaft engine may never get off the ground. House-Senate committee cut the Boeing/Vertol heavy lift helicopter for which engine was intended out of FY 1976 budget.

Allison reportedly has built and delivered three engines for the helicopter program so far — and is to complete construction of additional four engines remaining under initial contract. Any follow-up work is uncertain at this time.

U.S. Army has budgeted some $9 million for cancellation costs on the R&D project, no funds available or on the horizon after FY 1976, and both Boeing and Vertol getting ready for extensive layoffs. Army has already put $179 million into prototype — would need $40 million more over next 3 years to complete flight test. DDA may proposed XT-701 to U.S. Navy to fill the 10,000-hp slot.

EPA stationary source combustion symposium

U.S. Environmental Protection Agency has announced a major national symposium on "stationary source combustion" to be held at Fairmont Colony Square Hotel in Atlanta, Georgia on September 24 through 26, 1975.

Symposium is designed to provide technology transfer from contract and in-house programs sponsored by EPA's Combustion Research Section to government and industry. Presentations to include fundamental research, fuels R&D, process R&D, and field testing and surveys.

More than 30 speakers and panelists are scheduled to take part in the 3-day session. Symposium being coordinated by Arthur D. Little. To register or for further information, suggest you contact Anita Lord at (617) 864-5770, ext. 3185. Registration fee of $40 covers cost of food and materials.

Oberhausen closed cycle plant shut down for repairs

World's first helium closed cycle gas turbine plant at Oberhausen, W. Germany, reportedly been shut down for repairs. Turbine provides 50,000 Kw of electric power and the equivalent of 54,000 Kw in district heating energy.

Apparently the closed-cycle turbine started leaking lube oil through the labyrinth seals which contaminated the helium working fluid and coated most of the components in the closed loop.

Repairs now being carried out — consist mostly of cleaning oil off the components. GHH Sterkrade, builders of the turbine, working on a fix.

Could have been messy if operating with nuclear source

Oberhausen was built as pilot plant for component testing of future helium closed cycle nuclear stations of up to 1,000 Mw capacity. All turbine components — including lube system — supposedly developed for eventual use with high temperature gas cooled reactors.

Test program has already paid off with discovery of the lube oil leak. No problem clearing up the problem in prototype plant — but would have been a real mess, say design engineers, for a nuclear installation.

21

Critique by

Victor C. Clarke, Jr.
Jet Propulsion Laboratory
Pasadena, CA 91103

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

34LPE-77-180-21

June 29, 1977

Mr. Victor C. Clarke, Jr.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103

Dear Mr. ~~Clarke:~~ Vic.

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Your JPL Interoffice Memorandum VCC-75-28 of October 17, 1975 presents a good case for the hydrocarbon fuel cell as an alternative automotive power plant. In our restructured automotive propulsion studies, this concept may be examined as an element of electric hybrid power systems, although it is not currently authorized by our sponsor. A brief summary of the current study program is enclosed.

The fuel cell was not inadvertently omitted from the subject report. It was initially considered during the study, then dropped as a candidate alternative for at least two reasons: (1) The state of fuel cell development was considered too immature to qualify it as an Otto engine competitor considering the factors of engine size and weight, and the enormous size of the automotive market, and (2) its high capital cost, which may not be sufficiently offset by its durability and low maintenance. In short, we did not feel that the fuel cell qualified for serious consideration within the groundrules of the original study. In the long term, say beyond 1990, the fuel cell hybrid you suggested might be a viable and important power plant for general use. We hope to have the opportunity to evaluate it.

Sincerely,

Harry

H. E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:gpa

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM
VCC-75-28

TO: C. R. Gates/R. Stephenson

17 October 1975

FROM: V. C. Clarke, Jr.

SUBJECT: COMMENT ON APSES STUDY, "SHOULD WE HAVE A NEW ENGINE"

REFERENCE: "Solid Polymer Electrolysis Fuel Cell Status Report," L. J. Nuttall, IECEC '75 Record

I have commented to you earlier regarding my dismay that the APSES Study virtually ignored the hydrocarbon fuel cell as an automotive power plant. Your verbal response that APSES considered engines which only required near-term development, was unsatisfying. The reason is that a brief survey of the literature (e.g., reference paper) shows that the fuel cell is really in as an advanced state of development as is the Stirling or Brayton engine. Indeed, there is 20 years of development experience at GE alone. Substantial technology improvements have been made during that time under NASA sponsorship. GE recently completed a 5 kw, 57% efficient, unit for JSC and produced a unit for LeRC which has a specific weight of 10 lb/kw. This is quite low. Lab tests show that this value can be further reduced by a factor of 2. A 50 hp engine for a minicar could be replaced by a 15 kw fuel cell and a "peak power" battery. The whole power system for a minicar would probably weigh only about 300 lbs. It would be pollution-free, virtually maintenance-free, and be highly efficient ($\sim$ 40%) when operated on air and using a reformer to make the hydrogen. Besides it uses no fuel when "idling" and can use regenerative braking. This would enhance overall vehicle efficiency.

Fuell cells have no moving parts and have high reliability, very long life, and are compact and lightweight. They are noiseless, too--an important feature in a society dominated by automotive noise. Many kinds of fuels, including propane, kerosene, and hydrogen can be used. A very important feature is that an automotive fuel cell would really be an individual's or family's electric plant. Thus, a person could easily power his home, recreational vehicle, etc. It is indeed a highly portable, high-power, personal electric plant.

I visualize that a person would buy a fuel cell separate from the vehicle, as one can now do with a battery. Auto manufacturers would sell vehicles with or without fuel cells, because since they have such long life they would be transferable from one vehicle to another. Actually, they have to be because they would cost substantially more than heat engines. Cost is projected at $200/kw. Purchase of a fuel cell would be a major lifetime investment for a person. I visualize a thriving "used" market.

In summary, I urge you to test my assertions by simulating the hybrid fuel cell/battery auto in the VEEP Program. I am convinced the results will startlingly show it to be far superior in many respects than heat engine or all-battery powered cars. The major reason being their light weight per kw.

Please respond.

Vic

V. C. Clarke, Jr., President
Low Pollution Auto Club

VCC:jm

cc: R. Baugh
T. Hamilton

Critique by

Massachusetts Institute of Technology
Alfred P. Sloan School of Management
50 Memorial Drive
Cambridge, MA 02139

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

22

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-182-22

June 29, 1977

Professor Richard S. Morse
Alfred P. Sloan School of Management
Massachusetts Institute of Technology
50 Memorial Drive
Cambridge, Massachusetts 02139

Dear Professor Morse:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

Your letter concerning the Dresserator carburetor discussion in the subject report is acknowledged, and it will be very useful in our restructured study. The current program, as reoriented, and the plan for responding to the critiques is described in the enclosure.

Thank you for the additional test data on the Dresser Industries inductor which you included with your letter. We are encouraged by the results of the fuel economy and emissions tests on Dresserator-equipped automobiles carried out by Dresser Industries as well as by the EPA. The improvements are noteworthy. As suggested in your letter, we visited Mr. Lester Berriman who provided us with updated details on the Desserator device relative to the information in the subject report. Incidentally, the 800 fps we gave for velocity in a sonic throat is a typographical error; it should have read "1000" (about 10% below that under ambient conditions due to the exchange of temperature for velocity).

The results of our correspondence with you and of our meeting with Mr. Berriman will be incorporated in the appropriate reports mentioned in the enclosure. We appreciate your contribution, and look forward to further contact to keep abreast of your progress in this important area of automotive technology.

Sincerely yours,

H. E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:jms

Enclosures (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

Massachusetts Institute of Technology
Alfred P. Sloan School of Management
50 Memorial Drive
Cambridge, Massachusetts, 02139

October 27, 1975

Mr. R. Rhoads Stephenson
Principal Investigator
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Stephenson:

In connection with your report, "Should We Have A New Engine?" I note a reference to the Dresserator and inference to the effect that some of the Dresser information might be "overstated." As a Director of Dresser Industries, and I am writing in that capacity, I have been in fairly close touch with this program since its inception and some of the people here at M. I. T. such as Professor Glenn Williams and Ascher Shapiro, until recently Head of the Mechanical Engineering Department, have assisted me in the technical evaluation of this device.

As you may know, the Ford Motor Company is also quite familiar with this development and perhaps the following information might be useful:

> Sonic velocity of air under usual ambient temperature conditions is $\sim$1100 fps. It is called a Dresserator Inductor to distinguish it from conventional carburetors. A fuel bar is only one way for fuel distribution. Fuel is delivered into the subsonic entrance zone for good distribution before it arrives at the throat. Because of the excellent energy recovery, the two most important advantages of the Inductor are: (1) control of the mass flow of air down to the unchoke vacuums and (2) control over the atomization process also down to the unchoke vacuums. The latter vary with geometry of the devices and with capacity but are generally in the range of 3 to 6" Hg vacuum. Concerning the drawbacks, altitude compensation can be most easily obtained in one of the geometries. Temperature compensation is needed and for mass flow of air it is $\sim$ to $\sqrt{T}$. Dresser has seen no durability

problems owing to sonic conditions, has been pleasantly surprised at the lack of such problems, and has not reported any such problems. There is no difficulty in achieving sonic velocity; when one cylinder fires, you have it. The excellent atomization even under subsonic operation assures good combustion initiation and engines have operated on fuels with all C_4's and C_5's removed. Dresser has reported good emissions with up to 10% fuel economy. The EPA obtained $>$ 20% improvement on fuel economy in the Capri and $>$ 5% on the Monte Carlo. Recent results at Dresser, where spark was varied and the Inductor was used in a catalyst-equipped Monte Carlo, showed the car met 1977 Federal Standards with an increase of 15-20% in economy. The Capri met 1975 California Standards with a 25-30% increase.

Very truly yours,

R S Morse

Richard S. Morse
Senior Lecturer

RSM/as

Critique by

D-Cycle Power Systems, Inc.
2541 Stratford Road
Richmond, VA 23225

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

23

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-169-23

June 29, 1977

Dr. J.G. Davoud, President
D-Cycle Power Systems, Inc.
2541 Stratford Road
Richmond, Virginia 23225

Dear Dr. Davoud:

Subject: Critique of the JPL Report SP43-17, "Should We Have A New Engine?"

Thank you for your informative letter and enclosures in regard to your work on the wet steam D-cycle Rankine engine. We are interested in it, and want to keep abreast of your progress in pursuing the concept. Hopefully, you will transmit to us enough non-proprietary information that we can include both the D-cycle Rankine and Stirling concepts in our current work.

Upon completion of the subject study, the project was restructured and a plan for responding to the multitude of critiques was developed. The reorientation of our work under ERDA direction is described in the enclosure. In the current program, Rankine cycle engines are scheduled to be reassessed as candidate alternative engines for automobiles, and continued data interchanges with you would enhance the scope of the analyses.

We appreciate your keen interest in the study and your effort in reviewing the report.

Sincerely,

H E Cotrill

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:nrw

Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

D-Cycle Power Systems, Inc.

November 4, 1975

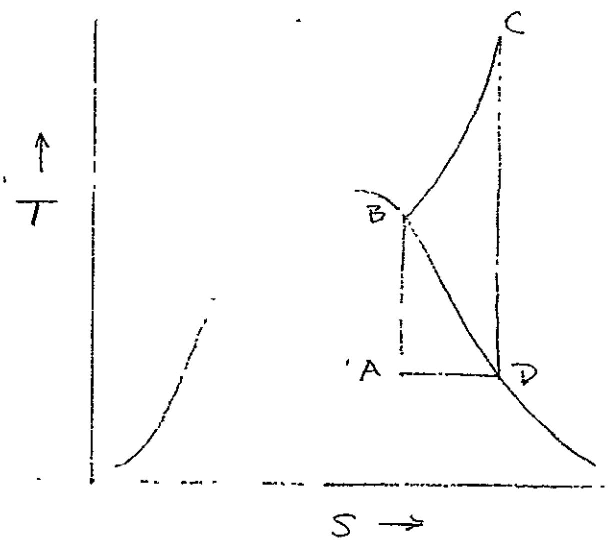
Mr. R. Rhoads Stephenson
Principal Investigator
Automobile Power Systems Evaluation Study
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Stephenson:

We have received and read with great interest Volume I and II of the California Institute of Technology, Jet Propulsion Laboratory Report entitled, "Should We Have A New Engine? An Automobile Power Systems Evaluation".

We found the penetrating comments on the Rankine cycle particularly interesting; because we reached some of the same conclusions about it some years ago and devised, as an improvement, a steam compression cycle which is called, for commercial purposes, the D-Cycle. I am enclosing a couple of Papers read before the 8th and 9th Intersociety Energy Conversion and Engineering Conference meetings which describe its application in power generation and automotive use.

The D-Cycle on a TS diagram is particularly revealing set against your Figure 2-8 on pg. 2-20 of Volume II of your Report. I enclose a sketch and you will see that the D-Cycle overcomes some of the theoretical deficiencies of the Rankine.



A-B COMPRESSION (2 PHASE)
B-C HEAT ADDITION, CONSTANT PRESSURE.
C-D EXPANSION, ISENTROPIC
AT D REMOVE 1/3 STEAM; CONDENSE
INJECT CONDENSATE RESULTING IN WET STEAM AT STATE-POINT A
CYCLE REPEATS.

2541 Stratford Road • Richmond, Virginia 23225 • Phone 703-320-1905

We have not tried to push it for automotive use, really for almost political reasons. However, we have like you watched with the closest interest the development of the SES steam car and the Carter car. The personnel are well known to us, and indeed are our friends. We have informed them fully of our own work which includes compression of wet steam on which the D-Cycle depends, and the construction and running of a D-Cycle engine.

We are currently the recipients of a contract from MARAD (Maritime Administration of the Department of Commerce) for a technical and economic feasibility study of the D-Cycle for ship propulsion using turbine expanders. We are also hoping to receive some financial help from EPRI for electricity generation. In the case of turbine expansion, the problem is the compression methods; and in this connection, we have some very interesting information given to us on modern compression technology by various companies, as we pursue our MARAD contract.

Returning to smaller reciprocating engines suitable for cars, we right now are working up an engine which we think is the best distillation of all the latest developments in Rankine type expanders plus our own I suppose unique experience with wet compression. This engine, we believe, would overcome just about all the objections in your admirably phrased conclusions on the future of the Rankine engines for cars. We specifically avoid exotic metals. The engine is virtually valveless, it makes use of such things as Rulon rings for lubrication, and blow-by-free operation; and we think it could be a suitable answer to the automobile engine and one which would not require too drastic a departure from current automobile engine technology.

We have, in addition, a patent application for a D-Cycle Stirling engine, using a condensable vapor as the working fluid. This engine cools the working substance by liquid injection during compression. It makes use of the Rinia type of valveless engine. After the usual heat exchange between hot and cold space, a portion of the working substance is removed and condensed; condensate is injected into the cold space during compression; the heat loss to the atmosphere is by condenser. Pressure (and hence power) change is very easily effected by increasing or decreasing liquid injection rate; and no costly and complicated methods are required to prevent loss of working substance. Water is pretty cheap still! We have an application to AAPS section of ERDA for component development of this so-called "Vapor Stirling".

In closing, I would like to compliment you and your staff on what we think is an excellent technical appraisal of a number of complex systems and certainly one made against a complicated background socially, economically, and technically. We do not altogether agree with some of your conclusions, but there is plenty of ground for opinions; and we think it is a first class work. I do hope we may have the pleasure of meeting you sometime; and if you would like to be kept informed of our various activities, we would be glad to do so. One of our staff will be in California this month and it would be a privilege for him to see you. No doubt he will be getting in touch with you directly. His name is Jerry A. Burke, Jr., and he is vice president of this company and chief engineer.

Yours sincerely,

J G Davoud

Dr. J. G. Davoud
President

JGD/nc

Enclosures

77-40

D CYCLE POWER SYSTEMS, INC.
2541 STRATFORD ROAD
RICHMOND, VIRGINIA 23225

8th Intersociety Energy Conversion Engineering Conference PROCEEDINGS

University of Pennsylvania
Philadelphia, Pa.
August 13-17, 1973

American Institute of Aeronautics and Astronautics

American Institute of Chemical Engineers

American Nuclear Society

American Society of Mechanical Engineers

Institute of Electrical and Electronic Engineers

Society of Automotive Engineers

American Chemical Society

Proceedings Published by
American Institute of Aeronautics and Astronautics
1290 Avenue of the Americas, New York, N.Y. 10019

D-CYCLE APPLIED TO FOSSIL PLANTS

J.C. Corman, J.G. Davoud* and R.P. Shah
Corporate Research & Development
General Electric
Schenectady, New York

ABSTRACT

The D-Cycle is a thermodynamic cycle which employs wet vapor compression as an integral part of the cycle. This concept can be applied to any power producing cycle which employs evaporating and condensing fluids. Theoretical increases in thermodynamic efficiency result from utilizing this cycle rather than the standard Rankine Cycle.

The effectiveness of this new cycle is strongly dependent upon the efficiency of the wet vapor compression process and the state point selection. An analytical evaluation has been performed which parametrically studies these variables for large fossil fired cycles. These studies also characterize the equipment performance which would be required to make this cycle competitive with other advanced cycle concepts. The initial experimental results obtained on the wet vapor compression process indicate the potential for producing the required efficiency for this critical cycle component.

I. INTRODUCTION

The Rankine Cycle forms the basis of most of the vaporization-condensation, power producing cycles. In the simplest format, this familiar cycle employs four components; boiler, expander, condenser and pump, and the total flow of the working fluid passes through each component.

The heat input to the cycle is employed to : 1) increase the temperature of the feed water, 2) evaporate the working fluid and 3) superheat the vapor. It is consequently introduced through a temperature range varying from approximately the lowest to the highest temperatures in the cycle. However, the major portion of the thermal energy is utilized at relatively low temperatures during the vaporization process.

A new cycle introduces another process into the power producing cycle described above. This process is wet vapor compression and the cycle is the D-Cycle[1]. Other investigators[2,3,4] have, in the past, considered different aspects of compression in vaporization-condensation cycles. The major focus of these earlier works was on establishing a combined Rankine-Brayton Cycle.

Basic D-Cycle

In a simplified D-Cycle, the feed water pump is eliminated and replaced by a wet vapor compression process. The flow is split and the total vapor flow is not passed through the condenser. In the simplest case, with reciprocating machinery, the expansion and compression step can be carried out in the same cylinder-piston arrangement. A schematic of the cycle and the thermodynamic state points are shown in Figures 1 and 2.

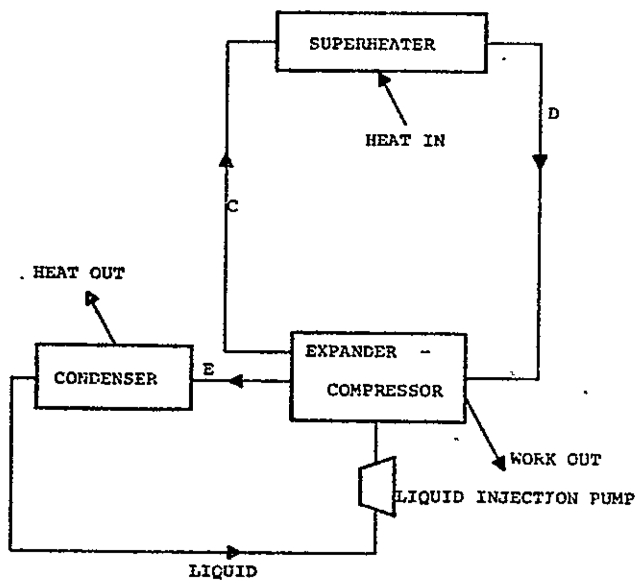


Figure 1:Schematic of Simplified D-Cycle

The four processes for this cycle are:

1) Compression - Wet vapor at state point, J, is compressed to high pressure and exits at saturation, C.

* D-Cycle Power Systems, Inc.
Richmond, Virginia

Critique by

Hon. Andrew Maguire
of New Jersey
US House of Representatives
Extensions of Remarks E5820
Congressional Record
November 4, 1975
U.S. Government Printing Office
Washington, DC 20402

24

ISSUES TO AMENDING THE CLEAN AIR ACT OF 1970

HON. ANDREW MAGUIRE

OF NEW JERSEY

IN THE HOUSE OF REPRESENTATIVES

Tuesday, November 4, 1975

Mr. MAGUIRE. Mr. Speaker. In the near future, Congress will consider amendments to the Clean Air Act of 1970. One of the principal issues is whether to maintain or relax the statutory requirements relating to automobile emissions.

STATUTORY EMISSIONS STANDARDS CAN BE MET

As many of my colleagues, are aware, there has been considerable controversy over what the automobile industry can technically achieve in terms of emission control. There is further controversy over the cost of such control to the automobile purchaser and owner. Opponents of the existing statutory requirements claim that it will be technologically infeasible to meet these standards.

However, the National Academy of Sciences, which reviewed the issue of technological feasibility as well as cost, issued findings which indicate the opposite. The NAS concluded in the June 5, 1975. "Report of the National Academy of Sciences, Conference on Air Quality and Automobile Emissions," that the 1978 emission standards for hydrocarbons (HC) and for carbon monoxide (CO) are "both feasible and worthwhile", and that the standards for nitrogen oxides (NO) are probably feasible.

As far as cost is concerned, the NAS report indicated that pollution control devices to meet the tighter 1978 emissions standards would not cost much more than those required for the 1975 model year vehicles. Furthermore, significant fuel economies can be realized on cars with catalysts, which can save money over the life of the car as well as help alleviate the energy crisis.

To further understand the complexities of this automobile emissions issue, I urge all Members to examine the NAS report. I would also like to call my colleagues attention to my comments on this matter in the September 23, 1975 RECORD (E4937) which includes the conclusions and recommendations from the NAS report.

SHOULD THE INTERNAL COMBUSTION ENGINE BE PHASED OUT?

As all Members are aware, environmental and energy matters are linked. The automobiles in this country are great consumers of energy as well as being a significant source of pollution. The Nation would go a long way toward alleviating both energy and environmental problems if automobiles could be produced which are more economical in consumption of fuel and create less pollution. This possibility is outlined in an August 1975 report of the Jet Propulsion Laboratory—JPL—of the California Institute of Technology. Entitled, Should We Have a New Engine? An Automobile Power Systems Evaluation, the report indicates that the refinement and application of existing technology can provide America with a fuel-efficient, and virtually pollution-free automobile by the mid-1980s. The report is based on a comprehensive study by JPL commissioned by the Ford Motor Co. It examines several engine types including alternatives to the Otto-cycle engine, or common internal combustion engine, which now powers the vast majority of cars manufactured in the United States.

JPL concludes that,

> The results show that goals for emission standards and energy conservation for the automobile over the next 5–10 years can be met by improvements to the Otto-cycle engine and to the vehicle.

JPL recommendations to the Nation concerning future possibilities are very dramatic:

> Accelerate and direct the development of two particularly promising alternate engines—the Brayton and Stirling—until one or both can be mass-produced, with introduction in the improved cars targeted for 1985 or sooner. The report explains that both engine types have been in existence for many years and that recent technical developments have made them suitable for passenger car application.

Concerning energy conservation and emissions, JPL writes:

> Both offer dramatic savings in fuel usage, adaptability to a wide variety of liquid fuels, and emissions low enough to take the automobile off the list of major polluters.

JPL foresees fuel savings of up to two million barrels daily.

There is strong public support for the development of improved engine technology. An August 1975 public opinion poll commissioned by the Federal Energy Administration asked: "How willing are you to pay $10 per year more in taxes to have the Federal Government help the auto industry produce a car that would cause less pollution and save you $120 per year in gasoline costs—very willing, fairly willing, not too willing, not willing at all?" Over seventy percent responded favorably with 46 percent very willing to pay the additional costs and 24 percent fairly willing. These findings indicate exciting possibilites, and I urge my colleagues to carefully consider them in determining their positions on energy and environmental matters. For the information of the members I ask that the Abstract, Synopsis and Major Findings of the JPL report be included at this point in the RECORD:

["Should We Have a New Engine? An Automobile Power Systems Evaluation," Abstract, Synopsis and Major Findings, Report of the Jet Propulsion Laboratory, California Institute of Technology, August, 1975.]

ABSTRACT

Alternative automotive powerplants were examined for possible introduction during the 1980–1990 time period. Technical analyses were made of the Stratified-Charge Otto, Diesel, Rankine (steam), Brayton (gas turbine), Stirling, Electric, and Hybrid powerplants as alternatives to the conventional Otto-cycle engine with its likely improvements. These alternatives were evaluated from a societal point of view in terms of energy consumption, urban air quality, cost to the consumer, materials availability, safety, and industry impact.

The results show that goals for emission reduction and energy conservation for the automobile over the next 5–10 years can be met by improvements to the Otto-cycle engine and to the vehicle. This provides time for the necessary development work on the Brayton and Stirling engines, which offer the promise of eliminating the automobile as a significant source of urban air pollution, dramatically reducing fuel consumption, and being saleable at a price differential which can be recovered in fuel savings by the first owner. Specifically, the Brayton and Stirling engines require intensive component, system, and manufacturing process development at a funding level considerably higher than at present.

SYNOPSIS

"What should be done in the near future to improve the automobile, from the standpoint of society's needs and problems? Specifically, should some other type of engine be used to power the automobile in the coming decade, instead of the familiar Otto[1] (spark-ignited internal combustion) engine?" These are the questions that the Jet Propulsion Laboratory was asked to address in this study.

The automobile affects the quality of our lives in many ways. On the positive side is the convenience of the personal care, all-important in providing mobility for business and pleasure. On the negative side are the problems it creates or to which it contributes heavily. The air we breathe is fouled by its exhaust. Increasing use of cars causes congestion in our cities and leads to injuries and deaths on our highways. Demand for imported metals and minerals, needed to manufacture automobiles, is continually growing. Our enormous energy consumption, to which the automobile's demand for gasoline is a major contributor, gives rise to large deficits in our national balance of payments each year and leaves us vulnerable to international embargoes. The group of industries involved in the production and operation of automobiles are strongly linked to our nation's economy and employment. These factors show the importance of the automobile and its infrastructure.

Over a period of about 18 months, the Jet Propulsion Laboratory studied the technologies available for improving the automobile and its powerplant, within the framework of the key issues: the role of the automobile and other transit systems in providing personal mobility, energy and fuels availability, material resources, air quality, highway safety, and the changeover capability of the automobile industry. In the course of this study several fundamental realizations—some of them at variance with widely held opinion—emerged:

The automobile will maintain its dominant role in personal transportation through the foreseeable future. Public transit will be able to take a larger share of the burden. However, the time and effort required to build new public transit systems, or to expand existing facilities, together with their limited applicability, preclude more than a 10–15% substitution for automobile driving in the next 10 to 20 years.

The production of over 10 million automobiles per year is the combined, and highly specialized, undertaking of an industrial complex that extends back to the iron ore mines. A major change in the product cannot happen overnight regardless of money available, technology applied, or legislation enacted. There will be an estimated minimum time lag of over three years in beginning to mass-produce a new design, given a fully developed producible model.

Liquid fuels, natural and/or synthetic, will be used in cars through at least the end of this century. World resources are sufficient to permit the introduction of another generation of combustion engines.

The necessary materials of construction can be obtained for the recommended heat-

[1] Named after its inventor, Nikolaus Otto.

engine-powered automobiles, given adequate planning.

The financial resources required for conversion to vehicles with alternate engines would be readily available in our economy.

Automobile pollutant emissions and—equally important—emissions from other moving and stationary sources must be controlled more stringently than at present, and in a concerted manner, in order to meet the National Primary Ambient Air Quality Standards through the next decade. To conform with this requirement, automobiles powered by an alternate engine considered must meet, or better, a set of emission standards appropriate to the region in which they are driven.

Given some additional development, cars with catalytically controlled Otto engines do not have to give up fuel economy to comply with the strictest legislated emission standards. In fact, some improvement in the efficiency of such engines can be obtained without rexalation of those emission standards.

In the light of these realizations, our answer to the questions originally posed, stated in a few words, is:

Begin immediately the rapid implementation of design changes to the car itself which can significantly reduce fuel consumption, independent of the kind of engine used. Concurrently, accelerate and direct the development of two particularly promising alternate engines—the Brayton and Stirling engines—until one or both can be mass-produced, with introduction in the improved cars targeted for 1985 or sooner. In the interim, press the development of the conventional Otto engine to its limits.

The vehicle design changes referred to are primarily weight reductions, along with some modest improvements attainable in transmissions, power-consuming accessories, and the aerodynamic characteristics of the car. Many of these are relatively easy to achieve and should be put into production in the next five years, since they can reduce normal driving fuel consumption by 14 to 35% over the range of car sizes The remaining changes, requuring some additional development, should be introduced as soon thereafter as practical and will provide even more impressive fuel savings. A further reduction in national fuel consumption can be obtained if a moderate shift in consumer preference toward smaller cars can be brought about. All of these gains are essentially unrelated to the type of engine in the car and, once achieved, will by-and-large be retained when the alternate engine is introduced.

The Brayton engine is better known as a gas turbine, one form of which is presently used on large commercial aircraft Braytons have already been employed in some racing cars and experimental automobiles The Stirling engine, a newcomer to the automobile, utilizes the heat from the burning fuel to make a separate closed gas system do the work. Both types of engines have been in existence for many years, but only recent technical developments have made them suitable for passenger car application. Both offer dramatic savings in fuel usage, adaptability to a wide variety of liquid fuels, and emissions low enough to take the automobile off the list of major polluters. Although both could eventually be produced at acceptable cost, in neither case do engines delivering this attractive performance presently exist in a form that can be economically mass-produced. Therefore, Brayton and Stirling engine development must be greatly accelerated until one or the other reaches the stage where the auto industry can give a production go-ahead This may not happen if the industry operates in a business-as-usual manner, since development spending in excess of present levels for these alternates is necessary. Government funding and/or incentives will be required to promote a firm industrial commitment.

A small improvement in fuel economy can still be squezed out of the conventional Otto engine, at no sacrifice in emission control, while the alternate engine is being readied for production. More effective air/fuel mixing and conditioning devices, together with improved exhaust converters, can make the evolving Otto engine a very worthy stopgap powerplant. Developments in this area must also be spurred.

The electric car, in a form that could substantially replace liquid-fueled automobiles, remains a prospect for the more remote future. It is a very alluring long-term option since its supply of electric energy is drawn from generating stations which can use any energy source—chemical, solar, geothermal, or nuclear. However, present technology limits the electric vehicle to very specialized applications, and the electric energy storage system required to make it competitive with liquid-fueled cars for general use has yet to be developed. The mandatory battery research must be intensified now, if a practical, general-purpose electric car is to materialize.

Implementation of the foregoing recommendations will result in major benefits to the nation as a whole in transportation and energy consumption Enlightened planning now, embodied in a firm national commitment, can put efficient automobiles powered by Brayton/Stirling engines on our streets by 1985 and provide us with the options needed for the century to come.

II. MAJOR FINDINGS

The feasibility and desirability of introducing an alternate automobive engine were assessed in the context of relevant national needs and problems: (1) the demand for mobility; (2) energy consumption, especially as petroleum fuels; (3) availability of raw materials; and (4) urban air quality. Studies of these issues resulted in an automotive outlook for the balance of this century which is probably not surprising: (1) personal automobiles are here to stay, regardless of increased usage of public transit and other changes in vehicle use patterns; (2) liquid fuels, some combination of natural and synthetic hydrocarbons, will be used in cars throughout the time frame of interest; (3) world resources can supply the automobile's expected demand for fuels and materials of construction; and (4) environmental air quality will demand continued attention, necessitating more restrictive emission standards for stationary as well as mobile sources.

Against that backdrop, the APSES study has derived some major findings, the rationale for which is outlined in detail in subsequent sections and supported in detail in Volume II of this report. Briefly, those findings are as follows:

(1) Comparatively simple vehicle design changes—primarily weightsaving, essentially independent of engine type and functionally acceptable to the buyer—can reduce the conventional automobile's fuel consumption by 14 to 35% of present usage. Such changes can be incrementally introduced and all be in production by 1981. Other modifications, requiring some additional development, can further reduce fuel usage. All of the vehicle improvements can and should be incorporated by 1985, since their benefits would largely be retained when an alternate engine is introduced A modest shift in market preference toward smaller cars would also yield a short-term payoff in fuel saving.

(2) Vehicles powered by Brayton or Stirling engines can reduce national automotive fuel consumption by about one-third from that of equivalent cars with conventional engines (for the same usage) and with emissions below the strictest presently legislated standards Introduction of either of these alternate engines can be accomplished without significant adverse impact on the nation's economy. One or both should be introduced as soon as these benefits can be realized in economically mass-productible hardware.

(3) The present development status of the Brayton and Stirling engines does not at this time, permit a decision to begin mass production; hence their introduction cannot be forced by an abrupt change in emission standards or legislation of a fuel economy standard over the next few years. Rather a more aggressive development program, involving at least a five-fold increase over the present rate of spending, must be pursued. Such a program requires a firm commitment on the part of industry, supported by government funding or incentives An introduction target date of 1985 (earlier, if possible) should be incorporated in the development schedule

(4) While the Brayton Stirling development is proceeding, about 9% reduction in fuel consumption from that of the average 1975 conventional Otto engine can be obtained, without giving ground on emissions control, through improved induction systems and exhaust converters The combination of such upgraded Otto engines with the improved vehicles discussed in finding (1) constitutes not only a good stopgap automobile configuration, but also a very acceptable "fallback" position if intractable difficulties arise in both alternate engine developments.

(5) Intermittent-combustion alternate engines—the Stratified-Charge Otto and the Diesel—do not offer enough advantage over the improving conventional Otto engine, in vehicles of equivalent performance, to warrant their widespread introduction in general-purpose automobiles. Also, conversion of the entire fleet to such an engine could further delay introduction of a Brayton or Stirling.

(6) Meeting the presently mandated National Primary Ambient Air Quality Standards requires coordinated emission reduction from both automotive and nonautomotive sources For areas outside the Los Angeles basin, national automotive emission standards of 0 4/3 4/2 0 g/mi (HC/CO NOx) are adequate through 1990 In addition, evaporative hydrocarbon emissions must be effectively controlled nationwide. The Los Angeles basin should mandate 0.4/3.4/0 4 g/mi emission standards as soon as practicable; even at those levels the photochemical oxidant (smog) standard will not be met, with still stricter hydrocarbon (and possibly NOx) control being ultimately required.

Other sources, especially heavy-duty vehicles and stationary sources must also be aggressively controlled nationwide, or else they will be the major polluters

Brayton- and Stirling-powered cars can comfortably meet the strict statutory standards, and even the Otto-engined car, with projected improvements, will be equal to that task. Further tightening of the automobile emission standards would eventually rule out the Otto engine, however.

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Critique by

National Science Foundation
Office of Energy R/D Policy
Washington, DC 20550

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

OFFICE OF ENERGY
R&D POLICY

November 20, 1975

R. Rhoads Stephenson
Systems Analysis Section Manager
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Dear Rhoady:

Thanks for sending me your November 5 letter to Dick Strombotne, along with Bob Husted's memo to Dick. I want you to know that I wasn't one of the ADP members polled to develop the comments that Dick sent you. Your use of the OEE concept was certainly valuable, and many other aspects of your report are certainly valuable. I don't think your report is an adequate "technology assessment," but it is certainly a contribution to the important work in progress to improve automobile engine technology.

Sincerely,

Len Topper (m.)

Leonard Topper
Energy Policy Analyst

Critique by

Cummins Engine Company, Inc.
Research Division
Columbus, IN 47201

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

26

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-185-26

June 29, 1977

Mr. W. T. Lyn
Vice-President - Research
Cummings Engine Company, Inc.
Columbus, Indiana 47201

Dear Mr. Lyn:

Subject: Critique of JPL Report SP43-17, "Should We Have A New Engine?"

We wish to acknowledge your letter with appreciation for the interest you showed in the subject study. Since the time your critique was received, our program has been restructured, and background information on it, including the critique response plan, is enclosed. Your observations are well made regarding the many factors of a non-technical nature which can strongly influence the choice of an engine, and we did attempt to include some of these factors in the study. In the follow-on work, summarized in the enclosure, we expect to expand the evaluation of alternative engines beyond that which was possible in the original study.

Regarding your observation on the emergence of a viable NOX decomposition catalyst, it would indeed impact the results of our study, especially in respect to the diesel engine. Because such a device does not yet appear on the horizon, although it is the subject of considerable research, we chose to omit it. In response to your second point, we expect the internal combustion Stirling engine to have higher levels of emissions and lower efficiency than one with a closed cycle due to the inherent characteristic of a regenerator which would make open-cycle regeneration more difficult. Therefore, we excluded this approach from further consideration.

We are glad that you appreciate the limitations of our study as a result of necessary restrictions of scope. Hopefully, we will be able to deal with most of the important limitations of the study in our follow-on program. We value your comments, and plan to respond to them in more detail in an appropriate Technical Task Summary.

Sincerely yours,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

CUMMINS ENGINE COMPANY, INC.

COLUMBUS, INDIANA 47201

CUMMINS

TELEPHONE | AREA CODE 812
372-7211

December 12, 1975

Mr. R. Rhoads Stephenson
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Stephenson:

Thank you for the copies of the JPL report on "Should We Have a New Engine". As it turned out, we have already had access to this report, and our people have been at the various meetings during which the report was discussed.

Since the terms of reference are in automobile application, they are outside our normal business. However, the report could not help but generate a keen interest in our company.

Few can argue against the contention that it is easier to arrange the combustion processes in a continuous flow machine, and in particular an external combustion machine where combustion takes place under atmospheric conditions; and so if emission is the sole, or even the major, criterion, this machine could be the preferred solution. However, in real life, the choice of a particular machine depends on so many factors, many of which are not technical in nature (e.g. economics, capital availability, legislative constraint, etc.). This is what makes the projection so difficult and fascinating and rewarding for those who make the correct crystal gaging.

On the technical ground, I noticed that two items have been left out, presumably for good reasons unknown to us. One is the impact of the emergence of a viable NO decomposition catalyst; and the other is the internal combustion stirling. However, in a report of this nature, one simply has to draw a line somewhere; and in general, our people thought the report stimulating and well executed.

Sincerely,

W. T. Lyn

W.T.Lyn/pe

Vice President - Research

Critique by

Robert A. Harmon
25 Schalren Drive
Latham, NY 12110

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

27

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-188-27

June 29, 1977

Mr. Robert A. Harmon
Consultant
25 Schalren
Latham, New York 12110

Dear Mr. Harmon:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Thank you for your letter and for the summary of developments on the Warren Reciprocating Brayton Cycle engine which have occurred since publication of Dr. Warren's 1969 SAE paper. We regret that we were not aware of this progress during preparation of the subject report. Our automotive studies have been reoriented since receipt of your letter, as summarized in the enclosure. As you are aware from our personal conversations, we have already accomplished a modest review of this work, including a trip to visit Dr. Warren.

We recognize the many desirable features of the engine concept, and hope that they can be verified in subsequent development. There are some serious difficulties, we feel, that must be overcome in the Warren engine; for example, the cooling of the inlet valve of the expander and the spring-loaded exit valve. It appears questionable if a spring-loaded valve is suitable for operation at the high RPM's that are necessary. We have not seen data to demonstrate that such difficulties can be overcome.

We hope that you will keep us informed on engine developments so that new data may be included in appropriate Technical Task Summaries, as mentioned in the attached summary. We greatly appreciate your interest in the subject report and your effort in reviewing it.

Sincerely,

H. E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:gpa

cc: Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

December 17, 1975

Dr. R. Rhoads Stephenson
Section Manager
Systems Analysis Section
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Dear Rhoads:

Once in a while I do some work with Dr. Glenn B. Warren, V.P. General Electric Co. (Retired), Past President of ASME, and Consulting Engineer. He has read with much interest your report, "Should We Have a New Engine?"

Based on comments at the ERDA meeting in Ann Arbor, Nov. 17, it seems likely that ERDA may provide funds for you to expand some sections of the report and to provide comprehensive answers to some of the many questions and comments which the report has stimulated.

In your report, Volume II, Page 2-15 you refer to "positive displacement, high expansion ratio Brayton engines with continuous combustion systems". You also refer to Dr. Warren's early SAE paper on the subject, Ref. 2-15.

Over $500,000 has been devoted to the preliminary design and analysis of this engine since about 1967. A great deal of progress and additional information has been developed since publication of the SAE paper in 1969.

In view of the recent emphasis on low fuel consumption and near term solutions to energy problems as well as low emissions, the Warren Engine is being reconsidered by a number of automotive, industrial and Government organizations. It has been suggested that you would want to provide more in-depth treatment of this type of engine in any supplemental material which you might publish under ERDA or other sponsorship.

Because the Warren engine looks particularly attractive for the short range with relatively low risk and low investment required, I have taken the liberty of forwarding herewith three brochures on the Warren Engine. Brochure A is a concise summary of the background, status, and projections for the engine. Brochure B and C have much of the technical back-up and supporting details.

In essence the Warren Engine promises:

- More Transportation miles per barrel of crude oil than any other near term candidate engine. Fuel rate, particularly at part load, is very low - diesel competitive.

- Very low emissions including the 0.4 gm/mi NOx requirement.
- Near term mass production capability at conventional engine cost without materially changing existing tooling.
- Efficient use of broad range fuels.
- Suitability for export to World-wide markets.
- Ability to meet peak power requirements as well as part load fuel economy and emission requirements by use of a low cost, high production turbocharger. The turbocharger supplies excess air for regenerative cooling of the burner liner and the high temperature inlet valve of the expander. This provides the maximum power capacity and alleviates the cooling problems associated with these critical components.

This material should provide additional insight into the potential value of this type of engine; no doubt it will also raise additional questions.

I am sure Glenn Warren will welcome further inquiries and questions about the Warren engine. Additional information and documentation can be provided as required.

Sincerely,

Bob

Robert A. Harmon
Consultant
25 Schalren Drive
Latham, NY 12110
518-785-8651

cc: Glenn B. Warren
Consulting Engineer
148 East Coronado Road
Phoenix, Arizona 85004

Critique by

Glenn B. Warren
1361 Myron Street
Schenectady, NY 12309

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91003

28

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-192-31

June 29, 1977

Dr. Glenn B. Warren, Consulting Engineer
1361 Myron Street
Schnectady, NY 12309

Dear Dr. Warren:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

The informative letter from your associate Mr. Harmon to Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA) regarding the subject report has been forwarded to us for reply. We were interested to learn of the significant developments that have occurred on the Warren Reciprocating Brayton Cycle (RBC) engine since 1969, and regret that we were not aware of this progress at the time the subject report was in preparation. In the meantime, our work has been reoriented, and background and status of the restructured program are summarized in the enclosure.

Many of the points raised in your letter will be addressed in the course of our current study, and the results will be included in an appropriate Technical Task Summary (TTS). In the meantime, we would like to comment on the following items selected from your letter.

1) Horsepower Sizing

We agree that vehicle acceleration is a characteristic of importance and, of course, at least one aspect of acceleration was included in the criteria for the Otto Equivalent Engine (OEE). It is not clear at this point, however, whether other acceleration criteria except the 0-60 mph time should be included. It is also not clear what weighing acceleration should be given in sizing an engine. The entire question of engine installed horsepower at JPL is being reconsidered now and the results will be published early in 1978 as a Technical Task Summary (TTS).

2) Driving Cycle

The mix of urban and highway driving assumed for the subject report was 55% urban/45% highway on a mileage basis. And of course there are detailed studies of driving patterns which support this ratio. Note

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that a 55/45 mileage mix leads to a fuel usage split of 65% consumed in urban driving and 35% on the highway. The fuel consumption split is based on the assumption that the highway mileage (in mi/gal) is 50% higher than the urban mileage.

3) Fuel Consumption During Idle

The vehicle fuel consumption projections given in the subject report do include the effect of idle fuel consumption. In order to produce an OEE vehicle, since very few if any exist, we generated them by means of a computer simulation program. So, while there is in general no direct experimental data, all the projections are based on experimentally derived engine maps and do include idling fuel consumption data.

4) Control of Stirling Engines

Stirling engine control is an area of active research. Our opinion is that automatic control is a difficult but solvable engineering problem. Status of control technology for Stirling engines will be included in an appropriate TTS and in our annual reports to ERDA.

Your critiques have been most helpful to us and we appreciate the time you have spent preparing them.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:nrw

Enclosure

PHONE FR 4-8683

GLENN B. WARREN, M.E. P.E.
CONSULTING ENGINEER

VICE PRESIDENT
GENERAL ELECTRIC CO.
RETIRED
PAST PRESIDENT A S M E.

1361 MYRON STREET
SCHENECTADY, N. Y 12309

April 15, 1976

Dr. R. Mercure:
U.S. Energy Research and Development Adminstration
Heat Engines Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Subj: The Warren Engine
A Reciprocating Brayton Cycle(RBC)Engine

Dear Dr. Mercure:

We wish to submit the above Engine to the Jet Propulsion Laboratory Automotive Power Systems Evaluation for inclusion in the Evaluation of Alternate Systems.

We have been in communication with the Ford Motor Co., and with Mr. Ford direct in connection with the above Engine Proposal. We expressed regret that we had not been ask to help in presenting our more recent work on this project to the JPL before their very comprehensive Report was finished. Mr. Ford's Nov. 21, 1975 letter to me had the following paragraph:

"As you know, the JPL Report was done under a grant from the Ford Motor Co. As it was an independent study, I would suggest that you contact them directly and provide them with the latest information as we believe they are earnestly trying to make a complete and factual assessment of the alternative engine field and, therefore, would welcome additional information."

I immediately requested my associate, Mr. Robert A. Harmon, Consultant, Latham, N.Y. to send Dr. Stephenson copies of our recently prepared Brochures describing this proposed engine, which I understand he did. I am sending you another copy of this material with some supplementary information with this letter.

Further, I have a copy of the ERDA "Announcement" of last month requesting critiques and other suggestions and data from individuals relative to this JPL Report. This we wish to do. Please note the attached Supplement.

We have spent much time and effort in studying the very comprehensive Jet Propulsion Laboratory investigation and Report. Because of its broad scope and finite funding it is recognized that everything could not be considered in detail. The Reciprocating Brayton Cycle was mentioned, and my 1969 SAE Paper thereon was cited. It was not studied in detail, and apparently none of our developments since then were known to JPL. My associates and I, however, have studied this system in depth over the past seven years and we feel that it should be reconsidered by the JPL Automotive Power System Evaluation for a number of reasons, some of which are summarized below, and in the accompanying Brochures, A, B, and C. The engine as we now envision it is illustrated and described in these Brochures, its key features and advantages reviewed, and the problem areas are identified and discussed.

THE WARREN ENGINE, a modern Reciprocating Brayton Cycle Engine(RBCE).

The RBC Engine fits the description of the George Brayton Engine of his 1873 patent as described in 5-1.1 Vol.II of the JPL Report. This present Brayton Engine Concept was presented by me in an SAE Paper No. 690045, also attached. These Brochures describe the results of a continuous refinement of the design and calculations and some component tests carried out since the SAE Paper was published.

This proposed engine from the emissions standpoint should have the advan-tages of the Brayton Cycle which are pointed out on page 59 of the JPL Report Vol.I when it is stated "The continuous combustion power plants... Braytons, Rankines, and Stirling....are capable of emissions well below the statutory standards, and (if used) would relegate the automobile to a secondary place in the list of major polluters. Their advantage in this regard stems from the fact that the combustion process is physically divorced from the work-producing process. Simultaneous control of formation of the three pollutants necessitates an increase in the time interval allotted to combustion and, in these engines, efficiency is not sensitive to the combustion interval." This is restated in the JPL Report Vol. II, page 2-12.

Computer studies based upon the "fuel-air cycle" of the limited pressure Diesel engine including corrections for the Brayton Cycle deviation from the Diesel cycle indicate that this engine with the advantages of modern design details and materials should equal or exceed the energy efficiency of the automotive Diesel of comparable displacement and comparable supercharging. As is generally known the automotive Diesel is the most efficient automotive engine in active production and use today where it has not been detuned to reduce emissions. This high efficiency is particularly so at light loads and low speeds which characterize motor car use in urban areas. These same computer results indicate that its specific capacity should be comparable.

These high efficiencies are possible with the Brayton system also because the reciprocating compressor and expander construction, in contrast to the turbine, permits high internal efficiency with high compression ratios, and relatively low volume gas flows at flow values proportional to rotative speed. Further the water and regenerative air cooling of the expander elements permits the use of high temperatures and therefore full utilization of the air injested without the metal temperatures approaching too closely the working gas temperatures.

The matter of the comparative economy which it is expected this Reciprocating Brayton Engine will show in comparison to the conventional Otto Cycle engines now in wide use on motor cars is treated in an accompanying copy of a Mar. 12, 1976 letter from me to one of my associates, Mr. Robert Harmon. In this letter it is pointed out that the Diesel has outstandingly good fuel economy in the stop and go driving so characteristic of urban area, and in which a large proportion of the automotive fuel is consumed. It is expected that the RBC Engine can do as well and still meet the required low emissions.

The high relative fuel consumption of the Otto Engine in this stop and go driving mode was brought out in my 1965 ASME Paper No. 65-WA/APC-1 titled "Some Factors Influencing Motorcar Fuel Consumption in Service" copy attached. This subject is now brought more up to date by a recent Schultz(Perkins)SAE Paper No. 760047. A copy is attached of the Press Release of this Paper.

Another way of looking at this relative fuel consumption at lower speeds and loads for the present Otto engine(1969 performance) pre-emission control, the present automotive gas turbine with regenerator and free power turbine, the Diesel automotive engine, and the Warren Reciprocating Brayton Engine is shown on page 4 of Brochure A, and page 6 of Brochure B.

Warren to R. Mercure, ERDA. 4/15/76 Page 3.

We earnestly recomment a careful and exhaustive study and consideration of this alternative since the correctness of its potentialities can be so easily and quickly determined at a relatively low cost by building a few prototypes for dynamometer testing. Then if it turns out that our expectations are realized, or it looks as tho with some development they can be, then it should permit its gradual introduction into production in less time, and with less developmental and manufacturing cost, and industry disruption than could be had with the adoption of any of the other alternatives now being seriously considered. This would be because of the basic structural similarity of the proposed Reciprocating Brayton Cycle Engine and the present Otto Engine of the Industry.

The requested detailed Critiques and Suggestions relative to the present outstanding and exhaustive JPL Reports are attached.

If you have questions we would be pleased to supply additional data and details, and we would welcome an opportunity to discuss this engine concept with the proper ERDA or/and JPL people directly.

Sincerely

Glenn B. Warren

Glenn B Warren

Enclosures:

Brochures, A, B, and C on the Warren Engine.
Explanatory Letter, Mar. 12, 1976, Warren to Harmon
Page 7 from Brochure A.
Copy of ASME Paper No. 65-WA/APC-1
Press Release of Schultz(Perkins) SAE Paper No. 760047
Copy of SAE Paper No. 690045 on RBC Engine.
Critique of JPL Report.

PHONE FR 4-8683

GLENN B. WARREN, M.E. P.E.
CONSULTING ENGINEER

VICE PRESIDENT
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1361 MYRON STREET
SCHENECTADY, N. Y. 12309

April 15, 1976

SUPPLEMENT to letter of April 15,1976 to R. Mercure, ERDA.

Response to "ANNOUNCEMENT"(Mar. 1976) from ERDA Requesting Critiques of the Original JPL Report as to "Should We Have a New Engine."

1) Acceptable Design Maximum Horsepower in the Various Alternative Engines.

It seems that the low relative values of the equivalent maximum horse-power of the alternative engines of the Brayton GT,Stirling and Rankine Engines shown on Table 4, page 55, Vol.I are based upon an incorrect assumption. On page 33 of Vol.I is a discussion of the Otto Engine Equivalent,(OEE). In addition to the two criteria as to performance in Item (5) of page 33 I am sure that another performance criteria is equally or more important from the safety and drivers' standpoint, and that is the time required to accelerate from about 50 to 60 mi/hr. or even more when attempting to pass with safety a trailer truck on a 1 or 2% grade. To do this safely requires Horsepower. A modern Otto enginecan do this if necessary in the 1st or 2nd(accelerator gear) in a three speed transmission without undue overspeed of the engine, and in these gears and at these speeds almost the full rated power of the engine is available. The Brayton and Stirling motor vehicles listed in Table 4 of Vol.I will be distinctly under-powered in such a situation when compared to the UC Otto. Further with a suitable transmission on any one of the engines the shape of the "speed-horse-power curve" is not a proper criterion of the maximum power required. This is very clear on the JPL estimates made in the report relative to the single shaft GT performance in which the speed power curve is very disadvantagious but is overcome by an IV transmission. This therefore gives these alternatives an unfair overall advantage.

The above comments are made with the background of more than 60 years of driving USA motor cars, and about 30,000 miles of driving two 2800 lb. European motor cars with about 70hp engines in each, 1/3d of which was in Europe and the remainder in the USA.

2) Driving Cycles Which Are Determining From the Emissions and Fuel Use Standpoint.

The study does not seem to put enough emphasis on thelight load, low speed, stop and go traffic conditions with the short trip length which are typical of so much of the use to which the average privately owned motor vehicle is put today. I believe it is frequently assumed that 55% of fuel is used in urban driving and 45% in highway driving. This is probably more nearly 70 and 30%, or is apt to be in a few years.

3) Fuel Consumption in Real Driving Experience.

The writer pointed out in an ASME Paper No. 65/WA/APC-1 in 1965,copy attached, the almost 2 to 1 difference in the miles/gallon obtained from motor cars with Otto Cycle engines when they are driven an average of 100 miles per day compared with the miles per gallon when they are driven but an average of 10 miles per day. This is recognized today when City mi/gal. are given as about 2/3ds Highway mi/gal.

In contrast based upon many thousand miles of operation on duplicate motor cars, one with an automotive Diesel engine, and three with Otto SI engines the Diesel gave about the same miles/gallon in the Summer time whether operated an average of 100 mi/day or 10 mi/day, and dropt down only slightly when operated 10 mi/day in the five months of a New England Winter.

Further as shown also more than 100% greater mi/gal. were obtained on the Diesel car when driven 25 mi/day as compared to the Otto SI engined duplicate cars. I do not have specific figures but it is probable that the average motor car is driven but an average of about 25 mi/day thruout its useful life.

This difference in economy between the Diesel and Otto engined vehicles is undoubtedly due to three basic differences in these two motive power systems: 1) The Diesel(and the Reciprocating Brayton Cycle) engine operate on a very lean fuel air mixture, and this being nearer the air-cycle has inherently a higher efficiency, particularly at light loads, than an engine as the Otto which must have a working fluid which is only slightly lean or fuel rich most of the time; 2) The Otto Engine throttles the air inlet for light loads, thus introducing a pumping drag on the engine whereas the Diesel or the RBCE do not throttle the air, but control the load by the amount of fuel injected;and 3) the latter two engines need no"choke" for cold starting which gives an over rich mixture to the Otto, whereas the other two engines will operate "lean" at all times.

4) A 1976 SAE Paper No. 760047 by Schultz(Perkins),Press Release attached, shows new data regarding actual relative fuel consumption by many different Otto Cycle and Diesel motor cars under various driving conditions. The plotted data indicates also the major influence which the idle fuel consumption has on total fuel consumption in this kind of driving in traffic, and at various speeds and trip length conditions. Further by showing the high proportion of fuel consumed in such traffic conditions it points out that any new automotive engine system which is expected to show a substantial fuel saving must perform outstandingly well under these difficult stop and go traffic conditions.

5) <u>Fuel Consumption Under Varying Loads With the Alternate Engines</u>.

We have been given to understand verbally that the present fuel consumptions shown for the Stirling engined cars are based upon "steady state data." We find no evidence in the Reports, Vol. I or Vol. II, which show the expected idle fuel consumption of the Gas Turbine, present-Mature-or Advanced, or of the Stirling or Rankine engines. Without these data it is difficult if not impossible to determine the relative fuel consumption which these Alternative Engines will have in real-life driving conditions as compared to the US Otto or the Present Diesel Engines.

6) <u>Control of Stirling Engine for Varying Loads</u>.

It is apparently necessary to change the "Mean-Pressure Level" of the hydrogen working fluid in the Stirling Engine to operate efficiently at different loads. Altho the amount of hydrogen is small, at full load it must be at a pressure level of nearly 3000 lb/sq.in. This requires storing hydrogen by pumping from the engine to a storage tank to operate at a lower MPL, and so operating at a lower load with high efficiency. Then hydrogen is valved from this storage tank back into the engine to permit operation at higher loads. Obviously the stored hydrogen in the storage tank must be at higher pressure than 3000 psi. This is a good system for a marine or stationary power plant where load changes are infrequent, but is not well adapted to the constantly changing load conditions when the Stirling is used in a vehicle for urban driving.

Such changes in MPL, I would assume, would have to be supplemented by changes in "by-pass flow" for short periods, or changes in "dead volume." These must reduce the otherwise high efficiency for these short periods of time, would require complex control mechanisms, since it cannot be expected that the driver can do this manually. This certainly must seriously increase the otherwise low fuel consumption of the Stirling engine when used under those varying load conditions.

7) Efficiency and Operating Conditions of the Gas Turbine Alternatives.

The automotive Gas Turbines of either the two shaft or one staft versions, re. based upon present technology, are particularly deficient in this respect in that the idle flow seems to be about twice that of the equivalent size UC Otto engine, and about 4 times the idle fuel flow of the Present Diesel engine. The idle fuel flow of the RBCE is expected to be about the same as the equivalent Diesel.

Further, at idle conditions the GT compressor and turbine have to be slowed down to about 50% full rpm in order to get even these values of idle fuel flow. At this 50% rpm its stability of operation is borderline, and compressor "stall" is apt to take place if the throttle is opened, that is if fuel is fed, too fast in the expectation that the GT will operate at higher power. As indicated on Fig. 4 of Brochure A this situation is avoided on the Present Two Shaft GT by holding the vehicle with the brake at the stop light and increasing the speed of the compressor-turbine combination by depressing the accelerator pedal so as to prevent this stall on subsequent acceleration when the green light comes on. This causes a material increase in the idle fuel flow, and hence a decrease in the mi/gal. in such operation.

The adverse effect of this traffic operating condition on the Present 2 Shaft GT fuel consumption in Urban traffic is so great, as indicated in Table 5-10, that it is expected the Mature version will have to make a 100% improvement (8.9 to 17.2 mi/gal) to be satisfactory. In view of the fact that the 8.9 mi/gal. represents the best result of almost 25 years of intense and outstandingly competent R&D work on this engine by the Chrysler Corp. To make such a large gain now on this phase of the performance is a very difficult objective to meet.

The Reciprocating Brayton Cycle Engine is not faced with this problem. It should be able to take on Wide Open Throttle Load without stall, stumble, or hesitation by simply increasing the fuel flow since the air flow to the combustion chamber is that required for WOT at whatever rpm the engine is running, and the resulting increase in combustion chamber pressure cannot make the reciprocating compressor stall.

Based upon my 42 years of personal experience with the design and operation of steam and gas turbines, including their R&D, the projected improvements in gas turbine efficiency indicated for the Mature and Advanced GTs on Table 5-1 will be difficult if not impossible to obtain. The same is apt to be true for the compressor efficiencies at 10 and 15 to 1 pressure ratios. The turbine efficiencies are also going to be more difficult to hold up at the higher pressure ratios. One reason is that the shorter blades required for lower maximum capacities and higher pressure ratios mean less efficient nozzle and bucket flow paths. Another reason in this same direction is that if the pressure ratios are increased it puts many of the turbine nozzle and bucket passageways in the supersonic region and flow losses are almost certain to take place.

Further, experience indicates that turbine nozzle and bucket efficiencies are reduced by relatively large "fillets" and thicker "trailing edges". Such conditions are going to be hard to avoid with ceramic rotors and nozzle rings.

8) CERAMIC MATERIALS FOR GT ROTORS.

So far as I can see the outstanding material R&D being done now in connection with the development of ceramic materials for this program is firmly based upon the understanding that everything possible should be done to increase the ductility of the ceramic materials comprising the turbine rotors. Several recent SAE papers indicate, however, that "low ductility is a major problem." SAE Paper 760262 points out further that creep or apparently ductile flow in ceramics is really "a slow crack growth phenomenon rather than plastic flow as in metals and ...can lead to catastrophic failure." The experience of turbine manufacturers here and abroad has been disastrous in connection with rotor material in which the ductility is ~~even~~ extremely low, even with metals. This difficulty has been where ductility has been sacrificed in favor of higher apparent strength material.

9) "Boiler Efficiency" of Stirling Engine?

The Stirling and Rankine Cycle engines have an atmospheric pressure furnace which heats the working fluid thru metal walls. In the Stirling all of the heat is apparently put in to the hydrogen gas heating elements at 1300-1400°F at all loads. The furnace gases must be appreciably above this temperature to keep the weight of these heating elements to a minimum. Then since there are no lower temperature surfaces which can usefully absorb heat the rotary regenerator must be sufficiently good as to reduce the "stack losses" to a minimum. This is particularly urgent because I believe that the furnace is run with about 30% excess air to keep the NOx down. Further such a regenerator must produce a very high air preheat to the furnace which makes low NOx a problem.

Also the walls of the combustor are in contact with the hot inlet air and the radiant heat from the combustion and must be insulated, but for such a small furnace the radiation losses are apt to be an appreciable percent, particularly will be so at lower loads and at idle since it is indicated that the top gas temperature remains relatively constant with varying loads. At no place in Vol.II was it apparent that these losses were recognized or accounted for.

10) FACILITIES------Table 11. Summary Vol.I

This apparently does not take into consideration in connection with the investment in Manufacturing of the very large amount of present tools which would not have to be renewed completely but which could be adapted for continuing use if the new engine or engines were to have the similarity of major parts to the UV Otto which the Diesel, Stratified Charge, or Warren(Reciprocating Brayton Cycle) Engines would have. This would be in distinct contrast to the almost complete change over which would be required in the case of the GT or the Stirling. In the caseof the Single Shaft GT a complete change in the transmission manufacturing facilities would be demanded. These considerations it would seem would represent a very great difference in the investment required over the next decade depending upon which of the Alternative Engines is adopted.

11) SPECIAL MATERIAL CONSUMPTION. Table 12, Vol.I page 75.

In view of the great size of the automotive industry, not only in this country but in the world the percentage of potential total consumption of some critical materials by the 2 Shaft GT, the Stirling, and the Rankine engines should be of real concern in case we should get into another national emergency. The RBCE should be better even in this respect than the Single Shaft GT.

Sincerely

Glenn B. Warren

PHONE FR 4-8683

GLENN B. WARREN, M. E. P. E.
CONSULTING ENGINEER

VICE PRESIDENT
GENERAL ELECTRIC CO.
RETIRED
PAST PRESIDENT A. S. M. E.

ORIGINAL PAGE IS
OF POOR QUALITY

copies to Collins, SWRI, Morgan

148 E. Coronado Rd.
Phoenix, Ariz. 85004

Mar. 12, 1976

Mr. Robert A. Harmon
Consultant
25 Schalren Drive
Latham, N.Y. 12110

Subj: Answers to Some of the Questions Raised at the Feb. 24th meeting in Detroit with the SWRI and Ford people. Re. your letter of Mar. 2nd to me.

Dear Bob:

This letter and the attached Supplement dealing with the energy available to and utilized by the Exhaust Turbine Driven Supercharger as raised by Carlos Coon of SWRI are only answers to some of the questions raised at our Detroit Meeting with Ford and SWRI. Other matters will be dealt with later, after we receive Mr. Collins' expected letter.

I should like to reconsider here, particularly, the comparison made in Par.3, page 3 of your letter of Mar. 2nd to me reporting on this meeting. This is needed because of its importance and apparent misunderstandings. I quote:

"Efficiency is a key consideration and is shown to be approximately 10% less than the diesel. This does not seem to be a stong incentive to initiate a high risk program. This is a SWRI concern."

This is not the proper comparison to make because the diesel is not a viable alternative motive power plant to assume for the passenger and light truck automotive vehicles of the future. (This is confirmed by the JPL Summary Report page 75, Par.4)

A prime consideration for the future automotive vehicles is that of energy and oil conservation with respect to what we are doing now, and what the automotive industry is proposing for the next generation of automotive engines, namely the present uneconomical Otto engine with exhaust treatment. This was very cogently put in the presentation of Mr. Coppac, VP of Texaco on "getting more miles from each barrel of oil" quoted more completely later in this letter, and in Mr. Zarb's presentation to the SAE on Feb. 25th when he stated:

"A complete energy program.....will not happen in just a few years. It will be a slow, gradual, painstaking process that will make heavy demands on capital, manpower, and material, and perhaps heavier demands on our ability to resolve apparent conflicts between economic, environmental and social issues.

It is these demands that make energy conservation such a vital part of our total strategy. Without conservation our vulnerability will continue to grow until new resources can be tapped. And as engineers, you know better than most of us that building power plants and oil refineries takes time, as does the development of every (new) energy source. Conservation can buy us that time.

Conservation can also enable us to develop these resources deliberately, with the least possible environmental or economic disruption."

The comparison of importance should not be between the diesel and the Warren Engine, but between the conventional engine as now planned for the immediate future and the proposed Warren Engine, and then later between the Warren Engine and the Gas Turbine and Stirling Engines being considered for the further future.

Warren to Harmon. 3/12/76 Page 2.

As has been stated from the beginning in my SAE Paper No. 690045, and in our Brochures that it is expected the Warren Engine can attain about the same economy in the utilization of petroleum fuels as the automotive diesel, particularly in stop and go light load operation. It has been generally anticipated that this will be as compared to the "prechamber diesel". That is this prechamber diesel is needed because of reduced noise, roughness, and odor as compared to the direct injection open chamber automotive diesel usually used in the larger trucks, despite its being about 10% less economical of fuel.

I will not quarrel with SWRI's estimate that the Warren Engine will be 10% poorer than such a diesel because neither they nor I can calculate the performance closer than that. I acknowledged this on Fig. 17 of the SAE paper when in addition to plotting the comparative calculated performance at steady speed, level road operation at from 30 to 70 mi/hr., I also made a comparison with the calculated performance of the Warren engine depreciated 10%, and both compared to the test performance of a conventional engine of 1967 vintage before its depreciation for emission control. Even on this depreciated basis I still showed 55% gain in mi/gal. at 30 mi/hr, 36% at 55 mi/hr, and 27% at 70 mi/hr. The statement was made that the 10% reduction in economy was considered "because of uncertainties" in the calculations, and could be considered because the gains were already apparently so great. However, I still believe that with reasonable development this proposed engine will equal the automotive diesel on an energy basis, particularly in stop and go urban driving.

Further my 1965 ASME Paper No. 65/WA/APC-1, partially reproduced on page 7 of Brochure A, shows a gain between the conventional Otto Cycle engine and the automotive diesel on a dupplicate vehicle of 100% in stop and go low milage perday driving in mi/gal. The literature is full of similar data including some advertisments of Ford Diesel light truck conversions from conventional engines which stated that the diesel conversions used one half the gallons per mile in urban driving that the conventional engined vehicles used.

This great difference is largely due to the fact that the conventional engine obtained the light load operation by throttling the inlet air which increases the "frictional losses", and that it frequently enriches the mixture by partial operation of the "choke" on short runs between stops. The diesel and Warren engine do not have these losses.

Now bringing this comparison between the diesel and conventional Otto engines up to date we have the Schultz(Perkins) paper No. 760047(SAE) presented at the recent Annual Meeting(News release copy enclosed) which shows a gain in miles per gallon of automotive diesels in the 200 to 300 cu. in. dis. sizes of 15% to 150% when associated with realistic driving cycles.(This is 35% to 150% at speeds of 55 mi/hr. and less.) Data is also shown as to trip frequency times the length between stops from which they can deduce that the average motor car operates in a region in which thegain in mi/gal is apt to be in the neighborhood of 100% for summer operation and probably more for cold weather operation, since the diesel, as would the Warren, operates at all time with excess air, and has no "choke" which causes over-rich uneconomical operation under many conditions.

This great difference is frequently depreciated by saying that the comparison is not fair because the diesel of the same displacement does not have the performance of the comparable Otto engine. This is not true if the diesel has an exhaust turbine supercharger.

This is the comparison in performance which needs to be made. We believe that we can come close to matching the performance of the diesel in such service, but that we are not in competition with the diesel because it is not a viable alternative automotive passenger and light truck vehicles.

------The reasons that the automotive diesel is not a viable alternative power plant for the above is that in addition to its being heavy, rough running, noisy, costly, and with difficult cold weather starting problems, reliable oil company papers indicate that is so critical of specific fuel specifications that only a fraction of the total automotive need could be supplied with diesel quality fuel. (See SAE 750673 by Texaco researchers Tierney, et al, and page 76, Par. 4 JPL Summary)

Further it cannot, so far as I can ascertain, possibly meet the anticipated final emission levels for NOx without excessive fuel injection retard with the resulting economy and performance degradation. If EGR is used to attempt to meet the NOx levels required similar reductions in economy and performance take place and in addition roughness increases and CH and odor increase. I understand catalytic converters are of no value here because the exhaust temperatures at lower speeds are too low, as is also the CO content, and that the necessary chemical conversions do not take place.

The proposed Warren Engine should be able to meet the Schultz shown gains of 35% to 150% as compared to the conventional engines now in use and proposed for the immediate future, and should have greater gains in colder weather and at high altitude locations. Under these conditions the 10% poorer performance predicted by SWRI, if real, should be of academic interest only.

In addition it is my conviction that the Warren Engine will:

1) have a cost nearer that of the conventional engine of comparable displacement than to the cost of the diesel.

2) be able to meet the proposed final emission standards which have been set up, perhaps with some EGR which will have no adverse effect on smoothness of operation, & drivability, and but little on economy or maximum capacity.

3) it will have a smoothness, low noise level, and drivability that compares with the finest present day conventional multi-cylinder engines, even with a low power V-4 Warren Engine for light cars.

4) will be able to use a broad boiling range fuel independent of cetane or octane requirements which covers a broader spectrum of fuels than gasoline, which will permit more gallons of fuel for transportation needs at less refinery costs for operation and new facilities. This the diesel cannot do.

Such an engine will permit meeting the triple requirements of the industry, 1) high energy efficiency on cars of a weight that the American Consumers have indicated that they require, and which incidently will have a greater safety than will the light vehicles now proposed, 2) low emissions combined with high economy and performance, and 3) lower manufacturing and tooling change over costs and less time for such required than are presented by the alternates, namely the automotive diesel, the Gas Turbine, or the Stirling Engine.

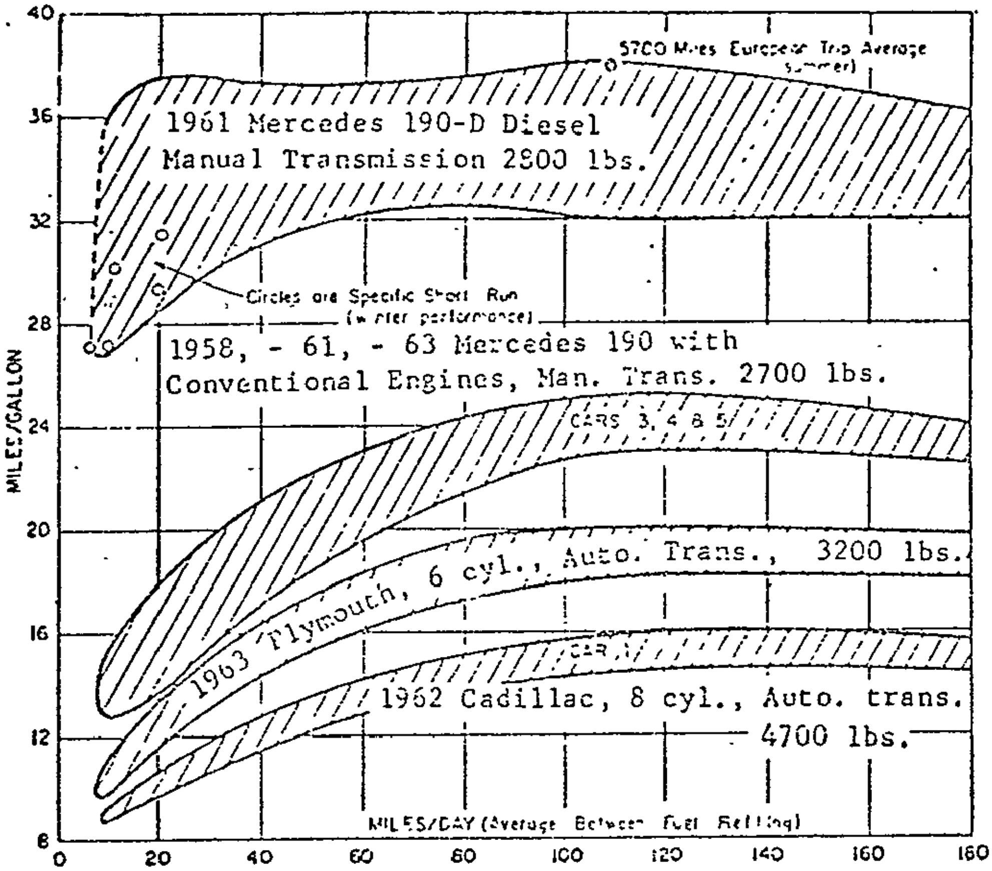
In view of these facts I think it should be judged that the Warren Engine does present a strong incentive to initiate what should be a low risk and low cost development program, and one in which the potentialities of the engine can be determined in a relatively short time, and for a low cost, particularly as compared to the alternatives being considered.

Sincerely

Glenn B. Warren

Glenn B. Warren

The fuel consumption characteristics of the Warren Engine will be similar to those for the Diesel as presented in Glenn B. Warrens' ASME Paper 65/WA/APC-1 "Some Factors Influencing Motorcar Fuel Consumption in Service". However the many disadvantages of the Diesel which have prevented its' widespread adoption in automobiles d. other light-weight vehicles will not be present in the Warren Engine.



:iles per Gallon Fuel Consumption versus Miles Per Day Vehicle Operation for Six Representative Automobiles During Typical Year-Round Driving.

This diagram indicates, clearly, the great difference between the fuel con- :umption characteristics of the Diesel engine and those of conventional - i.e., park-ignited, carburetor-fed, air-throttled engines especially when operated oout TWENTY MILES PER DAY, which is average for most privately owned automobiles. he data within the envelopes comprise hundreds of points from more than 100,000 iles of year-around driving in Northeastern U.S.A. The miles per day information as obtained by always completely filling the gasoline tanks and recording the ates, gallons required and odometer readings at each filling.

Note that, at only 8 miles per day, the Diesel still shows excellent miles er gallon even in winter. It is expected that the Warren engine will duplicate nis low specific-fuel-consumption since among its other advantages it does not ave a choked-carburetor. The outstandingly good low-fuel-consumption of the Warren ngine during stop-and-go driving will thus conserve our energy supplies and at e same time meet the 1978 Air Pollution standards.

Brochure A - Warren Engine

29

Critique by

Marcus Lothrop
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December 22, 1975

File: 3705-S[5]

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Attention: R. Rhoads Stephenson

Gentlemen:

I am particularly grateful for the receipt of both volumes of your report "Should We Have a New Engine?, etc.". This is indeed a formidable work, and I have not finished it yet in detail but have seen enough to extend my compliments to you not only for the extraordinarily comprehensive nature of the report but particularly for the sharp decisions in the field I know, the Rankine cycle engine.

I noted in the authorization that certain copies were to be furnished free whereas others were to be supplied at cost. I inquire into which class my copies fall.

I may take the liberty of addressing you further when I have been able to make a more thorough study of the appreciated volumes.

Sincerely yours,

Marcus Lothrop

Marcus Lothrop

ml/cm

Critique by

United Turbine AB and Company
N. Grangesbergsgaten 18
2140 Malmo, Sweden

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

30

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Re: 34LPE-77-201

June 29, 1977

Professor Sven-Olof Kronogard
United Turbine AB & CO
Kommanditbolay
N. Grangesbergsgaton 18
2140 Malmö, Sweden

Dear Professor Kronogard:

Subject: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

In reply to your letter and the very informative memorandum enclosed with it, we want to first explain the restructuring of our work and the plan for responding to the subject critiques. A summary of our reoriented program is enclosed for that purpose.

We find the Kronogard Three-shaft Turbine (KTT) concept to offer much promise (1) by virtue of the inherent capability of a turbine to function in the role of a torque converter; and (2) by providing more efficient recovery of those losses which are primarily responsible for the poor fuel economy of the gas turbine when operated under off-design and transient conditions. Based upon the information available to us, it appears that the KTT concept offers significant improvements in part load economy, response, engine length, weight, and cost compared with a two-shaft engine that depends on an external hydraulic torque converter.

In our view the basic advantages of the Kronogard approach are that the full stop and torque conversion capability of a two-shaft engine can be retained while simultaneously solving the problems of gasifier inertia and accessory drive power take-off. By driving the accessories off the auxiliary turbine, which is in motion all the time, you enable the power turbine to accommodate a full stop and without having to be disconnected during idling.

With regard to the torque balanced coupling of the auxiliary turbine with the gasifier and the power turbine, you enable the turbine designer to distribute the expansion as necessary for design optimization. The power of the auxiliary turbine can be shifted between the power and the compressor turbine during operation by means of relatively cold variable guide vanes at the auxiliary turbine inlet. A potential problem, of course, is that of system stability. The major components

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of two-shaft turbines, such as represented by the gasifier and the power turbine/ vehicle drivetrain combination, are inherently stable. The combination of two or more major system components linked together through differential gears introduces the possibility of internal power feedbacks resulting potentially in internal power fluctuations and instability.

Regarding the trend to higher compression ratios, two-stage compression, and the use of recuperative heat exchangers, the capability of the KTT concept to equalize internal power changes and flow discontinuity may be helpful in resolving some of the problems associated with the off-design operations of high compression Brayton engines.

Through the mechanism of the Technical Task Summaries (TTS) as described in the enclosure we will address the KTT and other advanced gas turbine engine concepts in detail. During the execution of the Brayton assessment activity we will be especially interested in further discussions. Your cooperation is greatly appreciated.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:nrw

Enclosure

UNITED TURBINE AB
& CO. KOMMANDITBOLAG

Vårt datum/Our date
April 30, 1976
Ert datum/Your date

Vår beteckning Our reference
UT 22.191 SOK/se
Er beteckning Your reference

Mr R Mercure
U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545
USA

Vår handläggare/Our contact-man

Dear Mr Mercure:

As a complement to my letter of March 17, I hereby enclose some comments as regards the manufacturing cost of different gas turbine engine, including the 3-shaft KTT-system.★

I also refer to a summary of the KTT-system which will be printed in the next ERDA Quarterly Report. If you need any further information please let me know.

Sincerely yours

Sven-Olof Kronogård

★Ref: "Automotive Turbine - Advantages of Three Shaft Configuration," Gas Turbine International, November-December 1975.

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Manufaturing cost of a three shaft automotive gas turbine power plant - KTT-system.

In the report by JPL,"Should we have a new engine", a cost comparison is made between a single shaft and a two shaft gas turbine. As we have stated before this is a misleading comparison for the 2-shaft gas turbine for the following reasons:

The cost and weight of the turbine parts of the 2-shaft engine is much overestimated mainly because the calculation has been made with a very badly designed 2-shaft engine as foundation. (The compressor turbine rotor and the transmission duct weights and costs are far too high).Reference our letter of March 17, 1976.

We consider it is possible to manufacture the 2-shaft turbine power plant, i.e. including transmission, controls and auxiliaries for less cost than the single shaft engine if both engines have the same level of technology and cost optmization.

Two further emphasize this trend we have made a comparison between the calculated cost of our KTT-system with 3 turbine stages and the cost calculated made by William Research in 1973 on the WRC 2-shaft engine. The cost calculation has been carried out in the same way for the two engine types.

This comparison shows that the KTT 3-shaft gas turbine including the integrated transmission would cost about the same as the 2-shaft gas turbine to which then of course has to be added the cost of an automatic transmission.

	KTT 3 shaft GT	WRC 2 shaft GT
Engine + auxiliaries	226	220
Automatic transmission	- 1)	80 à 150 2)
	226	300 à 370

1) Is integrated in the engine.

2) Three stage automatic with torque converter.

The total cost for the turbine wheels are $ 32.70 for the KTT engine and $ 36.60 for the 2 shaft engine. The wheels are cheaper in the 3 shaft case because for the same total turbine power the diameter and thus the weight of the wheels can be made smaller with 3 turbines compared to 2.

UNITED TURBINE AB
& CO, KOMMANDITBOLAG

Vårt datum/Our date
March 17, 1976
Ert datum/Your date

Vår beteckning Our reference
UT 22.172 SOK/iba
Er beteckning Your reference

Vår handläggare Our contact-man

Dr R Rhoads Stephenson
Jet Propulsion Laboratory
Automobile Power Systems Evaluation Study
California Institute of Technology
4800 Oak Grove Drive,
Pasadena,
California 91103 USA.

Dear Dr Stephenson:

Thank you very much for sending me copies of your two volume report, "Should we have a new engine? An automobile power systems evaluation." This report has stimulated much interest not only in my organization.

In my personal opinion, this report represents a very outstanding and comprehensive effort on this subject.

In our review of the report, we came across a few but important questions, which are listed in the attached memorandum.

As regards the gas turbine evaluation I think you should not overlook the 3-shaft configurations of the KTT-type. For your information I have enclosed a copy of my recent paper "Automotive turbine - advantages of three shaft configurations", a summary of which will be enclosed in the next ERDA quarterly report. Further information on the KTT-system will be furnished to ERDA for updating of your JPL-report.

I appreciate the opportunity to review and comment on your report. I hope these few comments will be helpful to you in preparing the supplementary report on your investigations. If there is need for further clarification on these points, please do not hesitate to contact me. Of course you are most wellcome to visit us in Malmo for further information as regards our turbine systems for updating of your JPL-report.

Sincerely yours,

Sven-Olof Kronogård

Encl. Memorandum
Automotive turbine-advantages of 3-shaft config.
cc. Mr. R. Mercure, ERDA, Wash.

Postadress/Postal address	Telefonnr/Telephone	Telegramadress/Cable	Telex	Bankgiro/Bank cheque account	Postgiro/Post cheque account
N. Grangesbergsgatan 18 214 50 MALMÖ SWEDEN	040 - 801 50	turboab malmo	32420 TURBOAB S	434-0550	62 91 12-4

MEMORANDUM

Subject: Critical comments relative to important elements of JPL report "Should we have a new engine? An Automobile power systems evaluation."

The subject investigation is a very broad and comprehensive treatment of a difficult subject. Because of its potential influence on important future developments, a number of critical comments and questions are listed here for consideration and future clarification.

These are submitted in accordance with the request of ERDA as a result of verbal comments offered by Professor S O Kronogard at the contractors coordination meeting, which ERDA held at Ann Arbor, November 1975.

I. Closed cycle engines

We agree with your comments in the JPL-report disposing of closed cycle Brayton machines for automobiles, quoted as follows:

"In principle, both open- and closed cycle Braytons could be used in automotive applications. With current technology and foreseeable developments, however, there is little to recommend the closed-cycle engines. They offer no significant performance or efficiency advantage over well-designed open-cycle machines, and yet are heavier and much more complex by virtue of the multiplicity of flow paths and heat exchangers that must be provided. These practical considerations bar the closed-cycle machine from the low-cost, high production-volume automotive engine-millieu."

There is justification to extend these conclusions to other closed-cycle engines also such as Rankine systems and Stirling systems for the same reasons. Correction of the weight figures discussed below, further supports this suggestion.

II Weight and fuel consumption comparison between mature single and two shaft gas turbines

Concerning the turbine wheel weight for the mature single shaft 4:1 pressure ratio machine (4,1 lbs in table 5-4) it is hard to understand that the gasifier turbine wheel in the free-turbine (two stages) mature machine (4.7 lbs in table 5-5) weighs more when it operates at about half pressure ratio. Further, it is not suitable to use a radial turbine for a low pressure ratio (4:1) two shaft engine since the inlet scroll and nozzle ring becomes unproportionally large and the transient duct between a radial and axial stage distorts the design and causes unacceptable size, weight and cost penalties.

A two stage axial turbine is the logical arrangement for a low pressure ratio, two shaft machine (see attached schematic sketches, which are approximately to scale for comparative purposes, fig 1 and 2).

If you thus assume a 2-shaft engine based upon 2 axial stages, this engine will have a weight about the same as the single shaft engine and thus the same power requirement in the car.

Furthermore a 2-shaft turbine and with variable turbine nozzles will have a lower fuel consumption and emission at low load than a single shaft engine (lower inertia, more efficient torque conversion and heat loss recovery).

This together with the less complicated transmission needed (better torque characteristic) should give the car with a two shaft turbine, a better fuel consumption and over all economy than the same car with a single shaft engine.

III Weight and fuel consumption comparisons of Stirling, Otto and diesel engines

For the mature Stirling engine, the cylinder block assembly is made of aluminium alloy and weighs 112 lbs (table 6-3, page 6-18). The cross head blocks and the high pressure block account for 96 lbs of this total. Why is aluminium used for this highly stressed, high quality part (pressure 200-250 atmosphere) when for the mature Otto cycle engine the head and block/housing is of ferrous material. If steel was used for the Stirling (90-100 lbs more weight) and aluminium were used for the Otto cycle, a logical choice practically proven, the difference would be more like 300-400 lbs in favour of the Otto cycle for the same power.

This was just one example to show why we think you have assed the weight of the Stirling engine too optimistic. We can see no possibility that a complex closed cycle system like the Stirling system, could be made lighter in weight than the diesel engine with automotive manufacturing and cost practice. We suggest you look further into this matter because, as we see it, this part of the foundation on which you build your favourable picture of the Stirling engine.

If you assume the same weight as the diesel engine the Stirling engine powered compact vehicle would need 131 hp instead of 99 according to your calculation.

This would affect as well the cost of the powerplant as the fuel consumption of the Stirling powered car drasticly.

The complexity of the Stirling engine, its heat exchangers and controll system (closed cycle machine) is a factor which should receive much more attention and have a stronger influence on the conclusions drawn from the investigation.

Sven-Olof Kronogard

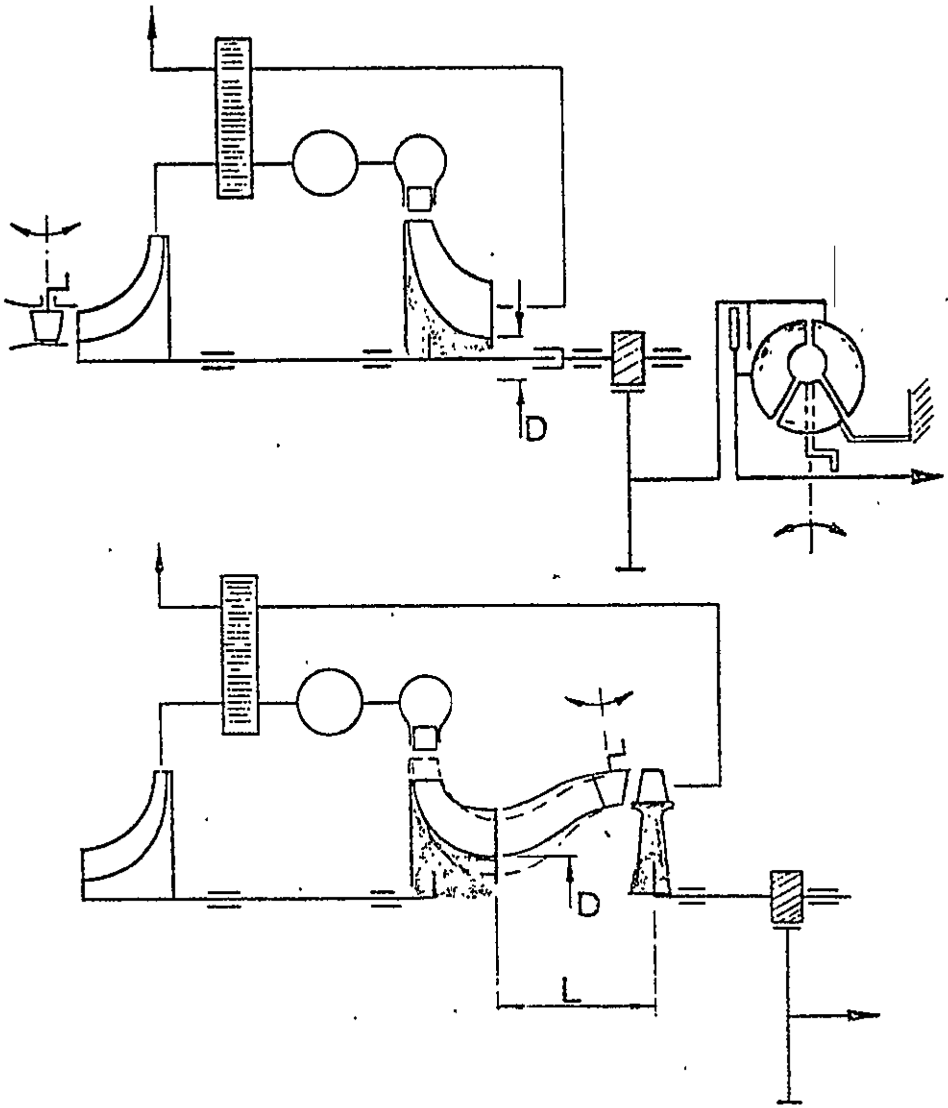

Fig. 1 Radial Single-Shaft and Radial-Axial Two-Shaft Engine Schematics (Penalties in D and L Dimensions)

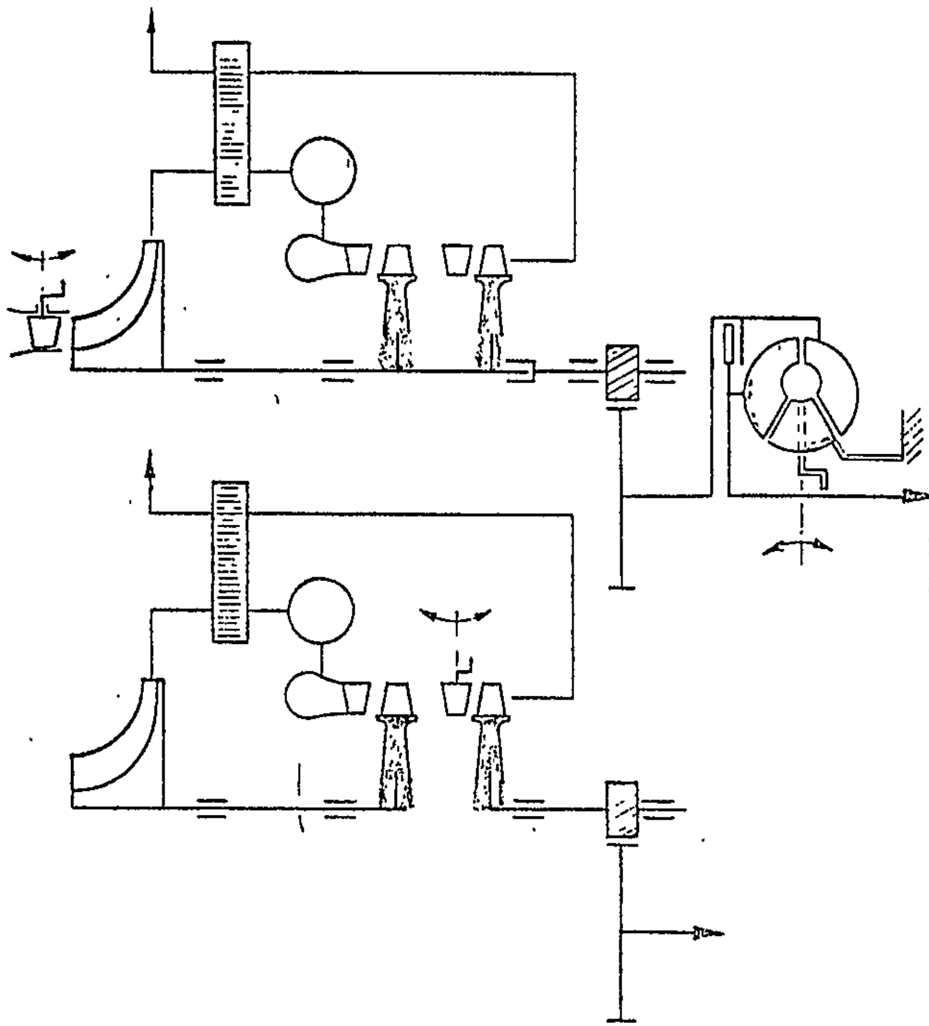

Fig. 2 Two-Stage Axial Arrangement for Both Single- and Two-Shaft Engines (Penalties Minimized)

Critique by

National Aeronautics and Space Administration
Lewis Research Center
Power Systems Division
Cleveland, OH 44135

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

31

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-187-30

June 29, 1977

Mr. Donald G. Beremond/5200
Power Systems Division
Lewis Research Center
National Aeronautics and
Space Administration
Cleveland, Ohio 44135

Dear Don:

Subject: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

We appreciate the in-depth review you performed on the subject study. The many points you made on the Brayton engine will be very helpful on our follow-on work which is summarized in the enclosure. We are assessing several of the points which you brought up, and they will be included in an appropriate Technical Task Summary along with related points from other reviewers.

We are looking forward to a continuing interchange of information and ideas with you on alternative automotive engines.

Sincerely,

Harry

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

MAR 26 1976

REPLY TO ATTN OF: 5200

TO: Jet Propulsion Laboratory
Attn: G. W. Meisenholder

FROM: 5200/Donald G. Beremand
Power Systems Division

SUBJECT: Review of JPL Automotive Power Systems Evaluation Report

As you know, we have a substantial interest in the automotive gas turbine area. We are currently supporting ERDA in the ongoing Chrysler gas turbine engine effort, and are planning a major effort, in support of ERDA, for an advanced automotive gas turbine engine. We, therefore, found your APSE report of great interest and have had the gas turbine section, Chapter 5, reviewed by some of our system and component experts relative to their areas of expertise.

Overall we believe the report presents an adequate comprehensive evaluation of the automotive gas turbine engine, its potential benefits, and its problems. The following is a summary of the comments of our reviews.

<u>Overall System and Cycle Analysis</u>

The engine analysis presented in the report relied heavily on engine performance information generated by AiResearch in previous paper studies. This had the effect of limiting the scope to engine cycles evaluated by AiResearch, and of carrying over some of the optimism inherent in the AiResearch results to the JPL effort. Further, this optimism was amplified by some of the assumptions made in the report in regard to advanced engine performance projections. As a result, for the specific configurations and cycle conditions selected we estimate that the fuel economies projected for the mature and advanced engines are optimistic by about 10% and 30% respectively. However, considering possible modifications of the configuration and adjustments in cycle state points, such as those cited below, the fuel economy presented for the Advanced System is still considered to be a reasonable projection.

The choice of a 4:1 design pressure ratio for the Advanced System can be questioned. Although the cycle efficiency peaks at 4:1 in figure 5-3 (a), this is for 1900°F and not 2500°F. The optimum pressure ratio increases with increasing temperature as well as with increasing component efficiencies. Further, an increase in design pressure ratio is desirable in order to increase the much lower pressure ratio, and associated poor performance at part power. The report discussed regenerator temperature limits; however, the results do not appear to include such limits. It is likely that proper consideration of regenerator temperature constraints would have lowered engine performance levels and also have led to selection of a higher compressor pressure ratio for the 2500°F engines.

The study apparently has not considered the possible advantages, in terms of engine performance, of a single-shaft gas turbine engine with completely variable geometry. That is, an engine with variable inlet guide vanes, variable compressor diffuser vanes, and variable turbine nozzles. Such an all-variable engine concept appears to be a highly attractive candidate for the advanced automotive gas turbine and merits evaluation in any future studies of the automotive gas turbine. It should be noted that control of such an all-variable engine concept may be quite complex and could require a sophisticated control system to provide the desired combinations of settings over the required range of steady-state and transient conditions.

In the description of engine analysis, it is not clear how fuel consumptions were derived from the AiResearch engine maps. Compressor efficiency adjustments for horsepower less than 100, and engine-accessory power needs are not included in these AiResearch maps.

We agree with the Otto Equivalent Engine approach taken in comparing alternate engine concepts; however, consideration should be given to hot-day performance. The report only presented gas turbine performance for an 85°F day. It is assumed this is also true for the other engine concepts presented. To date, automobile design horsepower has been established by hot-day performance. The effect of ambient conditions on engine performance is different for different engine concepts. In addition, approaches to power augmentation differ from one engine concept to another. Therefore, it would appear that a more realistic approach to defining OEE vehicles would be to do so based on hot-day performance.

Turbines and Compressors

Some of the turbine and compressor efficiencies in Table 5-2 are rather high; however, these are for the simple cycles, which are not the recommended selections. It is recognized that these may have been intentionally set high to give the simple cycle systems all possible consideration. For the Mature and Advanced regenerated systems, the efficiencies are optimistic, but not necessarily unachievable. The use of one particular map (figure 5-10) to represent the efficiency characteristics of all the radial turbines studied for the Mature system is questionable. The use of a small-size efficiency penalty for compressors but not for turbines is inconsistent. Also, it should be recognized that, in design of a real machine, turbine and compressor efficiencies are not entirely independent. The specific heat ratio of 1.35 used for the turbine is a little high; values should be about 1.32 and 1.30 for the Mature and Advanced systems, respectively.

Combustors

In general, the report is quite factual and does a good job of bringing out both the good and the bad points in regard to gas turbine engine combustors for automotive application.

As stated in the report, the variable geometry premixing/prevaporizing combustor is one promising approach for meeting the low NO_x emission requirements in the automotive gas turbine engine. However, while the effectiveness of the basic concept has been demonstrated, a large amount of work is needed to perfect the controls necessary for the variable geometry, to develop a sensing device and an intelligence to operate the variable-geometry controls, and finally to incorporate this into the overall fuel control system. The constant changes in speed and power typical of the Federal Urban Driving Cycle, with its accompanying transient modes, further complicate the problem.

Another approach which should be considered for the Advanced system, where adequate development time is available, is the catalytic combustor. While the technology for such combustors is still very limited, the testing of candidate catalytic bed materials indicates an excellent potential for extremely low emissions of HC, CO, and NO_x.

In regard to the ceramic combustor liners necessary for the Advanced Engine at 2500°F, it should be pointed out that they may also become a critical item even at somewhat lower temperatures for the following reasons:

a. The trend toward operation at very lean primary-zone equivalence ratios, necessary to achieve low NO_x levels, reduces the amount of air available for liner cooling.

b. If, because of availability problems, fuels high in aromatic content were to be used in gas turbine engines, problems with liner cooling would most certainly be aggravated because of increased radiation from the highly-luminous flames.

While it is true that "The gas turbine engine has a multi-fuel capability", there are certain qualifications that should be noted. As pointed out above, fuels high in aromatic content tend to give problems with liner cooling and also with smoke formation. (In automotive-type combustors, smoke is generally not a problem because of the lean primary-zone mixtures needed to suppress NO_x formation.) Additionally, heavy fuels with final boiling points considerably higher than #2 diesel fuel may present problems with fuel vaporization and hence high HC and CO emissions. Finally, fuels with high fuel-bound nitrogen content (such as those derived from coal and oil-shale syncrudes) may present severe NO_x problems because of the high conversion rate of fuel-bound nitrogen to NO_x.

Transmissions

No disagreement was found with the major findings reported in terms of transmission requirements and the suitability of conventional and advanced transmission components for automotive gas turbine engine applications. Since little quantitative data or detailed design information appeared in the transmission section, it is not possible to comment on any of the performance projections associated with the various engine-transmission combinations. One observation is offered in regard to the variable-angle stator torque converter in combination with a three or four-speed automatic gearbox suggested for the single-shaft engine. The torsional softness (slip) of the torque converter may make it difficult to maintain a desired speed ratio across the transmission without a rather sophisticated control system.

Regenerative Heat Exchangers

Selection of a regenerator, rather than a recuperator, for the Mature engine is certainly the logical choice, considering their relative development status. However, for the Advanced engine, where more time is available for fabrication development, serious consideration should be given to the use of a recuperator. The seal leakage inherent in the regenerator can represent a significant performance penalty, and regenerator seal life and durability can be expected to present continuing difficulties with the desired low leakage rates. (The assumed leakage is 3% for the Mature and Advanced configurations at regenerator temperatures of 1800°F (Mature) and 2000°F (Advanced)). These inherent problems provide substantial incentives for development of the recuperative-type heat exchangers. It is believed that the desired effectiveness could likely be achieved in a ceramic recuperator. However, a substantial effort may be required to develop the necessary fabrication technology and techniques required to make such a unit practical. Further, heat exchanger fouling, from dirt in the incoming air supply, may be a more difficult problem with recuperators considering the more complex flow paths and unidirectional flow conditions compared to the regenerator.

Materials

One area of concern not discussed in the report relates to the large volume production of ceramic components for automotive use. Demanding high volume, high technology production from the ceramic industry, which currently is very limited in tonnage capability and in trained highly technical personnel, will require a gross departure from their historic position of producing low technology items such as white ware and refractories.

The following comments are offered in regard to the discussion in the report of ceramic fabrication processes.

The report indicates that with hot pressing SiC and Si_3N_4 parts can only be made one at a time. Admittedly, hot pressing is much slower than the cold press and sinter route; however, the use of multiple die cavities is a viable approach. Thus, there is a hot pressing process that could be automated for mass production. Furthermore, development is currently being done on hot pressing to near net shape which would minimize component machining.

One process for low-cost mass production of ceramic parts not mentioned in the report is REFEL. This process involves the formation of SiC plus carbon shapes by slip casting or injection molding followed by impregnation with silicon. The resulting parts have excellent strength up to the melting point of silicon which is about 1400°C.

Regarding advanced ceramic processes, it seems unrealistic to state that there is no reasonable basis for projecting significant advancements in CVD SiC. It is true, however, that the process is a long way from even approaching viability in mass production. Also, the point seems to have been missed regarding the advantage of SiAlON's. Their development is important from the standpoint of their reported ease of fabricability, <u>not</u> their higher use temperature capabilities.

Some reservations should be stated regarding the assumption that uncoated superalloys could be used with TIT temperatures of 1900°F. Coatings may be required at least in the turbine nozzle since less than perfect combustion pattern factors usually result in local metal temperatures exceeding the average inlet gas temperature. Also, contrary to the authors' statements, coating of superalloys generally will improve low-cycle-fatigue resistance. Finally, coatings may be required to inhibit hot corrosion that is likely to occur due to the use of road deicing compounds.

The following typographic errors were also noted.

Subscript " g " in equation (12) should be "b "

The exponent " λ " in equation (13) should be " ψ "

Labels B and C on the curve in Figure 5-3 (a) are reversed

Donald G. Beremand

Critique by

Paul Huber
500 S. Highland Avenue
Dearborn, MI 48124

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

32

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-170-32

June 29, 1977

Mr. Paul Huber
500 South Highland
Dearborn, MI 48124

Dear Mr. Huber:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We have been asked by ERDA to respond to each letter submitted in the form of a critique of the subject report. Background information is presented in the enclosure to clarify the reorientation and restructuring of our automotive technology work.

The first point made in your letter addressed the question of adequate lead time necessary to produce by 1985 an alternate engine having performance and economy equal to or better than the Otto engine, and which would meet the Federal emissions standards of 0.41 HC, 3.4 CO, 0.4 NO_x gm/mi. The lead times between the concept of a new engine and production version as used in the subject report were developed in part with the auto manufacturers, but require an operating mode other than "business as usual". The Synthesis chapter addresses the question of significantly altered incentives including fund sharing. To meet the time scale in the study requires a national commitment, the absence of which would make the 1985 data unlikely of fulfillment.

The production date for any new engine would, of course, be governed by three primary forces: the magnitude of technical and economic difficulties encountered; the extent of government funding of research and development; and the degree of overall corporate motivation and resource commitment. We believe the lead times which appear in the APSES report are achievable, although the inevitable uncertainties in projecting technology result in unknown tolerances on the numbers. A significant factor in this prediction is the assumption of government support for research and development.

Your second point dealt with the need to make clear the distinction between developing a propulsion device and developing a saleable vehicle package which incorporates that propulsion device. The 1985 date included recognition of this distinction, and assumed a significant degree of parallel development of the engine and the vehicle elements most critically engine-dependent. It seems

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to us that engine and powertrain development would be the dominant factor in the schedule to evolve a marketable vehicle. The APSES report did not ignore "powerplant safety, vehicle noise levels, durability, maintainability, and driveability", but rather the assumption was made that these considerations are basically the same for all alternative engines. That is to say these factors will not be the pivotal issues. Further it was assumed that these system level problems are not worked in series with the engine development but that there is a significant degree of parallel development.

Your third point addressed the reality that meeting economy and emission goals in an engine development program should not be taken by the public to mean that the entire problem is solved. We strongly concur that successful laboratory demonstration is only a first step in a series, and that the engineering community has an obligation to the public to make clear that the purely technical hurdles are only a part of the total problem. There are other hurdles, including economics, safety, driveability, etc., as you pointed out.

In our current studies for ERDA we will continue to examine lead times for new automotive technology and hope to refine the estimates. The advances in automobile technology which have taken place since the date of publication of the report should significantly improve projection accuracy.

Your comments were most pertinent and appreciated.

Sincerely,

H. E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:tm

Enclosure (1)

500 S. Highland
Dearborn, Michigan
48124

March 26, 1976

U. S. Energy Research and
Development Administration
Heat Engine Systems Branch
Division of Transportation Conservation
20 Massachusetts Avenue, N. W.
Washington, D. C. 20545

Attention: R. Mercure

Reference: JPL Report "Should We Have a New Engine?"

Gentlemen:

As an automobile engineer with over 30 years of experience covering all parts of the car, including emissions, I want to accept ERDA's invitation to comment on the subject report, and will discuss three points.

Before doing so, I must state that I am in general agreement as to the relative advantages of the various mature engines as possible alternates to the Otto cycle engine, and, if viewed as research projects, I can, with a few exceptions, agree with the advanced engines.

(1) The major point is the time scale used for production of these alternate engines. It is far too short for anything except a major war effort where the government assumes the risk of failure to meet job #1 date. Commercial companies, self-financed, cannot accept such risk. JPL assumes success of the alternate engine program and schedules vehicle production for 1985. It must be emphasized that as far as public announcement is concerned, no vehicle with an alternate engine, comparable to, or better than, the Otto engine powered car in performance and economy, has yet passed the urban test of .41 HC, 3.4 CO, 0.4 NO_x.

(2) The reason for my objection to this time schedule lies in the fact that the automobile companies do not sell engines; they sell vehicles which must provide satisfactory transportation to the customer over the entire nation. JPL, on the other hand, enumerates its evaluation criteria as (a) fuel economy, (b) HC, CO, and NO_x emission rates, (c) vehicle retail price differential, (d) and ownership cost differential, and then adds a disclaimer: "It was assumed in this study that the manufacturer would not release a new powerplant for mass production until the 'bugs' normally encountered in system, and experimental fleet, testing were worked out.

"There are other engine-related vehicle criteria which are difficult to quantify: powerplant safety, vehicle noise levels, durability, maintainability, and driveability. These characteristics are normalized out of the evaluation, being assumed adequate when the respective development programs are complete, and hence are not discriminators among alternate vehicles." When JPL rejects durability, maintainability, and driveability in their broad sense as a part of their objective, they are ignoring the very factors which require a very great development time. Further, JPL states in vol. 2, 12.3, APPROACH, that cost and time were worked out by a modified Delphi procedure by a panel of five noted experts (unnamed) in each engine field. It would seem that these experts estimated time and cost for the production of an engine, not for the production of an automobile using that new engine. A second point can be made from the weight data in table 4, p. 55, executive summary. The turbo-charged diesel would increase the weight of the 3100 lb compact car by 240 lb, all on the front suspension. It must be redesigned. The single shaft Brayton would reduce weight 440 lb, calling for a new chassis. Again, much development time.

(3) ERDA's help to industry to make clear to the legislative branch of government and to the media that the successful conclusion of the alternate engine programs for economy and emission, and the vehicle device programs for fuel economy only show the possibility of attaining these limited goals, and that the use of these engines or devices in production must await the completion of programs likely to be longer than the time spent so far.

Paul Huber

Paul Huber

PH/slc

ORIGINAL PAGE IS OF POOR QUALITY

33

Critique by

W. B. Powell
Jet Propulsion Laboratory
Pasadena, CA 91103

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

34LPE-77-183-33

June 29, 1977

Mr. Walter Powell
722 Morada Place
Altadena, CA 91001

Dear Mr. Powell:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

Thank you for your comments and analyses of March 15 and May 4, 1976 relative to the subject report. The long gestation period between your suggestions and the formal response is explained in the enclosure.

Your analysis of a high pressure ratio, positive displacement, non-regenerated Brayton cycle is most interesting, but as we have discussed earlier we have several areas of concern. These are summarized below.

Your use of an "adiabatic Stirling cycle" as opposed to an isothermal cycle unfairly penalized Stirling engines. There are several reports which show compression and expansion strokes that are very close to isothermal. Thus we feel the use of the classical Stirling cycle in the subject report is justified. The Brayton engine of your analysis would not compare as favorably on this basis.

In order for the Brayton engine you suggest to be competitive in terms of thermal efficiency, the high pressure ratio, positive displacement compressors and expanders must achieve high efficiency. While there are no inherent thermodynamic limitations which make this impossible we believe it to be very difficult to attain such high efficiencies.

The subject report did address the positive displacement, high-expansion Brayton engine and concluded that it was not as attractive as either the regenerated, aero-dynamic Brayton or the Stirling engines. Pages 2 though 15 of Volume II of the report contain the discussion. Briefly, the key findings there were: (1) High expansion ratio Brayton engines suffer the limited air handling capabilities of positive displacement machinery. This leads directly to heavier weight and larger volume for a given power. (2) The maximum efficiency which can be reached by increasing the pressure ratio to very high values with positive displacement machinery is lower than that which can be reached by limiting the pressure ratio and utilizing post-expansion heat recovery. (3) For comparable maximum temperature, the brake thermal efficiency of the optimized single shaft regenerated Brayton was approximately 24% higher than the optimized high pressure ratio non-regenerated Brayton.

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Mr. Walter Powell -2- June 29, 1977

These considerations make us skeptical that a non-regenerated, positive displacement Brayton cycle engine is thermodynamically competitive with either the classical regenerated, rotating machinery Brayton or the Stirling cycle engine. We appreciate your critique and you continued interest in improved heat engines.

Sincerely,

H. E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:jms

Enclosure

March 15, 1976
May 4, 1976

A FURTHER LOOK AT THE "NEW ENGINE" PROBLEM

W. B. Powell

I. Introduction

A Jet Propulsion Laboratory study team has recently published the results of a study of alternate power plants which might be developed for automotive use in the next five to fifteen years, cf Ref. 1.

Dr. F. H. Clauser of the Division of Engineering and Applied Science at the California Institute of Technology, in an internal memorandum to the study team, raised some questions regarding the increase in overall efficiency that can be achieved by regeneration, if the efficiency of the heat exchanger is taken into account, and also developed a physical explanation for some of the real limitations of the Otto cycle engine, cf. Ref. 2.

The JPL study team presented convincing physical and practical arguments that the ideal Otto cycle and Rankine cycle engines cannot achieve the thermodynamic efficiency of Brayton or Stirling cycle engines at comparable conditions of temperature and pressure. The recommendation is made that development work be concentrated on two engine types:

1. Brayton Cycle: A low-pressure ratio, open-loop machine with continuous internal combustion and internal heat regeneration.
2. Stirling Cycle: A closed-loop machine with internal heat regeneration and with a pressurized hydrogen gas working fluid heated and cooled through heat exchangers, and using an external combustion heater with exhaust heat regeneration.

The "Further Look" in this paper is directed at:

1. A comparison of the ideal thermodynamic efficiency and specific power output of the recommended Brayton and 'Adiabatic Stirling' engines.
2. An examination of the high-pressure-ratio, non-regenerated Brayton and Adiabatic Stirling engines which are equivalent in thermodynamic efficiency and specific power to the recommended Stirling engine type.

1. The Open-Loop, Low-Pressure-Ratio, Regenerated, Brayton Cycle Gas Turbine Engine.

The Brayton Cycle has an ideal thermodynamic efficiency as high as that of any other practically achievable simple-cycle thermodynamic machine. cf. Fig 1 and Appendix I.

Compared to the thermodynamic efficiency at the maximum-specific-power design point condition ($T_2 = T_4$), for a Brayton cycle engine having a given value of the cold gas to hot gas temperature ratio $\tau = T_1/T_3$, the thermodynamic efficiency can be increased by increasing the adiabatic temperature ratio $\varphi = T_2/T_1 = T_3/T_4$, (with corresponding changes in the pressure and volume ratios, cf. App. III), or by decreasing the adiabatic temperature ratio and adding an internal regenerative heat transfer process to the system; cf. Fig. 1 and App I. In each case, for a given value of τ, the increase in efficiency is accompanied by a decrease in the specific power output. In the limit, by either procedure, the ideal Carnot efficiency $\eta_{Carnot} = (1 - \tau)$ can be obtained, but with zero power output.

Thus, the effect on the net power output must be considered when optimizing a Brayton cycle engine design for maximum thermodynamic efficiency.

In practice, the hot gas temperature, T_3, is limited by the temperature-strength capabilities of the materials which are used to fabricate the engine, and the combustion gases must be diluted and cooled to this temperature before they can be introduced into the working parts of the engine, cf. App IV.

The maximum power output of a Brayton cycle engine will be at the maximum hot gas temperature condition (or, more strictly, minimum τ). At this limiting minimum value of τ, a choice must be made between maximizing specific power or thermodynamic efficiency (or accepting some in-between compromise values of each); this choice determines the design value of the adiabatic temperature ratio (or pressure ratio, or volume ratio).

The aerodynamic compressor used with the gas turbine Brayton cycle engine is basically a low-pressure-ratio device (and also a low-adiabatic-temperature-ratio device). Thus the design point for the gas turbine engine will lie to the left of the locus $T_2 = T_4$ shown on Fig. 1, and regeneration must be incorporated into the engine system in order to achieve maximum thermodynamic efficiency at the design values of τ, φ, and specific power.

The power output of the gas turbine Brayton cycle engine operating in the region $T_2 < T_4$ can be decreased from the maximum design power by:

1. Decreasing the engine mass flow by decreasing the engine speed. This will, as a secondary effect, decrease the adiabatic temperature ratio, φ , and may result in a slight increase in thermodynamic efficiency if τ is held constant, and/or,
2. Decreasing the hot gas temperature (increasing τ), with a corresponding decrease in thermodynamic efficiency.

It should be noted that these power-control procedures require simultaneous coordinated control of the gas turbine inlet nozzles and they also imply the existence of a suitable matching automotive transmission.

The maximum internal gas working-fluid temperature that can be used in the open-cycle, internal-combustion gas turbine engine is higher that that for externally-heated-working-fluid machines, because the temperature drop across the walls of the heat exchanger is eliminated, and the cold gas temperature is lower, because it is itself air at ambient temperature. Both of these factors tend to reduce the design value of τ for the open-cycle, internal-combustion, gas turbine Brayton cycle engine compared to alternative engine cycles and configurations.

If for no other reason than above, the regenerated gas turbine engine has potentially better efficiency and power output than other alternative automobile engines.

Among the major problems which must be solved if the gas turbine engine is to "arrive" are:

1. Development of an effective, low-pressure-drop regenerator.
2. Development of a control system, including control of the hot gas nozzle to match the flow and pressure characteristics of the aerodynamic compressor to those of the gas turbine over a range of hot gas temperatures. and,
3. Development of a continuously-variable-ratio transmission.

2. The Closed-Loop, Pressurized, Internally-Regenerated Stirling Engine.

The ideal Stirling engine has isothermal compression and expansion processes joined by two constant-volume heating and cooling processes. This ideal Stirling cycle has a thermodynamic efficiency equal to that of the Carnot cycle.

In practice, there is no way to implement an isothermal compression or expansion in a simple machine. The actual engine then becomes an Adiabatic Stirling, and the attainable thermodynamic efficiency is exactly the same as that of the corresponding Brayton cycle machine operating with the same temperature ratios. The specific power of the Adiabatic Stirling engine is lower than that of the Brayton cycle engine by the factor γ, since the heat is added to the working fluid at constant volume, rather than at constant pressure. cf. App II.

The conventional Adiabatic Stirling engine is a low-volume-ratio machine ($V_2/V_1 \simeq 2.1$), so that $T_2 < T_4$, and thus operates in the region where regeneration can be used to increase the thermodynamic efficiency.

The heat exchangers and the regenerator in the conventional Adiabatic Stirling engine create a 'dead' volume which must be taken into account in the analysis of the performance of the real engine. When this is done, still assuming ideal heat transfer processes, it is found that the range of values of thermodynamic efficiency for a given value of τ, and the characteristic inverse relationship between efficiency and specific power, as volume ratio is varied, are the same as those shown on Fig 1 for the idealized Brayton and Adiabatic Stirling cycles.* As with the Brayton Cycle operating in the region $T_2 < T_4$, the effect of a decrease in the hot gas temperature from the maximum design value (increase in τ) is a decrease in efficiency as well as in the specific power.

The conventional low-pressure-ratio, closed-loop, positive displacement, regenerated Adiabatic Stirling cycle engine is pressurized in order to maximize the specific power. Hydrogen is generally used as the working fluid in order to maximize the performance of the heat exchangers and the regenerator. Even so, the effectiveness of the heat exchangers drops off at high flow and power conditions. Further, the use of high pressure hydrogen as a working fluid leads to some problems in sealing to prevent loss of hydrogen from the system.

* See Fig 6-12 of the APSES Report.

2. (continued)

The allure of the Stirling engine is based on:

1. The fact that as a closed system it can be made virtually noiseless and vibration free.
2. The fact that the engine has no internal valves.
3. The fact that the enclosed working fluid can be heated from virtually any type of heat source.
4. The illusion that somehow this engine will have higher thermodynamic efficiency than other engines.

3. High-Pressure-Ratio, Unregenerated Brayton Cycle Engines.

The analysis of ideal cycle performance contained in Appendix I, and summarized in Fig. 1, shows that in the region $T_2 < T_4$ there can be high-adiabatic-temperature-ratio (high pressure-ratio, high volume-ratio) versions of the Brayton cycle engine which do not require internal heat regeneration, and which have exactly the same ideal thermodynamic efficiency and specific power as the "conventional" internally regenerated Brayton cycle engine operating at the same hot gas temperature ratio, τ.

The high-pressure-ratio versions of the Brayton cycle engine would typically be implemented with positive displacement, piston in cylinder, compressors and expanders, and could be open-loop or closed-loop.

The closed-loop version would require heat exchangers both to heat and to cool the working fluid, and must have an external combustor or other heat source for heating the working fluid. An external combustor would require it's own exhaust heat regenerator, as with the conventional Stirling engine combustor and heater. Cf, Fig. 2. The closed-loop version could be pressurized, with any desired working fluid, in order to increase the power density of the engine.

The open-loop version of the engine would need only one primary heat exchanger to heat the working fluid, air, and could use it's cycle exhaust air as inlet air to an external combustion heater. An exhaust heat regenerator would be required in conjunction with an external combustion heater, Cf. Fig. 3. Internal combustion versions of the high-pressure-ratio, open-loop Brayton cycle engine are possible, and they would require no heat exchangers or regenerators whatsoever.* [Uniflow versions of all of the above forms of Brayton cycle engines are also possible, but are not considered further here.].

The closed-loop, pressurized, high-pressure-ratio, unregenerated, external-combustor-heated Brayton cycle engine is similar in many respects to the Stirling engine remommended for development as an alternative automotive engine in the APSES report. The two engines

* Incorporation of (combustion products) into the working fluid would decrease the effective value of γ, and would requier higher values of pressure ratio and volume ratio in order to maintain the same value of the adiabatic temperature ratio, τ, and thus of the thermodynamic efficiency, Cf. Appendices III and V.

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would operate at the same hot gas temperature ratio, τ , and thus would have the same level of ideal thermodynamic efficiency, but the Brayton cycle engine would have a higher specific power than the Adiabatic Stirling cycle engine.

The primary design and mechanical difference between the two engines is that the Brayton engine requires valves in the hot gas region, while the Stirling engine requires a heat regenerator in between the two primary heat exchangers, and has no internal valves. As a result of these primary differences, the Brayton cycle engine will have the following desirable features, compared to the corresponding Stirling cycle engine:

1. The heat exchangers are isolated from the compression and expansion volumes, and are thus not volume-limited, and can be made larger and more effective. As a result the drop-off of specific power with increasing power demand so evident with the Stirling engine can be greatly minimized.
2. Air can be used as a working fluid, because of the more-effective heat exchangers. Then the sealing problems associated with trying to retain a pressurized hydrogen working fluid, as in the Stirling cycle engine, are eliminated. A slight leakage of air can be tolerated, as it can easily be made-up by a small auxilliary pump.
3. The thermodynamic efficiency depends only on the pressure ratio or volume ratio, and does not decrease if the hot gas temperature decreases as a result of heat exchanger overloading or as a result of a deliberate decrease in the combustor temperature (as part of a power-control action).

Operator control of the power of the high-pressure-ratio Brayton cycle engine can be exercised, with respect to the maximum design power by:

1. Decreasing the engine speed.
2. In a pressurized closed-loop engine, by decreasing the system pressure.
3. Decreasing the hot gas temperature. (without loss in efficiency).

It should be noted that the continuously-variable-ratio transmission is almost essential to the development of a practical control system for these engines

A comparison of the relative size of the compression and expansion volumes for both the high-pressure-ratio and the low-pressure-ratio Brayton cycle engines operating at the same value of the hot gas temperature ratio, τ , and having identical thermodynamic efficiency and specific power, is shown in Appendix VI. It is found that the high-pressure-ratio machine has an appreciably smaller expansion chamber volume than does the low-pressure-ratio machine. Thus the non-regenerated engine, even though operating at a higher pressure level, should be smaller than the low-pressure-ratio machine.

The above considerations indicate that there are many potential benefits to be obtained by developing the required "hot valve" for the the high-pressure-ratio, unregenerated Brayton cycle engine, and that this engine should be evaluated as an alternate to the APSES-recommended Stirling engine for future automotive power plant application, and for other applications (such as solar power plants and waste heat recovery engines) as well.

4. High-Pressure-Ratio, Unregenerated Stirling Cycle Engines.

The analysis of the ideal cycle performance contained in Appendix II, and summarized on Fig. 1, shows that in the region $T_2 > T_4$ there can be high-adiabatic-temperature-ratio (high pressure-ratio, high volume-ratio) versions of the Adiabatic Stirling cycle engine which do not require internal heat regeneration, and which have exactly the same ideal thermodynamic efficiency and specific power as a "conventional" internally regenerated Adiabatic Stirling engine operating at the same value of the hot gas temperature ratio, τ.

It should be noted that while the values of the thermodynamic efficiency shown in Fig. 1 are exactly correct for the Adiabatic Stirling cycle, the specific power for the Adiabatic Stirling cycle is lower, by a factor of γ , than the specific power shown on Fig. 1.

Two unique design requirements become apparent when the implementation of the high-pressure-ratio Adiabatic Stirling cycle engine is considered:

1. Check valves are required to direct the working fluid through the appropriate heat exchanger as the working fluid displacements are performed.
2. The ratio of the maximum to the minimum volume is so high that the requierd sequence of volume displacements cannot be obtained by phased simple harmonic motion of the displacer and expander pistons. Instead, cam drives will probably be required to achieve the scheduled piston motions.

The high-pressure-ratio, unregenerated Stirling cycle engine does not appear to have been described before. However, since the design complications appear to be comparible to those associated with the development of the high-pressure-ratio Brayton cycle engine, and since the Brayton engine has additional desirable features, this class of Stirling cycle engines is not considered further here.

5. Summary and Recommendations.

The high-pressure-ratio, unregenerated Brayton cycle engine should be considered along with the regenerated Stirling engine as a potential future automotive power plant, and for other uses as well. Once the required hot-gas intake and exhaust valving has been developed, the advantages, with respect to the Stirling engine, of constant high thermodynamic efficiency, higher specific power, improved heat exchanger effectiveness, and of using air as the working fluid can be exploited.

Nomenclature

c_p	Specific heat of gaseous working fluid
$\dot{m}$	Rate of flow of working fluid thru system
p	Pressure of working fluid
P'	Specific Power $P' = \left[\dfrac{\text{Ideal Power Output}}{\dot{m}\ C_p\ T_1}\right]$
$\dot{Q}$	Rate of flow of heat
R	Gas Constant
T	Temperature of working fluid
V	Volume of working fluid

Subscripts: (1) Low pressure, low temperature point in cycle.
(2) At end of compression, before heat addition.
(3) High pressure, high temperature point in cycle.
(4) At end of expansion, before heat rejection.

γ Ratio of specific heats of working fluid

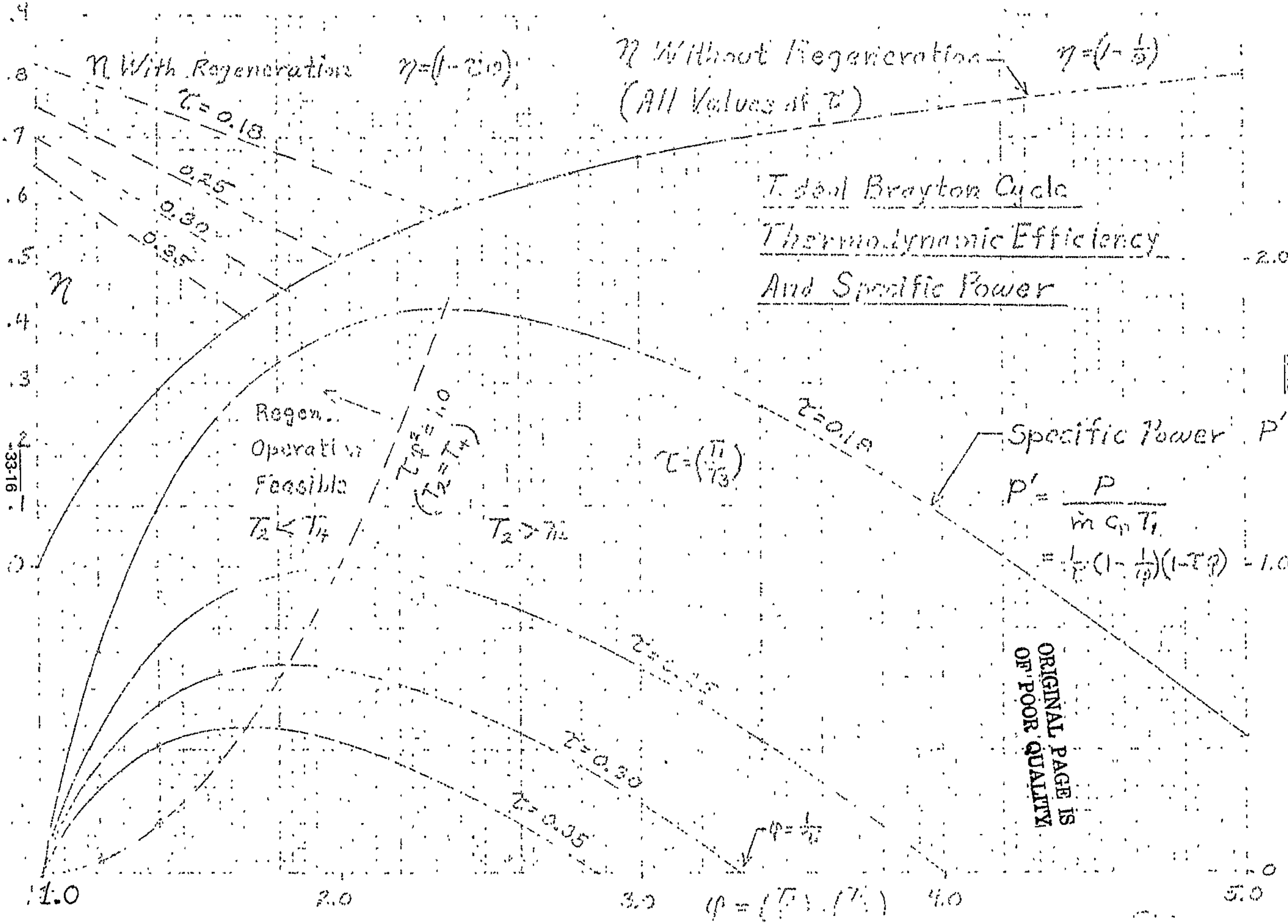
$\varphi = \left(\frac{T_2}{T_1}\right) = \left(\frac{T_3}{T_4}\right)$ Adiabatic temperature ratio.

$\tau = \left(\frac{T_1}{T_3}\right)$ Ratio of minimum to maximum temperatures.

References

1. Should We Have a New Engine - An Automobile Power Systems Evaluation Volume II, Technical Reports Jet Propulsion Laboratory, Calif Inst. of Technology. JPL SP 43-17, 1975

2. Clauser, F. H. personal communication to APSES Team. Dec 2, 1974.


η With Regeneration
η=(1-τφ)
η Without Regeneration
(All Values of τ)
η=(1-1/φ)
τ=0.18
0.25
0.30
0.35
Ideal Brayton Cycle
Thermodynamic Efficiency
And Specific Power
η
Regen. Operation Feasible
$T_2 < T_4$
$T_2 > T_4$
τ=(T1/T3)
Specific Power P′
P′ = P / (ṁ cp T1)
τ=0.18
τ=0.25
τ=0.30
τ=0.35
φ = 1/τ
1.0
2.0
3.0
4.0
5.0
0
1.0
2.0

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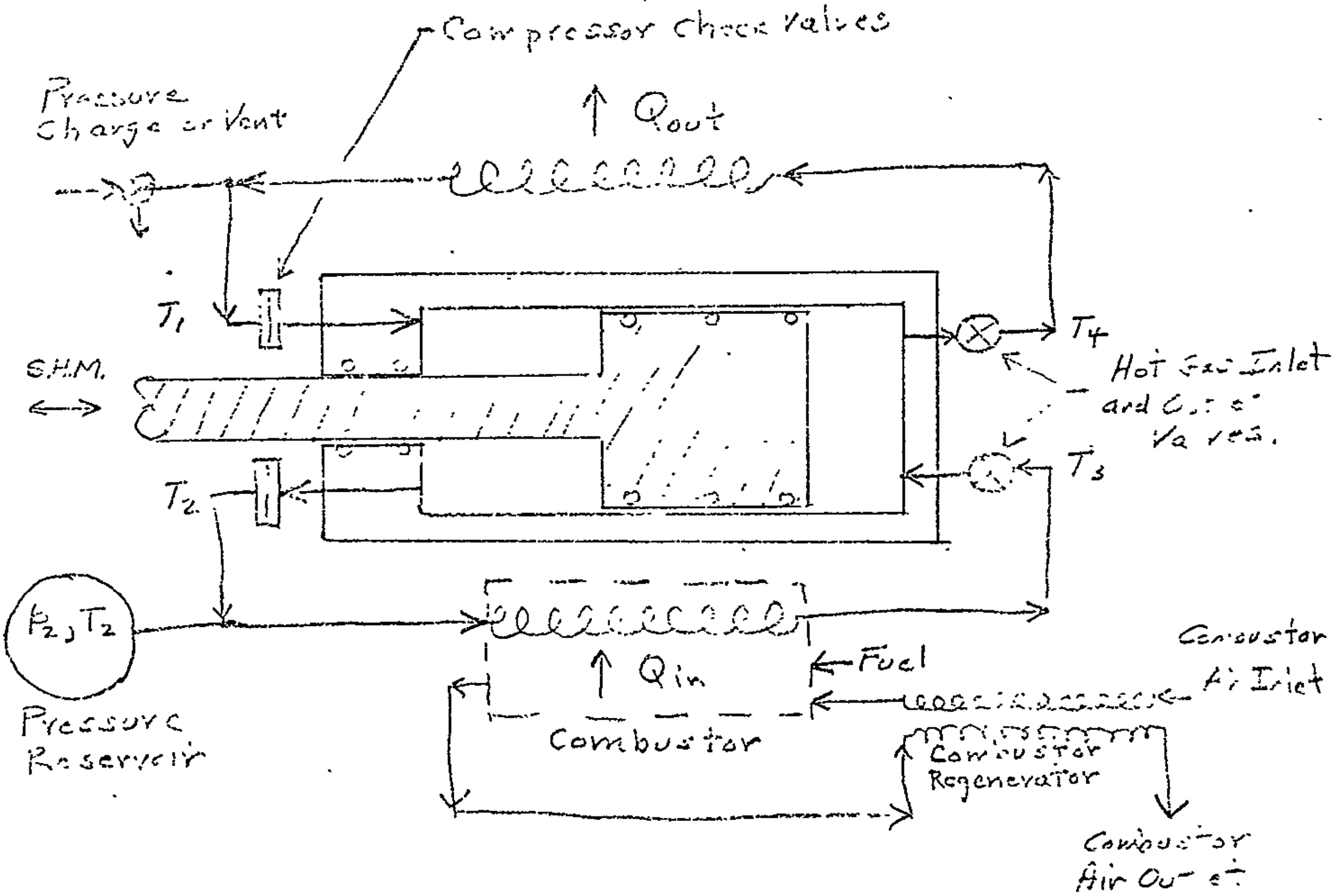

Fig 2. High-Pressure-Ratio, Unregenerated, Closed-Loop, Pressurized Brayton Cycle Engine.

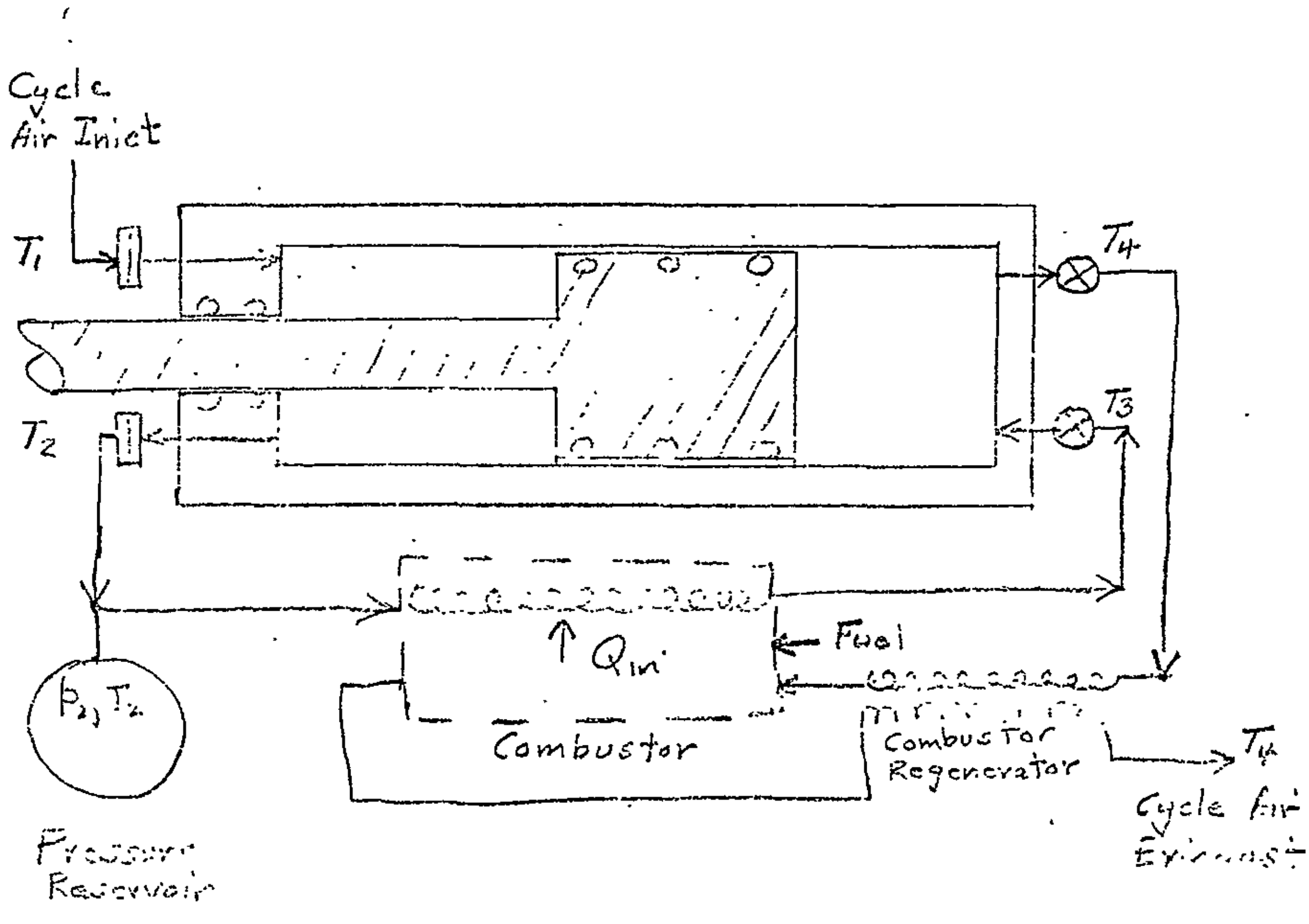

Fig 3. High-Pressure-Ratio, Unregenerated, Open-Loop Brayton Cycle Engine

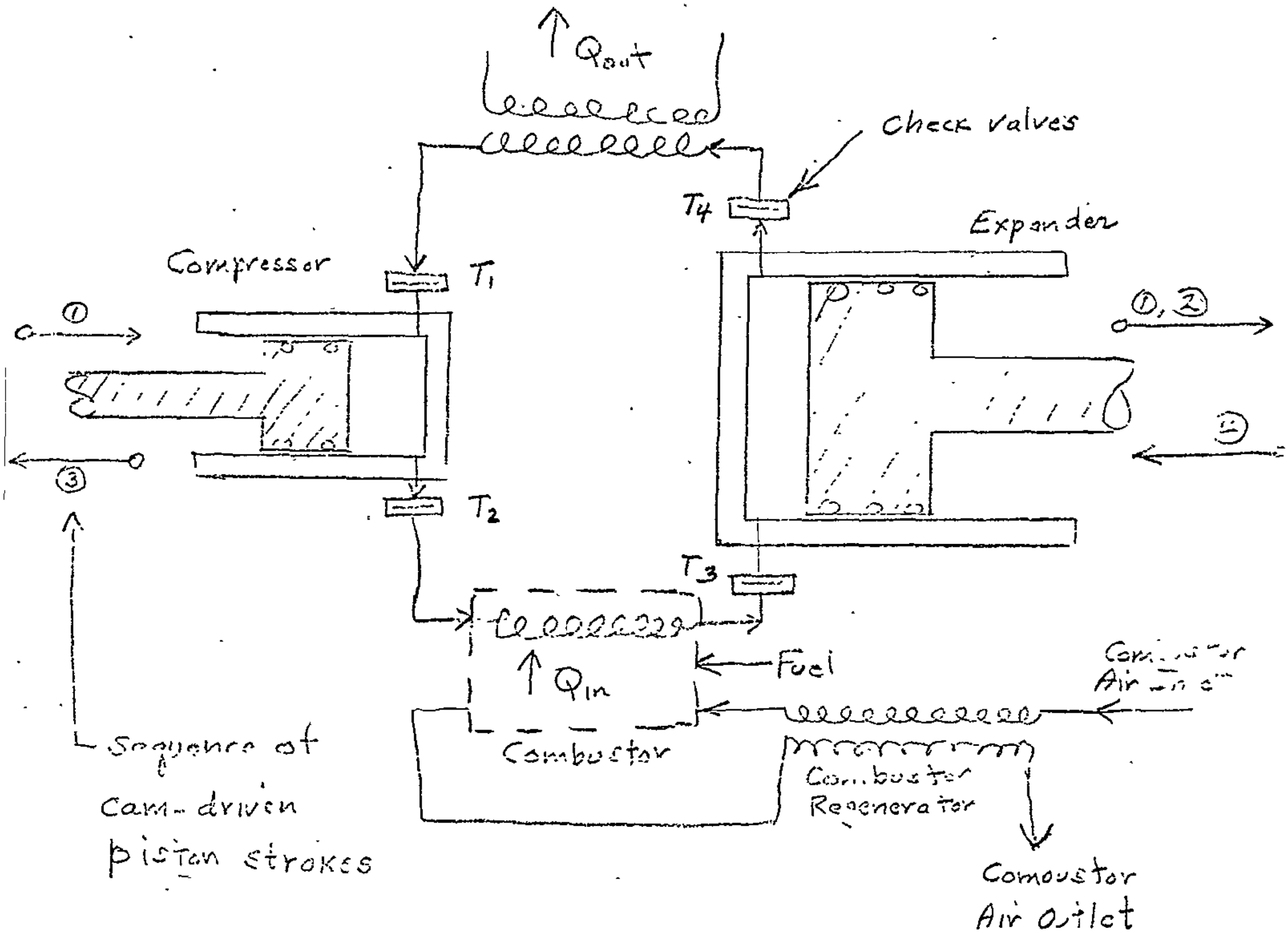

Fig. 4. High-Pressure-Ratio, Unregenerated Adiabatic Stirling Cycle Engine

Brayton Cycle With and Without Regeneration

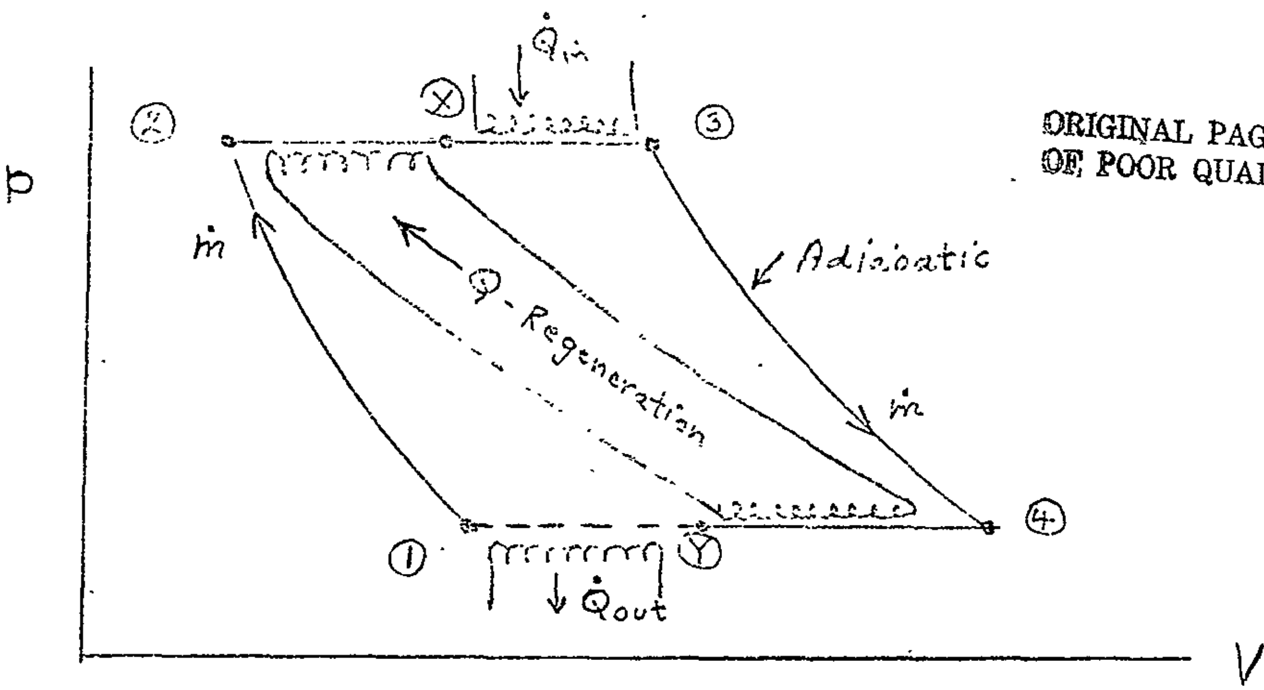

Fig I-1 Pressure-Volume Characterization of Brayton Cycle With Regeneration

Given Conditions: $p_1 = p_4$ and $p_2 = p_3$ (1)

Processes 1-2 and 3-4 are adiabatic (2)

Steady state; mass flow continuity (3)

From the adiabatic and pressure conditions:

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{T_3}{T_4}\right) = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \qquad (4)$$

From Continuity:

$$m_L = \frac{p_1 V_1}{RT_1} = \frac{p_2 V_2}{RT_2} = \frac{p_3 V_3}{RT_3} = \frac{p_4 V_4}{RT_4} \qquad (5)$$

Let: $\varphi = \left(\frac{T_2}{T_1}\right)$, etc. The adiabatic temperature ratio (6)

$\tau = \left(\frac{T_1}{T_3}\right)$, The ratio of minimum to maximum temperatures (7)

Then the following relationships can be written:

$$\left(\frac{P_2}{P_1}\right) = \varphi^{\frac{\gamma}{(\gamma-1)}} \qquad (8)$$

$$\left(\frac{T_2}{T_3}\right) = \tau\varphi \qquad (9)$$

$$\left(\frac{T_2}{T_4}\right) = \tau\varphi^2 \qquad (10)$$

$$\left(\frac{V_3}{V_1}\right) = \left[\tau\varphi^{\frac{\gamma}{(\gamma-1)}}\right]^{-1} \qquad (11)$$

$$\left(\frac{V_4}{V_1}\right) = \frac{1}{\tau\varphi} \qquad (12)$$

$$\left(\frac{V_4}{V_3}\right) = \varphi^{\frac{1}{(\gamma-1)}} \qquad (13)$$

Regeneration is only possible when $T_2 < T_4$

$$\text{or } \frac{T_2}{T_4} = \tau\varphi^2 \leq 1.0 \qquad (14)$$

Note: Shaft power is delivered only when: $1.0 < \varphi < \frac{1}{\tau}$.

(1) when $\varphi = 1.0$, there is no compression.

(2) when $\tau\varphi = 1.0$, there is no heat addition.

(3) When $\varphi > \frac{1}{\tau}$, machine operates as a heat pump and requires power input.

Cycle with Regeneration

With perfect regenerative heat transfer:

$$T_X = T_4 \quad \text{and} \quad T_Y = T_2 \qquad (15)$$

The heat flows are given by:

$$\dot{Q}_{in} = \dot{m}\, C_p (T_3 - T_X) = \dot{m}\, C_p (T_3 - T_4)$$
$$= \dot{m}\, C_p\, T_3 \left(1 - \frac{T_4}{T_3}\right) = \dot{m}\, C_p\, T_3 \left(1 - \frac{1}{\varphi}\right) \qquad (16)$$

$$\dot{Q}_{out} = \dot{m}\, C_p (T_Y - T_1) = \dot{m}\, C_p (T_2 - T_1)$$
$$= \dot{m}\, C_p\, T_2 \left(1 - \frac{T_1}{T_2}\right) = \dot{m}\, C_p\, T_2 \left(1 - \frac{1}{\varphi}\right) \qquad (17)$$

The thermodynamic efficiency is:

$$\eta_{Regen} = \frac{(\dot{Q}_{in} - \dot{Q}_{out})}{\dot{Q}_{in}} = \left(1 - \frac{T_2}{T_3}\right) = (1 - \tau\varphi) \qquad (18)$$

The net power output is:

$$P = (\dot{Q}_{in} - \dot{Q}_{out}) = \dot{m}\, C_p\, T_3 \left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \qquad (19)$$

From which the specific power is:

$$P' = \frac{P}{\dot{m}\, C_p\, T_1} = \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \qquad (20)$$

Cycle without Regeneration

Without regeneration: $T_x = T_2$ and $T_y = T_4$ (21)

The heat flows are given by:

$$\dot{Q}_{in} = \dot{m}\, C_p\, (T_3 - T_2) = \dot{m}\, C_p\, T_3\, (1 - \tau\varphi) \tag{22}$$

$$\dot{Q}_{out} = \dot{m}\, C_p\, (T_4 - T_1) = \dot{m}\, C_p\, T_4\, (1 - \tau\varphi) \tag{23}$$

The thermodynamic efficiency is:

$$\eta_{Non\text{-}Regen} = \frac{(\dot{Q}_{in} - \dot{Q}_{out})}{\dot{Q}_{in}} = \left(1 - \frac{T_4}{T_3}\right) = \left(1 - \frac{1}{\varphi}\right) \tag{24}$$

The net power output is:

$$P = (\dot{Q}_{in} - \dot{Q}_{out}) = \dot{m}\, C_p\, T_3 \left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \tag{25}$$

The specific power is:

$$P' = \frac{P}{\dot{m}\, C_p\, T_1} = \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \tag{26}$$

Mass flow rate for positive displacement machine:

$$\dot{m} = m_i \cdot N = \left(\frac{pV}{RT}\right)_i \times N \tag{27}$$

where N is speed in cycles per unit time.

Power from positive displacement Brayton machine:

$$P = \left[\frac{p_1 V_1 N c_p}{R}\right] \times \left[\frac{1}{\tau}\left(1-\frac{1}{\varphi}\right)\left(1-\tau\varphi\right)\right] \quad (2\text{-}3$$

Appendix II

Adiabatic Stirling Cycle

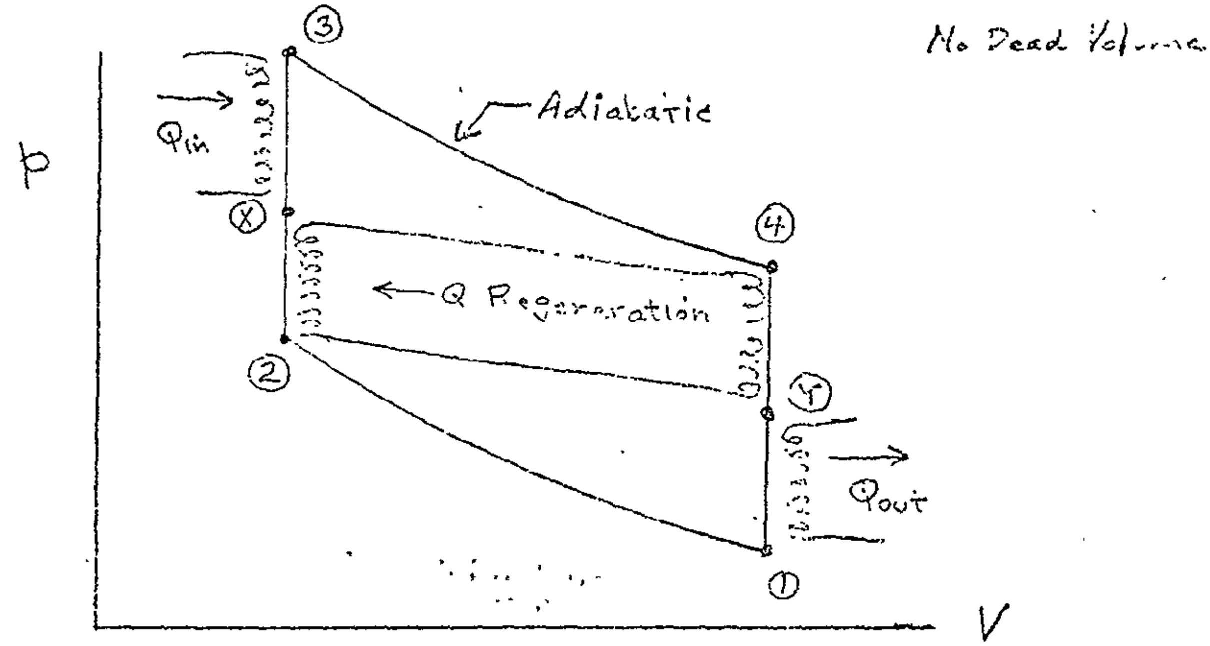

Fig II-1 Pressure-Volume Characterization of Adiabatic Stirling Cycle with Regeneration.

Given Conditions: $V_2 = V_3$ and $V_4 = V_1$ (1)

Processes 2-3 and 4-1 are adiabat: (2)

Steady state; mass flow continuity (3)

From the adiabatic and volume conditions:

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{T_3}{T_4}\right) = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} \quad (4)$$

From Continuity:

$$m_i = \frac{p_1 V_1}{R T_1} = \frac{p_2 V_2}{R T_2} = \frac{p_3 V_3}{R T_3} = \frac{p_4 V_4}{R T_4} \quad (5)$$

Let $\varphi = \left(\frac{T_2}{T_1}\right)$, etc., The adiabatic temperature ratio (6)

$\tau = \left(\frac{T_1}{T_3}\right)$, The ratio of minimum to maximum temperatures (7)

Then the following relationships can be written:

$$\left(\frac{p_2}{p_1}\right) = \varphi^{\frac{\gamma}{(\gamma-1)}} = \left(\frac{p_3}{p_4}\right) \quad (8)$$

$$\left(\frac{T_1}{T_3}\right) = \tau\varphi \quad (9)$$

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$$\left(\frac{T_2}{T_4}\right) = \tau\varphi^2 \quad (10)$$

$$\left(\frac{p_3}{p_1}\right) = \frac{1}{\tau}\varphi^{\frac{1}{\gamma-1}} \quad (11)$$

$$\left(\frac{V_4}{V_1}\right) = \left(\frac{V_3}{V_2}\right) = 1.00 \quad (12)$$

$$\left(\frac{V_1}{V_2}\right) = \varphi^{\frac{1}{(\gamma-1)}} \quad (13)$$

Regeneration is only possible when $T_2 < T_4$

$$\text{or} \quad \left(\frac{T_2}{T_4}\right) = \tau\varphi^2 \leq 1.0 \quad (14)$$

Shaft power can only be delivered when: $1.0 < \varphi < \frac{1}{\tau}$

(1) when $\varphi = 1$, there is no compression

(2) when $\tau\varphi = 1$, there is no heat addition

Cycle with Regeneration

With perfect regenerative heat transfer:

$$T_X = T_4 \quad \text{and} \quad T_Y = T_2 \qquad (15)$$

The heat flows are given by:

$$\dot{Q}_{in} = \dot{m}\, C_v\, (T_3 - T_X) = \dot{m}\, C_v\, (T_3 - T_4) = \dot{m}\, C_v\, T_3 \left(1 - \frac{1}{\beta}\right) \qquad (16)$$

$$\dot{Q}_{out} = \dot{m}\, C_v\, (T_Y - T_1) = \dot{m}\, C_v\, (T_2 - T_1) = \dot{m}\, C_v\, T_2 \left(1 - \frac{1}{\varphi}\right) \qquad (17)$$

The thermodynamic efficiency is:

$$\eta_{Regen} = \frac{(\dot{Q}_{in} - \dot{Q}_{out})}{\dot{Q}_{in}} = \left(1 - \frac{T_2}{T_3}\right) = \left(1 - \tau\varphi\right) \qquad (18)$$

The net power output is:

$$P = (\dot{Q}_{in} - \dot{Q}_{out}) = \dot{m}\, C_v\, T_3 \left(1 - \frac{1}{\varphi}\right)\left(1 - \tau\varphi\right)$$

$$= \dot{m}\, C_p\, T_1 \cdot \frac{1}{\gamma} \cdot \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)\left(1 - \tau\varphi\right) \qquad (19)$$

The specific power is:

$$P' = \frac{P}{\dot{m}\, C_p\, T_1} = \frac{1}{\gamma} \times \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)\left(1 - \tau\varphi\right) \qquad (20)$$

For a positive displacement machine:

$$P = \left[\frac{P_1\, V_1\, N\, C_p}{R}\right] \times \left[\frac{1}{\gamma} \cdot \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)\left(1 - \tau\varphi\right)\right] \qquad (21)$$

Adiabatic Stirling Without Regeneration

Without regenerative heat transfer:

$$\dot{Q}_{in} = \dot{m}\, C_v (T_3 - T_2) = \dot{m}\, C_v T_3 (1 - \tau\varphi) \qquad (22)$$

$$\dot{Q}_{out} = \dot{m}\, C_v (T_4 - T_1) = \dot{m}\, C_v T_4 (1 - \tau\varphi) \qquad (23)$$

The thermodynamic efficiency is:

$$\eta_{Non-Regen} = \frac{(\dot{Q}_{in} - \dot{Q}_{out})}{\dot{Q}_{in}} = \left(1 - \frac{T_4}{T_3}\right) = \left(1 - \frac{1}{\varphi}\right) \qquad (24)$$

The net power output is:

$$P = \dot{Q}_{in} - \dot{Q}_{out} = \dot{m}\, C_v T_3 \left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi)$$

$$= \dot{m}\, C_p T_1 \frac{1}{\gamma} \frac{1}{\tau} \left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \qquad (25)$$

The specific power is:

$$P' = \frac{P}{\dot{m}\, C_p T_1} = \frac{1}{\gamma} \times \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi) \qquad (26)$$

For a positive displacement machine:

$$P = \left[\frac{P_1 V_1 N C_p}{R}\right] \times \left[\frac{1}{\gamma} \times \frac{1}{\tau}\left(1 - \frac{1}{\varphi}\right)(1 - \tau\varphi)\right] \qquad (27)$$

Pressure Ratio and Volume Ratio vs Temperature Ratio For Adiabatic Process.

$\varphi = \left(\frac{T_2}{T_1}\right)$ $\left(\frac{P_2}{P_1}\right) = \varphi^{\frac{\gamma}{\gamma-1}}$ $\left(\frac{V_1}{V_2}\right) = \varphi^{\frac{1}{\gamma-1}}$

For $\gamma = 1.35$			For $\gamma = 1.30$	
φ	$\left(\frac{P_2}{P_1}\right)$	$\left(\frac{V_1}{V_2}\right)$	$\left(P_2/P_1\right)$	[illegible]
1.0	1.0	1.0		
1.1	1.444	1.313		
1.2	2.020	1.684		
1.4	3.661	2.615		
1.6	6.128	3.830		
1.8	9.652	5.362		
2.0	14.49	7.246	20.159	10.[illegible]
2.2	20.93	9.514		
2.4	29.28	12.20		
2.5	34.27	13.71		
2.6	39.87	15.33		
2.8	53.06	18.95		
3.0	69.23	23.08		

Appendix IV

Temperature Limits for Brayton Cycle Machines

Assumptions:

1. Intake temperature for open cycle machine (Ambient). $T_1 = 100°F = 560°R$

2. Intake temperature of working fluid cooled in a heat exchanger. $T_1 = 160°F = 620°R$

3. NOX-production limit to combustion temperature. $T \leq 3000°F$

4. Metal alloy maximum temperature with stress $T_3 = 1900°F = 2360°R$.

5. Advanced ceramic maximum temperature with stress. $T_3 = 2500°F = 2960°R$

6. Working fluid heated in metallic heat exchanger $T_3 = 1400°F = 1860°R$

7. Working fluid heated in ceramic heat exchanger. $T_3 = 2000°F = 2460°R$

Appendix III (Continued)

Temperature Ratio $\tau = \left(\frac{T_1}{T_3}\right)$ for various types of Brayton machines.

Technology	Open Cycle: Internal Combustion Turbine Bower wheel	Closed Cycle: Fluid Heated and Cooled in Heat Exchangers
Metal Alloy	$\tau = \frac{560}{2360} = 0.237$	$\tau = \frac{620}{1860} = 0.333$
Ceramic	$\tau = \frac{560}{2960} = 0.189$	$\tau = \frac{620}{2460} = 0.252$

Critique by

Mercedes-Benz of North America
Product and Service Engineering
1 Mercedes Drive
Montvale, NJ 07645

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

34

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

June 29, 1977

RE: 34LPE-77-217-34

Mr. K. H. Faber
General Manager
Product and Service Engineering
Mercedes-Benz of North America
One Mercedes Drive
Montvale, New Jersey 07645

Dear Mr. Faber:

SUBJECT: Critique of JPL Report SP43-17, "Should We Have a New Engine?"

Thank you for your letter of 6 May 1976 concerning the subject report. The reasons for our response at this time, and the restructuring of our heat engine program are explained in the enclosure. Your letter raised questions about some of the assumptions and conclusions of the subject report in respect to that part which deals with diesel engines.

Your comments are highly valued, and as explained in the enclosure, we will address them in an appropriate Technical Task Summary (TTS). In the meantime we wish to respond to your letter by expressing our present evaluation of some of the key issues which you raise. Our remarks follow the format of your letter.

1. Your comments relating to the pumping losses and thermal efficiency of a turbocharged diesel are in concurrence with our views. Pumping losses can probably be reduced under certain operating conditions, especially if the turbocharger is designed primarily to improve economy and not to increase power. Turbocharging affords the option of (1) leaning out the air-fuel mixture to increase the thermodynamic efficiency, (2) reducing piston speed to decrease frictional losses, or (3) increasing the specific power of the engine to reduce the fraction of work required to drive internal engine components. All will increase brake efficiency. The exact amount will depend on the engine and cycle characteristics, whether or not the engine is pressure limited, and the techniques used to control maximum pressure or reduce piston speed (variable timing, turbine bypass valve, compression ratio, stroke, rear axle ratio, etc.). Your estimate of five to ten percent sounds quite reasonable to us.

Telephone 354-4321 Twx 910-588-3269 Twx 910-588-3294

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2.(a) In our further evaluation of the diesel (see the enclosure), turbocharging, reduction in weight, and improved fuel injection will all be examined.

(b) One of the tasks we are performing at the present time is a review of engine-power sizing. The results of this study are to be published next year. Any benefits to be derived from better combustion and engine mechanics or from leaner mixtures under partial load conditions will be included. Reducing the rear axle ratio to increase fuel economy will degrade acceleration performance, of course, unless specific power is increased.

(c) Mileage was compared on a per unit energy basis in order to remove certain unpredictable variables. Because of the higher energy content in a gallon of diesel fuel, the diesel's performance was reduced eleven percent. It is true that in today's market the diesel has an advantage on a miles per dollar, or miles per unit total energy basis and that the comparison may have been somewhat unfair to the diesel. Another factor to be considered is that refinery constraints place a limit on the number of cars which could be converted to diesel engines without a significant increase in the total cost or total energy. In future comparisons we plan to take these factors into consideration.

Thank you for your interest and your constructive comments. We look forward to further exchanges following release of the TTS referred to above.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:nrw

Enclosure

MERCEDES-BENZ OF NORTH AMERICA, INC.

CABLE [illegible]
TWX [illegible]
OVERSEAS [illegible]
DOMESTIC TELEX [illegible]

ONE MERCEDES DRIVE
MONTVALE NEW JERSEY 07645
PHONE (201) 573-0600

May 6, 1976

U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Attn: R. Mercure

Subject: Update of JPL's Report "Should we have a new engine?"

Dear Mr. Mercure:

Mercedes-Benz of North America on behalf of its parent company, the Daimler-Benz A.G., Stuttgart, West Germany, hereby submits its comments in response to the ERDA Announcement and Invitation to Comment on the Jet Propulsion Laboratory Study (California Institute of Technology) "Should we have a new engine?" (hereinafter "JPL Study"). The comments contained herein have been limited to those areas of the JPL Study which deal with the diesel engine as an alternative power source. Mercedes-Benz has limited its comments to the diesel engine because of its long history of work and development with this particular engine.

General comments concerning the JPL Study are as follows:

1. Comments regarding section 4.2.4, page 4-22, Volume 2, Technical Reports.

   The comparison made in this portion of the JPL Study between a diesel engine and a gasoline engine is conducted on the basis of a Otto Engine Equivalent (hereinafter "OEE") diesel powered vehicle. This vehicle is equipped with a wastegate controlled turbocharged diesel engine. In this comparison no improvement of efficiency for the turbocharged diesel engine compared to the naturally aspirated engine is considered because of the negative pumping losses. However, the pumping losses in such an engine are not totally negative for all operating conditions. In addition, the thermal efficiency is improved due to a higher air fuel ratio as compared to the naturally aspirated diesel engine. Mechanical efficiency will also be slightly higher due to the relatively smaller amount of power needed to drive all accessories and internal engine components. For these reasons we would suggest that utilizing a five to ten percent improvement factor for the overall efficiency of the wastegate control turbocharged diesel engine should be considered.

2. Comments regarding section 4.5.1, page 4-32/33, Volume 2, Technical Reports.

   a. Since today's diesel vehicles do not meet the performance criteria of the JPL Study and since the improvement of efficiency -- as explained above -- is also not considered, it does not represent an OEE vehicle in the JPL Study. In addition, the fuel economy values for the mature engine in the CVS urban test are assumed to be even inferior to those of today's naturally aspirated engines. Therefore, in contrast to all other power plants under scrutiny, the diesel engine was not subject to any further investigation with regard to advancements in technology (for example weight reduction or improvement of the fuel injection system) not to mention the positive influences of supercharging.

   b. The decrease of fuel economy with increasing vehicle weight in Table 4-10 seems to be relatively high and not in line with examples available in today's market such as the Mercedes-Benz 240D vehicle as compared to the 300D vehicle. In actual fact partial load fuel economy has only decreased marginally due to added performance and weight. This is due to advancements made in combustion and engine mechanics as well as to the more direct rear axle ratio which can be used with high engine output. (See reference 1).

   c. All fuel economy figures of diesel vehicles are reduced in the JPL Study on the basis of equivalent gasoline consumption which is a reduction of about 11 percent. Since diesel fuel has a correspondingly higher energy content per unit volume this may be permissible for a pure scientific and engineering comparison on the basis of BTU output. This equivalency computation is not, however, relevant for comparing vehicle power plants on the basis of a total energy concept. A total energy concept considers the maximum number of transportation miles per barrel of crude oil processed. If this total energy approach is made the basis for all comparisons, then it can be shown that, aside from the reduction factor mentioned above, an improvement factor exists for the refinery process of diesel fuel (distillates), which depends on the proportion of distillates, since diesel fuel is mainly a straight-run product which requires less heat for its production than gasoline or even lead-free gasoline. This fact is acknowledged in the JPL Study on pages 17-27.

U.S. Energy Research and Development Administration

May 6, 1976
Page 3

The size of the improvement factor for diesel vehicle fuel economy value depends on the product pattern of the refinery, its set-up, and its relative proportion of distillates. References 2, 3, and 4 referred to below suggest this improvement factor to be in the order of 1.15 to 1.28. The product of both factors under all conditions is, therefore, larger than one, and the use of only a reduction factor in computing the diesel fuel economy values of road vehicles is, in our opinion, not justified.

We appreciate very much the opportunity to comment in this matter and hope that our comments will be of value.

Sincerely,

K. H. Faber
General Manager
Product and Service Engineering

BS/KHF/ck

References:

(1) K. Oblaender, H. G. Schmidt

The Mercedes-Benz LDV Diesel Engine.
Paper 2nd NATO-Symposium, Tokoyo
(See Fig. 5 - Fuel Consumption at Road Load)

(2) F. Sezzi, P. Garibaldi, M. Sposiwi

Diesel Fuels and Diesel Engined Vehicles in Some European Countries.
European Automotive Symposium
Nov. 1975, Paris (See page 5)

(3) Light Automotive Diesels -- A Case of Mistaken Identity. (European Automotive Symposium, Nov. 1975, Paris (See Table 9) -- R. Bertodo

(4) W. T. Tierney, E. M. Johnson, R. R. Crawford

Energy Conservation - Optimization of the Vehicle-Fuel-Refinery-System
SAE Paper 750673
Fuels and Lubricants Meeting, Houston 1975
(See Section 3)

Critique by

United Stirling, AB & Company
Kommanditbolaget
201 10
Malmo 1, Sweden

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

35

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

RE: 34LPE-77-208-35

June 29, 1977

Mr. Stig Carlquist
Kommanditbolaget
United Stirling, AB & Company
201 10
Malmo 1, SWEDEN

Dear Mr. Carlquist:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA) has forwarded your letter to us for response in accordance with a restructuring of our automotive assessment work under ERDA direction as described in the attachment. We note, however, that your letter is primarily an updating of your recent technical work rather than a critique of our work.

Your recent progress, along with your planned activities, continue to make us feel optimistic about the future of Stirling power plants. In our view, your conventional crankshaft engine approach obviates many difficulties in the development of a fully viable Stirling engine. Your report at the recent NATO/ERDA Conference in Washington in April 1977 was a most informative description of your development progress.

Regarding our continuing assessment work, our approach is, first, to document as Technical Task Summaries (TTS) the results of work in each technical area, and then to publish an annual Automotive Technology Assessment Report which summarizes the data in the TTS reports. The relationship between these reports is presented in an enclosure.

We thank you for your cooperation in support of our study, and we look forward to your continued involvement, especially during the Stirling reassessment phases.

Sincerely,

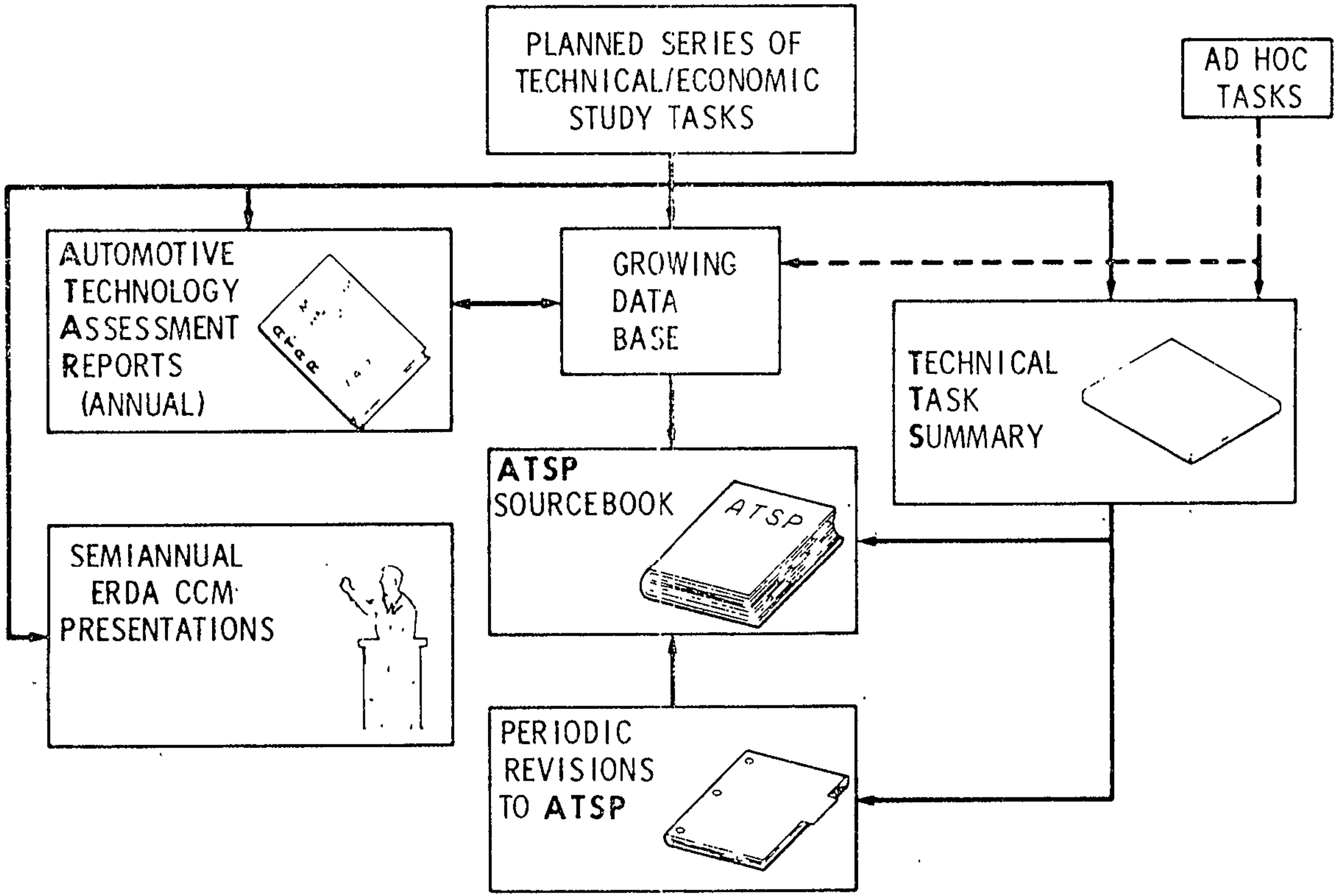
Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:jms

Enclosures (2)

Telephone 354-4321 Twx 910-588-3269 Twx 910-588-3294

PROGRAM STRUCTURE



35-3

77-40

KOMMANDITBOLAGET
UNITED STIRLING
(SWEDEN) AB & Co

Handläggare/Our contactman
S Carlqvist/MLN

Datum/Date
April 27, 1976

Referens/Reference

Ert datum/Your date

Er referens/Your reference

U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
WASHINGTON D.C. 20545 USA

For the attention of Mr R Mercure

Gentlemen:

Updating the Jet Propulsion Laboratory report
"Should we have a new engine?"

We have received your request for latest available information related to the report by California Institute of Technology Jet Propulsion Laboratory entitled "Should we have a new engine?"

Our development of Stirling engines is mainly concerned with engines for trucks, buses and for industrial and marine purposes. Basically two sizes of engines are under development:

1. The experimental engine V4X.

This engine has been developed since 1971 and serves as a test bench for components. In total seven engines have been used. One was used for an early test in a Ford Pinto car. See sectioned view in enclosure.

2. The project engine P150

This engine is intended to be developed into a commercial engine using the concept and experience gained from the V4X development. With the nominal power of 200 HP (150 kW) it consists of two V4-modules i.e. it is a V8 engine. A cross section of a prototype is shown in enclosure. At the moment three V4-modules are being tested.

The development objectives for the P150 engine are as follows: a near term goal of reaching a max overall thermal efficiency of 35 - 37% (phase 1 development) and a long term goal of reaching a max overall thermal efficiency of 40% and above (phase 2 development). The phase 1 development is at the moment taking the majority of our resources. For the phase 2 development only preliminary investigations are made mainly concerning the characteristics of ceramic materials.

Postadress/Postal address	Telefon/Telephone	Telegramadress/Cable	TELEX	Bankgiro/Bank cheque account	Postgiro/Post cheque account
Fack 201 10 MALMÖ 1, SWEDEN	040-100950	Unitedstirling malmö	32379	373-3938	39288-6

KOMMANDITBOLAGET
UNITED STIRLING
(SWEDEN) AB & Co

U.S. Energy Research and Development Administration
WASHINGTON D.C.

For the attention of Mr R Mercure

In an enclosure we have collected information that can be of interest for you in updating the report. We will glad to be in contact with you to keep you informed about our Stirling engine development.

Yours sincerely,

Kommanditbolaget
UNITED STIRLING (SWEDEN) AB & CO
R & D and Licensing

Stig Carlqvist

Stig Carlqvist

KOMMANDITBOLAGET
UNITED STIRLING
(SWEDEN) AB & Co

Enclosure to letter April 27, 1976 to:

U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue N.W.
WASHINGTON D.C. 20545 USA

For the attention of Mr R Mercure

The following corrections and additions to volume II of the report we would like to make:

1. Table 6-1. Engine characteristics

Some figures in characteristics for engines V4X and P150 have been changed. See enclosure. For P150 engine two values for power and efficiencies are given. First value represents goal that will be reached during this year while second value shows final goal in phase 1 development.

2. Power control system

Different types of power control systems are being investigated. We have found that the variable amplitude system (also called dead volume system) has many advantages. However, in order to facilitate the operation with good efficiency also at very low loads without using excessive dead volumes we are now concentrating our efforts on a new improved mean pressure level (MPL) power control system.

The new system incorporates a crank shaft driven hydrogen compressor, a three mode control valve and supply valves for each cylinder. See schematic drawing of the system.

The hydrogen compressor is provided with a short circuit valve to avoid that it absorbs power, when no pumping action is needed. The control valve has three modes of operation:

- Supply function for increasing power
- Dump function for decreasing power
- By-pass function for quick de-loading

During the supply operation the intermittent supply of working gas to the cylinders is a provision for very rapid torque response.

3. Figure 6-33, page 4-46

The picture shown in figure 6-33 on page 4-46 is really related to the V4-module of the P150 engine.

S Carlqvist/MLN

Critique by

General Power Corporation
225 Plank Avenue
Paoli, PA 19301

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

36

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-207-36

June 29, 1977

Mr. H. Burke Horton, President
General Power Corporation
225 Plank Avenue
Paoli, PA 19301

Dear Mr. Horton:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) asked that we reply to your letter in accordance with our automotive studies as restructured. The program reorientation is summarized in an enclosure. Your cogent and well-reasoned critique of the subject report contains recommendations that have been accepted and implemented in the new heat engine program under ERDA sponsorship.

Regarding the wave engine variant of the gas turbine, we appreciate your calling it to our attention, and we will address it in an appropriate Technical Task Summary (TTS) covering Brayton class engines. The role of the TTS as a stepping stone in generating the Automotive Technology Status and Projections source book is indicated in one of the two enclosures.

Regarding your suggestion of extending engine studies to include military applications, this could best be done in a subsequent stage. The primary optimization criteria of the subject study were high fuel economy with low emissions, and they deeply involved the federal driving cycle and certain automobile performance criteria uniquely related to safety in the modern highway environment. Clearly the optimization criteria for military vehicle engines are different. We suggest that the two areas of engine application should each be studied separately first, and then with the result in hand the areas of commonality could be explored along the lines you suggest. We concur in your concept of developing new automobile engines for application in larger vehicles and then scaling them down to passenger car sizes, provided that the scaling parameters are understood and have been validated.

Regarding decisions on which engines to develop, this complex process we feel should not be delayed in the hopes of a significant breakthrough, but should be made as quickly as an adequate basis can be established by means of such studies

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Mr. H. Burke Horton -2- June 29, 1977

as the one under discussion. The option of modifying a decision, of course, should be kept open, and contingency planning done in accord with the risks --- risks to the public as well as to the industry.

In reference to the breadth of the subject study, as discussed on page 4 of your critique, we doubt that a single study in itself would provide an acceptable basis for committing such large sums of money. The desirable result of the study is to direct attention to technical approaches to automotive propulsion which offer an apparent payoff. The critical technology should then be developed to the point that the engines are candidates in fact rather than only on paper. In this way maturation of the best engines can take place with greater assurance.

In regard to increased study flexibility, we feel that there is a limit that should be imposed as a function of depth of a study. For example, a survey study can be as wide as one's library resources permit. In the present case additional resources might be better directed, for example, toward an improved and more versatile computer simulation program for evaluating alternative engines under various driving cycles, where an engine's relative standing can be studied carefully, and the impact on an Otto-equivalent engine (OEE) from various portions of the driving cycle can be readily compared. This is, in fact, one of the efforts being accomplished in our current work.

Many of your comments will be reflected at appropriate points in the current program, but it is not feasible to respond fully by letter to your extensive 10-page critique. Your response is appreciated.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:nrw

Enclosures (2)

GENERAL POWER CORPORATION
225 PLANK AVENUE
PAOLI, PENNSYLVANIA 19301
215-644-0656

April 26, 1976

U. S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N. W.
Washington, D. C. 20545

Gentlemen:

In accordance with your request for comments on the JPL study entitled "Should We Have a New Engine?", I am submitting comments as an attachment to this letter.

I was very pleased to learn that ERDA planned to update the JPL study in this area of vital concern to the U. S. Your choice of phraseology to describe your objective, ". . . to update, expand and correct . . .", certainly hits the mark.

Members of our GPC staff will be glad to provide assistance to you in every way possible for this important undertaking. Our Engine Research Laboratory, located at the address above, is in suburban Philadelphia--readily accessible from Washington, D. C., Detroit, and California. We are looking forward to meeting with you and members of the staff for the new project.

Sincerely,

H. Burke Horton

H. Burke Horton
President

Attachment: Comments on referenced study
HBH:gah

Copies to: Richard R. Coleman
Helmut E. Weber
John Hancock

April 22, 1976

COMMENTS ON "SHOULD WE HAVE A NEW ENGINE?"*

H. Burke Horton, President
General Power Corporation

Introduction

In an outstanding example of corporate statesmanship, Mr. Lee Iacocca, President, Ford Motor Co., arranged for his company to sponsor a special study of national requirements and capabilities for developing an improved automotive power plant. Funding arrangements were made with the Jet Propulsion Laboratory (JPL), California Institute of Technology, in such a way as to exclude any bias by Ford. The resulting study was a pioneering effort to define needs, capabilities, feasible time schedules, and costs of possible alternatives. The original study arrived at certain tentative conclusions as to the feasibility and desirability of these alternatives. The study included recommendations for the following:

(1) A vigorous program to improve vehicle characteristics fruitful for any engine program (eg., weight reduction and improved aerodynamics).

(2) A continuing effort to improve the various types of Otto cycle engines to buy time (eg., development of stratified charge versions, and the use of catalytic converters for pollution abatement).

*Submitted in response to a general solicitation by the U.S. Energy Research and Development Administration for comments directed toward a follow-on study to the initial JPL report (same title) which was sponsored by the Ford Motor Company.

(3) A large-scale government-supported research and development program on Brayton cycle and Stirling cycle engines to carry these two particular types to the point where a decision could be made as to which type (or what mix of the two types) would be best overall.

(4) A long-range research program in areas where a major research breakthrough could create new favorable options (eg., research on electric storage batteries).

The U.S. Energy Research and Development Administration (ERDA) is currently sponsoring an effort by JPL to ". . . update, expand and correct . . . " the initial report. For this purpose, ERDA has solicited comments, suggestions and data relevant to the initial JPL study and the planned ERDA sequel to that study. The comments below have been prepared in response to the ERDA request.

Flexibility

The importance of flexibility in any major undertaking is generally recognized. Too much flexibility can become an excuse for procrastination; too little flexibility creates a rigid commitment to past decisions. Experienced managers of large-scale R. & D. efforts are well aware of these two pitfalls. In my opinion, the initial JPL study errs on the side of rigid commitment to two particular new engine alternatives. This restricted posture is disadvantageous for two reasons: (a) serious unforeseen technical barriers to success with the two chosen plans may be encountered, and (b) unforeseen technical breakthroughs, which could offer better solutions, may occur. There are numerous examples of such unforeseen opportunities in large operations. For example: (1) nuclear (rather than chemical) explosives; (2) lunar orbit (rather than earth orbit) as the preparatory step for lunar landings; (3) electronic (rather than electromechanical) arithmetic and logical devices; (4) magnetic (rather than optical) lenses for powerful microscopes; (5) solid (rather than liquid) propellants for military ballistic missiles; (6) tonnage oxygen (rather than air compressors) for blast furnaces; and (7) the captured Remagen Bridge (rather than pontoons) for crossing the Rhine in WW II. The list could go on indefinitely; however, these diverse events have one thing in common: the means for making a major improvement to achieve the objective was well off the beaten path. In most of the examples (items 1, 2, 3, and 6), the weight of established authority not only backed the inferior solution but was initially hostile to the dramatic new and unexpected solution. In several cases, it was necessary to identify and influence key individuals at high level (eg. Franklin D. Roosevelt on nuclear explosives; and Werner von Braun on lunar orbit) in order to direct adequate attention to the new ideas.

The most serious handicap to flexibility in the initial JPL study was the ground rule stated on p. 45, Vol. 1, which reads in part as follows: "This study limited itself to those (engines) which currently exist in at least experimental prototype hardware and . . . which offer the possibility of being economically mass-produced in the 1980's decade." This ground rule undoubtedly resulted from budgetary limitations. Nevertheless, it limited the scope of the study in a manner inconsistent with the economic importance of the problem and the extended period that the nation must live with the solution (well beyond 2,000 A.D.!). Limiting the scope of such an important project to engines <u>now in hardware</u> is undesirable and unnecessary in this era of extensive and detailed computer simulation of sophisticated hardware, weapons systems, and missions far more complex than most engines. On a problem of this magnitude and importance, we must have access to and utilize our total knowledge about engines and methods for their evaluation. Only in this way can we be reasonably sure of arriving at a high quality of solution(s) appropriate to this massive problem.

Breadth

The staff of J.P.L and Cal. Tech. are to be complimented for the amount and quality of work performed with limited funds and within a short time period. Considering the resources at their disposal, it would have been almost impossible to broaden the staff and scope of the study. The resulting study was an excellent "door opener" to cast a bright light on one of the great peacetime problems of our century. However, I am sure the J.P.L. staff will be the first to agree that a problem measured in decades of time and many billions of dollars deserves broader treatment. Broadening the scope of the next study should make it unnecessary to adopt restrictive ground rules that seriously handicap the investigators. (See last part of the section on Flexibility above.)

The knowledge and experience of many other U.S. research and industrial organizations must be focused deliberately on this problem. The haste imposed by a $500,000 study budget must not be allowed to determine our course of action on a program which will extend into the next century and which will determine in the long run how we spend trillions of dollars. In broadening the base of expertise, we must also consider individuals and organizations outside the U.S. Their ideas and involvement will contribute momentum to the program or programs which finally emerge. Broadening the base will also contribute to program flexibility (see above) and will thereby give us a better chance to discover one of those unexpected "lucky breaks" that could alter our entire approach to the problem.

Premature Commitment

The comments of this section are directly related to the general comments above. However, it is necessary to be more specific about the consequences of inadequate flexibility and breadth. Some of the general remarks contained in the initial JPL study suggest a general awareness of the historical importance of breakthroughs in engine development. For example, in speaking of the JPL concept of Present, Mature, and Advanced stages of heat-engine powerplant development, the study reads in part (p. 53, Vol. 1) "This approach recognizes the evolutionary and revolutionary improvements which will be made in these machines with advancing technology." However, it should be noted that in the JPL study, this awareness has already been narrowly channeled to ". . . these machines . . ."; i.e., those types of engines already selected for analysis.

Similarly, in continuing the discussion of the time frame for new developments (p. 54, Vol. 1), the JPL study reads in part "It is acknowledged that the actual course of engine maturation is more nearly one of continued incremental improvements, along with occasional remarkable gains when a totally new device or system is first introduced." It seems to this writer that speaking of a "totally new device" in the context of "engine maturation" puts an intolerable straitjacket on the concept of technological breakthroughs. The real quantum jumps in a technology result from dramatic new breakthroughs completely outside the bounds of a technological maturation process.

For example, a type of engine which could make effective use of ceramic components in its static (non-moving) parts would have a significant technological advantage over existing types that require the more advanced ceramic components usable for high-speed moving parts. Such a type of engine is known: it is a type of gas turbine whose rotor can be made of metal alloys because the rotor remains hundreds of degrees cooler than the hot gases from the combustor. The "cool" rotor results from the basic operating cycle which combines compression and expansion on the same rotor. In this respect, the rotor of such a turbine functions in a manner analogous to the parts of a conventional piston engine, which also remain cool (relative to the 4000-5000°F. combustion temperatures) as a result of the alternating functions of compression and expansion. This particular illustration, known generally as a wave engine, was chosen as an example for two reasons: (1) the author is familiar with its characteristics, and (2) failure to consider it in the initial JPL study illustrates the type of handicap that can result from a premature all-out commitment to particular solutions. To be more explicit, because of the combination of mechanical and thermal stresses in the hot rotor of the conventional Brayton cycle gas turbine, it is <u>not</u> the type of engine best suited to the use of ceramic components -- even though the present ceramic component research program has been carried on largely as a result of the serious heat problems inherent in the conventional Brayton cycle*. By choosing a different type of engine, less advanced ceramic technology, aimed at static parts of the engine, may enable us to achieve with metal rotors all of the thermodynamic advantages now being pursued with great difficulty by the use of ceramic rotors or ceramic rotor blades in the conventional gas turbines.

The cool-rotor wave engine mentioned above is only one example of the possible impact of new approaches. No doubt there are other similar technical possibilities, such as advanced fuel cells, and these should also be thoroughly explored.

Leverage

Partly because of a limited budget, the initial JPL study identified only two "reasonable" long-range solutions to the automotive engine problem. Each of these two proposed programs faces major multi-billion dollar obstacles to success. To mention only two of these major obstacles, consider the problems of developing (1) economically producible high-temperature heat exchangers, and (2) reliable ceramic components. Problems of this type are far off the beaten track and outside the range of industry know-how. Work in these areas must be funded almost entirely by the government, and if the technical barriers prove to be insurmountable, U.S.

*See for example, pp. 89 and 90, Vol. 1, the extremely difficult and costly component and materials research programs which must succeed before advanced versions of the Stirling and conventional Brayton cycle engines will even be possible.

industry will still be stuck with present engine technology. Considerable effort should be made to structure the research in such a way that government dollars will be spent in quantities and in technical areas that will tend to encourage rather than to displace contributions by industry. Use of government research funds in this way will increase the scope of the overall research program and will significantly reduce the time required for implementation by industry.

Defense

It was disappointing to find that the initial JPL study did not even mention, much less consider, the potential military applications and advantages of a new type of engine.* While this omission is understandable in the modest study funded by Ford Motor Company, national defense needs cannot be neglected in the new version to be funded by ERDA. Considerations such as the use of broad-base fuels, multi-fuel capability, logistic simplification, independence of foreign sources, weight reduction, mechanical simplicity, low cost, and long life are of great concern to the national military establishment. Furthermore, much of the funding needed for new engine development could be justified in various parts of the DoD budget. It is especially desirable in this era of budget limitations to avoid program duplication between the defense and the non-defense agencies of government.

*In the writer's view, the U.S. has passed through a post-World War II period in which it seemed for a time that our spokesmen were bent on a crusade to police the world. This was followed by a post-Vietnam period in which many disillusioned intellectuals seemed bent on a program of unilateral disarmament similar to that of the 1920's and 1930's. It is gratifying to see the nation now aiming for attainable defense objectives which will avoid the weak defense posture that proved to be so inviting to the dictators of the 1930's.

In some cases, it will be more efficient first to develop new types of engines in the larger sizes appropriate for military vehicles and trucks and then scale them down to passenger automobile sizes after certain tough problems have been licked. Contrary to the lay view, small sizes do not guarantee small research and development problems! -- Quite the contrary! In many cases, working with medium size devices can simplify and accelerate R. & D. This is especially true in dealing with completely new technologies such as economical heat exchangers, ceramic components, low-pollution combustors, wave engines, fuel cells, and improved energy storage systems.

For all these reasons, it is unfortunate that constructive interaction between our defense needs and our peacetime engine needs appears to have been neglected. The new Federally-financed study must rectify this deficiency by bringing the power of our Defense R. & D. structure to bear on the problem. Inter-departmental jurisdictional questions must be brushed aside to achieve total national objectives at minimum cost.

Conclusion

The initial JPL study (sponsored by Ford Motor Company), "Should We Have A New Engine?", is a major landmark. It opened the door and made preliminary recommendations for solving one of our most serious national problems. It is now generally agreed that we do in fact "need a new engine." The decision by ERDA ". . . to update, expand and correct . . ." the initial report is far-sighted. The follow-on study should be financed more adequately so as to provide means for (1) more flexibility in research approaches; (2) a broader base for technical input and review; (3) avoiding premature commitment of R. & D. effort to early choices; (4) incentives to generate research leverage through greater contribution by industry; and (5) serious attention to the relationship between our defense needs for, and defense contributions to, a new engine.

37

Critique by

Arthur F. Underwood
155 Tree Top Lane
Rochester, MI 48063

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-190-37

June 29, 1977

Mr. Arthur F. Underwood
155 Tree Top Lane
Rochester, MI 48063

Dear Mr. Underwood:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

The information on "Alternative Power Plants for Autos" that you sent to Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) was forwarded to us in accordance with a restructuring of the automotive studies as described in the enclosure. We were, of course, very interested in comparing your views with those expressed in the subject study.

There is no doubt that we need a large improvement in battery technology in order to make the electric car a serious all-around contender. We feel, however, that considerably less than your lower limit of a ten-fold improvement in the battery energy capacity (if obtained with reasonable economic aspects) would be acceptable for a reasonable volume/weight ratio specialty car.

We appreciate your comments and hope that your interesting follow-up article is published.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

ARTHUR F. UNDERWOOD
155 TREE TOP LANE
ROCHESTER, MICHIGAN 48063

April 23, 1976

Mr. R. Mercure
Heat Engine Sytems Branch, ERDA
Division of Transportation Energy Conservation
20 Mass. Ave., N.W
Washington, D.C.

Dear Mr. Mercure:

Your request for information relative to the JPL Report, prompts me to finish up a project I started some months ago.

When I retired as manager, General Motors Research Labs in 1969, "Machine Design" asked me to write an article on Alternate Powerplants for Autos. The Editor changed the title to "Requiem for the Piston Engine?" and published it, finally, in the Aug. 1970 issue. About half of my manuscript was published, - it was a rather complete discussion of all the alternatives, so it was long. A comparative chart listing the factors to be considered in making a judgment and how each engine stacked up, was not included by the editor.

About a year ago, it seemed to me that seven years later would be a good time to "See How It Came Out." If someone does not kill it, it may get published!

Yours truly,
Arthur F. Underwood

or
The Seven Costly Years
by Arthur F. Underwood

In the August 1970 issue of "Machine Design", an article was published by the author, under the title "Requiem for the Piston Engine?". "Piston Engine" was used to identify the Otto engine. In addition to it, all the other popular alternatives were considered and evaluations were made on each one. The conclusion at the end of 1969, when the article was actually written, was that the Stirling and some type of 2-phase combustion engine (the diesel is in this classification) were the two leaders.

Some seven years later it seems to be appropriate to review the results of the billions of dollars expended on alternate powerplants and to look ahead a similar period of time. In other words, this report is a management guide and aid in planning research and development of automotive power systems.

Hundreds, if not thousands, of technical reports are available with excellent to bad data and conclusions. As Mr. Kettering used to say: "Every library should have a plaque over the door saying 'Half the information is wrong; we don't know which half.'"

In 1969, driveability, performance, cold-starting and fuel economy had to be good to excellent according to the owner's opinion of acceptable compromises. Emissions were being improved. The owner expected a car which had good driveability, perfomance, cold-starting, etc with fuel economy at the top of the list. Then the Clean Air Act of 1970 mandated a 90% reduction in emissions. The fuel economy suffered and the Arabs mandated the fuel crunch. The obvious question is: how do we greatly improve fuel economy and yet retain as much as possible of the good driving characteristics.

There is increasing evidence that some common sense may yet prevail in the matter of emissions standards.Most certainly, based on present knowledge,the NOX should be in the 1.5-2.0 range.

OTTO ENGINE

As predicted in my 1969 article,the Otto engine will be around for a long time. There continues to be at least two good reasons.

1. The industry is set-up to make and service them and by patch-work engineering have been able to keep in business by meeting the only mandated requirement,-'emissions'. Until recently, no consideration was given by the authorities to the other important requirements.By ever-increasing "add-ons" at ever -increasing costs,these requirements for better fuel economy,driveability,etc are being upgraded.This work has been thoroughly documented in public print and there is no need to even review it here.

2. The diversion of funds to keep abreast of mandated requirements has made a real (perhaps unreal,sometimes) reason to neglect working on alternate powerplants.As will be indicated later,the investment of a few tens of million dollars in alternate powerplants would have produced useful results,if it had been correctly applied.Some authorities have concluded that in the past ten years,some $1,000,000,000 have been spent in the U.S.A. alone,on rotary engines.

DIESEL

Two-phase combustion should be used to identify this type of engine,one of which is the diesel.A rich mixture is ignited by compression ignition and the final burn is in a lean mixture combustion. This is one important area where research should have been carried on intensively for the past 10 to 15 years so that the industry would ~~now~~ have a first-class "diesel" when it is needed,-which is now. If the industry is to be critized for dragging its feet, government agencies are open to more severe criticism for not pouring dollars into "diesels" instead of many other year 2000 projects.

"Diesels" do not have to be smokey, noisy, heavy and stinkey. It is interesting that rather good 2-phase combustion engines are today running on American roads or are running in testing operations. They are, all, efforts of foreign companies or smaller American companies. We can only hope that someplace in the U.S.A., someone has a secret development which will soon spring forth a quiet, non-stink, "lightweight", high mileage "diesel" acceptable to a large portion of the American drivers.

"There is no substitute for experience" is particularly true in this area. Much of the newer technology is available but there are woefully few engineers who have had design and testing experience to apply it. Buckets of dollars will not yield overnight correction, but proper building, on experienced individuals, will.

The 1969 recommendation for "diesel" engines is still sound.

STIRLING

It may be difficult (if not embarrassing) to recall where this engine was in 1969. Because of a license agreement, only one American company was working on the modern Stirling engine.

Its many detractors claimed it was:

1. Too heavy
2. Too big
3. Not flexible to acceleration and deceleration
4. Hard to start
5. Extremely expensive
6. Required a bigger radiator

This was done in spite of the fact that long term tests and a new swashplate design ,showed the exact opposite.However,it still is not known how much more costly the Stirling might be compared to the complete Otto engine with emission controls.

Nearly everyone agreed that the engine was:

1. Quiet
2. An honest 38-40% thermal efficiency
3. An extremely low emitter of pollution products
4. Truly multi-fuel

In April 1976,the Ford Motor Co. held an exclusive contract and had a 3 day demonstration of the swashplate engine in a Torino. When published,the results should be interesting.

It is this author's opinion that it may take up to 10 years for it to appear in a car,but there are many near-term,not so cost conscious applications that will appear because of high efficiency,quietness and high adaptability to total energy installations as well as solar heat.

Reliable data are available in reports by Philips,Ford and General Motors.The Ford sponsored JPL report on alternative powerplants has a section on Stirling engines.

The 1969 recommendation for intensified development (the research phase is quite well in hand),is still valid.

GAS TURBINE

When General Motors made and demonstrated the first turbine powered American car,"The Firebird I",in the early '50's,it had several bad features:Slow response from a standing start,high consumption,high cost,rather noisy and high emissions.The subsequent 25 years brought substantial progress in these areas.

The fuel consumption is too high for an auto and the engineers say,as 25 years ago,that "all we need to do is to run high temperatures and to increase the efficiency of the components". Projects have been funded and yet more progress is needed.Cost has been reduced but a regenerator has had to be added.This one item can be as expensive as the total cost of an Otto engine.

Fuel consumption has been improved but often by making a smaller engine in a smaller car.One must be careful about this "honest gimmick" as it does not represent a fundamental improvement in efficiency.For instance,the use of an infinitely variable transmission can improve starting acceleration and mpg,but it can not be credited to the gas turbine.

A particularly forthright paper on gas turbines was written by Tibor F.Hagey,General Motors Corp. and published by ASME a few years ago.

We don't need more gas-turbine cars except for their public relations value (which can be valuable).Money should go into projects related to technical problems of components.

STEAM CARS

The numerous projects on this car have more than amply demonstrated that the steam car never should have been "dug up". Space age technology was to be the modern touch.No improvement has been demonstrated over the 50 year old steamers.Taxpayers and individuals have lost millions of dollars.

Practically,the only "improvement" has been to put smaller engines in smaller cars,which any engineer would know,gives more mpg.

A steam power plant is complicated and costly.

It is very difficult to understand why taxpayers' money should be, or ever was, spent here, except to keep someone busy.

ELECTRICS

These really should not be considered in a serious discussion of cars. They are satisfactory for specialized applications in specific operations. One thinks of golf carts, use in senior citizen complexes, delivery wagons in England.

The battery remains a principal obstacle. In fact, many engineers maintain that two types of batteries are required to optimize operation. "Anyone" can design another vehicle for electric power but we need a battery with ten to a hundred times the capability of the present box to make it interesting.

WANKEL ENGINES

When the author submitted his 1969 manuscript, the Editor requested a separate section on the Wankel engine, which was "the coming savior of the engine problem". Having visited NSU, Neckersülm, Germany almost yearly since it appeared on the horizon, the author had pointed out that there were certainly many advantages: small size, low weight per hp. and ability to run fast,

On the other hand, serious problems had to be overcome before a viable engine could be sold. The first was sealing for the rotor. When cranking it by hand, there was no compression. When running, it had horrendous blowby. The burning occurred in an area (or volume) which was never alternately cooled, as in a regular Otto engine. There was one good feature of the big blowby, -it gave a large amount of fuel in the exhaust to produce an afterburner.

As far as the author knows, there is no final report on this engine. The only reason for including a referance now, is to close that part of the 1969 article.

FUEL CELLS

From information that the author has received from competent sources, significant practical progress has not been made towards their use in cars. It is a grand way to spend money, if you want to go to the moon or Titan.

Arthur J. Underwood
155 Tree Top Lane
Rochester, MI 48063

Critique by

Robert Spies
1698 Cotter Place
Encino, CA

38

213-788-3621

CALIFORNIA LICENSE
M-11073

ROBERT SPIES
CONSULTING ENGINEER
16980 COTTER PL.
ENCINO, CA.

March 9, 1976

Mr. Robert Mercure
Project Officer for Highway Vehicle Systems
Division of Transportation Energy Conservation
Energy Research and Development Administration
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Dear Bob:

It was good to see you again and have dinner with you. I am forwarding the enclosed article which I am sure you have already seen because it struck me, as we lawyers say, right on point.

In the case of the alternative powerplant we have an identified area of new technology and we need to find means for the private sector to deliver. As Mr. Fri says, ERDA has to give the technology away. But what technology and to whom? The jpl study has not gone far enough because of the limitations imposed. It has only identified broad technology problems because of simplifications made, and has had to say that the technology will be available when needed because it must be. We think that it is imperative for ERDA to identify the technology gaps in detail so that the private sector can respond, plug the gaps, and deliver the systems. If ERDA is to "sell what we have developed to provate industry" it must know what its technology product is. Then industry can respond and "buy".

I have tentative plans to be in the D.C. area during the week of March 15. If I possibly can, I will give you a ring and maybe we can get together.

Sincerely,

Bob

Robert Spies

Critique by

University of Minnesota
Department of Mechanical Engineering
125 Mechanical Engineering Building
Minneapolis, MN 55455

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

39

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-198-39

June 29, 1977

Professor Thomas E. Murphy
Department of Mechanical Engineering
University of Minnesota
125 Mechanical Engineering Bldg.
Minneapolis, MN 55455

Dear Tom:

Subject: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded your letter to us for response in accordance with our obligations under a restructured program, as described in the enclosure. Your penetrating letter contains incisive review comments on the gas turbine and Stirling portions of the study as documented in the subject report.

In regard to Brayton machines, we acknowledge your reservations regarding the inherent limitations of scaling down the size of the gas turbine. However, in our view, this in itself does not conclusively prove the infeasibility of automotive-sized gas turbines. It does, however, put more emphasis on the need for higher cycle temperatures to obtain good fuel economy. In response to your suggestion, we will review the analysis of the Brayton cycle with a critical eye to revised component efficiencies as affected by scaling factors.

In reference to the Stirling engine, we will defer detailed comment at this time on your concerns about its size and weight relative to the Otto engine. The multifuel capability of the Stirling engine, of course, is an attractive feature, and this attribute will be of increasing importance in the future.

All of your points will be addressed in appropriate Technical Task Summaries mentioned in the enclosure. We are very appreciative of the interest you have shown in the study and the effort you made to review it, and we look forward to a continued interchange of data with you.

Sincerely,

Harry

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Mechanical Engineering
125 Mechanical Engineering Building
Minneapolis, Minnesota 55455

April 20, 1976

U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Attention: R. Mercure

Gentlemen:

The report by the Jet Propulsion Laboratory on long-range goals for power plants for the automobile of the future comes to some erroneous conclusions. Some very fundamental parameters involved in the areas of thermodynamics, fluid friction, and heat transfer have apparently not been fully recognized as one scales the power system up or down in size. This results in incorrect estimates of thermal efficiency and the resulting fuel consumption.

At the University of Minnesota a two-year study of power source systems, beginning in 1953, was made for the Signal Corps of the United States Army, Contract No. DA-36-039sc-56649, under the direction of Dr. Newman A. Hall, Head of the Power and Propulsion Division of the Mechanical Engineering Department. I had the privilege of doing one of the sections of that report.

We learned in this study that the most important characteristic of all power systems is that each one has an optimum power range in which one achieves maximum thermal efficiency (minimum fuel consumption) and minimum weight or size (box volume) per unit of output.

If one is selecting an optimum power system, one can quickly come to the conclusion that it is ridiculous to power your watch with a gas turbine or to fly your Boeing 747 with a wind-up spring. As the power range narrows, however, the differences become harder to define, and one must look for basic physical parameters for guidance. This characteristic occurs because the losses due to fluid friction and mechanical friction vary differently for the various systems as size changes.

In order to conserve energy for automotive transportation, we must expand great effort to reduce the power required by the vehicle. The power required by any vehicle moving in a fluid (air or water) increases as the cube of the speed. Therefore, the 55 mph speed limit is a step in the right direction. This speed limits means, however, that our automotive power plant of the future should never exceed a maximum of 100 KW and probably will operate in the 10-20 KW range.

Mr. R. Mercure
Page 2
April 20, 1976

The Signal Corps asked for a recommendation for a lightweight power system in the one to ten KW class. We looked at every known alternative, including batteries, mechanical systems (springs, etc.), stored energy (flywheels and fluid), engines of all kinds; gas turbines, Stirling, Rankine, and others. We came to the conclusion that the piston engine was optimum for this power range. Therefore, I agree with the first conclusion that the piston engine should be developed to the ultimate limit.

It is with the recommendation concerning alternate power plant development that I disagree! In our study we concluded that the gas turbine had fundamental limitations with respect to fuel consumption in this size range that could not be overcome by any amount of research and development. The reasons for these limitations are explained in the remainder of this letter.

In the various heat engine cycles the maximum thermal efficiency is about the same--30 to 40 percent. Therefore, the losses due to fluid and mechanical friction become the controlling parameters. In the case of the gas turbine, the mechanical friction is quite small, but as one scales the engine down in size the fluid friction becomes excessive. The fluid friction occurs in the wall boundary layer. One must have the same velocities and fluid properties in gas turbines of different size. This means that the Reynolds number decreases with size and pressure losses increase (see figure 2.2, page 23 in Turbomachinery, by Shepherd). One can see the same effect clearly in figure 2 of the paper "An Advanced Automotive Gas Turbine Engine Concept" by I.M. Swatman and D.A. Malone (SAE Transactions, 1961) which shows the loss of compressor efficiency as size is reduced for constant tip speed and fluid properties.

In the Jet Propulsion Laboratory report, Volume 1, page 55, table 4, the authors indicate design maximum horsepower values of 50-120 horsepower with a compact size vehicle at 85-90 horsepower. The calculated fuel economy is shown in table 5 on page 57 of the report. These calculations are based on the component efficiency shown in table 5-1, page 5-6 of Volume 2 of the report. These efficiencies were obtained from a consultant, Dr. R.C. Dean, Jr. Dr. Dean published an article on the centrifugal compressor which was published in Gas Turbine International, March-April, 1974. On page 53 of that article is shown figure 2A, and on that chart are shown predicted ultimate values for centrifugal compressor efficiencies.

These same values of component efficiencies are used in SAE Paper 760239, "The Ceramic Gas Turbine--A Candidate Powerplant for the Middle-and Long-Term Future" by A.F. McLean and D.A. Davis. The values appear in table 1 on page 4 and are indicated as being obtained from reference 5 at the end of the paper "The Fluid Dynamic Design of Advanced Centrifugal Compressors", TN-185, Creare, Inc., Robert C. Dean, Jr., July, 1974. Existing automotive gas turbines have been designed for about 200 horsepower with mass flows of 3-4 pounds per second. Referring to figure 4 on page 5 of the paper by McLean and Davis, it is obvious that for a 2500°F turbine inlet temperature the mass flow to produce 85-90 horsepower would be less than 0.3 pps. It would seem completely unrealistic to assume that even with an unlimited amount of effort the compressor and turbine efficiencies

Mr. R. Mercure
Page 3
April 20, 1976

shown could ever be achieved. In fact, as the engine is scaled down in size with increasing turbine inlet temperatures, great effort will be required to even retain the component efficiencies which we now have.

If these more realistic values of component efficiencies are used, the fuel economy of Brayton cycle powered automobiles would be much more than shown in table 5 of the Jet Propulsion Laboratory report. Therefore, I strongly recommend that the computations be redone with new values of component efficiencies based on a careful study of the scaling factors involved.

In the case of the Stirling engine, one can only achieve the cycle efficiency because regeneration is used, and a heat exchanger must be involved. We found in our study for the Signal Corps that the Stirling engine was quite high in weight per horsepower and volume per horsepower. We came to the conclusion that the size of the engine is really controlled by the rate of heat transfer. The maximum heat transfer rate across any metal surface is about 16 KW/sq.m. The equivalent heat generation rate in an engine flame is about 16,000 KW/sq.m. There is almost three orders of magnitude difference here. One comes to the conclusion that the Stirling engine would never approach the spark ignition engine in weight per hp or size (box volume) per hp. In the case of the passenger car, where weight and size are critical (80-90 percent of the problem; see SAE SP 383 dated 1973), it would seem unwise to spend much effort on such a power system. The Signal Corps was much impressed, however, with the low noise level and multifuel capability of the Stirling engine. Others are impressed with its low emissions.

Sincerely,

Thomas E. Murphy
Professor of Mechanical Engineering

ljs

Critique by

Harold A. Backus
PO Box 333
Wynnewood, PA 19096

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

40

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-196-40

June 29, 1977

Mr. Harold A. Backus, President
Backus Devices
Box 333
Wynnewood, PA 19096

Dear Mr. Backus:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have A New Engine?"

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded to us your letter concerning the Backus Combustion System for response. This is in accordance with our work statement as summarized in the enclosure.

While the subject report did not directly address alternative engine concepts at the subsystem level, we are, of course, interested in ideas which hold promise of better emissions control and/or more efficient combustion. As you are aware, the general approach of pre-treatment of fuel prior to combustion has been attempted by numerous investigators with varying degrees of success. We see several difficulties, some of which we think are of a fundamental nature, that must be overcome before the Backus Combustion System can be reduced to successful working hardware.

The preburner may suffer two problems. First, the overall air/fuel ratio may be far too rich to sustain combustion. Secondly, our own experience in the rich combustion regime has been that some of the fuel is cracked. This produces elemental carbon and tar-like, partially oxygenated hydrocarbons. These cracking products lead to clogging of small passages and to deposits which can significantly alter the geometry of downstream ducts, baffles, etc.

Mixing of the gasified fuel with preheated air may be difficult to achieve without developing regions in which the local air/fuel ratio varies drastically from the overall mean. Mixing the gaseous fuel and hot air by means of a shear layer will generate local eddies. Distribution of the fuel and air within the eddies will almost certainly vary from the mean. Some combustion will take place at near stoichiometric conditions, and hence at temperatures much higher than that required to suppress NO_x formation.

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JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Mr. Harold A. Backus -2- June 29, 1977

It is not obvious that the dilution zone should be eliminated, since the purpose of dilution downstream of the primary unit is not only cooling, but also the shaping of the temperature profile to the turbine. As to your point in regard to advantages in the afterburner and the elimination of the flameholder, this approach, as you may be aware, has been tried many times without success. With regard to eliminating torch ignition, choking of the main flow would be required as well as a high intensity spark source.

We value your comments and hope to continue an interchange of information on alternative power plants. Many of the points you raised will be addressed in appropriate Technical Task Summaries, as mentioned in the enclosure.

Sincerely yours,

H. E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

BACKUS DEVICES
INCORPORATED

Box 333 WYNNEWOOD, PA. 19096

May 15, 1976

Mr. Robert Mercure,
E.R.D.A; Transportation Energy,
20 Mass. Ave.,
Washington, D. C. 20545

It was a pleasure to talk with you and I am hopeful that our conference next Friday will be fruitful.

I am enclosing six sheets that give a very preliminary outline of the proposed combustion system. This system has adaptability to all liquid fuel burning heating and power equipment. The concept of treating the fuel to a distinct two stage preparation for combustion is unique. Many schemes are presently doing a half-way job of fuel treatment, including preheating,stratified charge, prechamber injection, etc, all with residual difficulties and shortcomings.

For turbines, the present combustor would be converted in space arrangement to an upstream "flash" generator ofgasified fuel premixed with products of combustion (from burning 2% of the fuel to heat and gasify the rest of the fuel), followed by the downstream main combustion nozzles with air admixture. The fuel would be burned in the correct amount of excess air to maintain proper temperature reduction and control for introduction to the turbine.

Of additional interest to Mr. Patrick Sutton would be the application to piston and Wankel engines where the result would be a sort of "super-diesel" with injection of hot gasified multi-fuels. Computer analyses show very low specific fuel consumption rates and the basic concepts provide the utmost favorability for eliminating pollutants, especially NO_x

I trust this introduction will suffice for the present.

Sincerely yours,
Harold A. Backus
Harold A. Backus, Pres.

BACKUS DEVICES
INCORPORATED

Box 333, WYNNEWOOD, PA. 19096

June 7, 1976.

Mr. Robert Mercure,
E.R.D.A; Transportation Energy,
20 Mass Ave.,
Washington, D. C. 20545

Dear Mr. Mercure;

I am pleased that in our telephone conversation of Thursday, May 27th you suggested getting J.P.L. to review this subject of the Backus Combustion System as applied to turbines. I believe you have already sent them the 6 pages I forwarded to you.

Herewith are 7 more pages giving a detailed explanation of the system, its performance and its advantages for transmission to J.P.L.

Please understand that I am ready to answer any comments that are made. I further trust that this project can be kept currently active in the hope of interesting the proper parties in its development.

Sincerely yours,

Harold A. Backus

Harold A. Backus, Pres.

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Critique by

US Army Materiel Command
TSARCOM
4300 Goodfellow Blvd.
St. Louis, MO 63120

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-193-41

June 29, 1977

US Army Materiel Command
TSARCOM
4300 Goodfellow Blvd.
St. Louis, Missouri 63120

Attn.: Mr. Albert Hall, BIS, MA
TSARCOM Equipment Manager

Dear Mr. Hall:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded to us your letter of 25 June 1976 in accordance with our restructured program as described in the enclosure. As you know, the objective of the subject study was to assess possible alternatives to present-day IC engines for automobiles which offer a promise of an increase in fuel economy and a decrease in emissions while retaining performance and marketability. Your concepts regarding overhauling a worn engine or exchanging it for a similar new engine affects the life-cycle cost of an automobile, and thus is an important parameter in automotive systems optimization studies. In the subject study, however, the parameters selected for optimization were emissions and fuel economy.

Our automotive assessment work has been restructured under ERDA funding as described in the enclosure which also includes a summary of the follow-on work. Cost factors will be included in this phase also, but we feel that first priority must be given to emission and fuel economy issues. We appreciate your interest in the previous study, and are pleased to have this opportunity to respond to your letter.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status and
Projections

Enclosure

HEC:gpa

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

25 June 1976

Division of Transportation
Energy Conservation
20 Massachusetts Ave., N.W.
Washington, D.C. 20545

Dear Sir,

Referencing article "Should We Have A New Engine?", Diesel and Gas Turbine Progress, June 76, enclosed you will find a copy of Proposed MIL-STD, Definition and Classification of Deficiencies Overhaul Maintenance.

TROSCOM recognized the need for such a document four years ago for many reasons. The principle reason was that many of our overhaul documents (approx. 135) used nebulous terms such as check for leaks, remove dents and corrosion, connections shall be tight, etc. The documents would be written at different divisions, thus, it was not always possible to be precise even when the same engine was used in two or more applications i.e., Caterpiller D333 in Marine application and the same engine used two years later in electrical generator application.

There were additional complications when considering the extent of overhaul. In some cases, it may be only those repairs necessary which led to interpretations all the way to complete rebuild. This could be very costly in repair parts but inspection costs were low. Limited overhaul, on the other hand, required intensive inspection and judgement with some sayings in parts that could be reused.

ORIGINAL PAGE IS
OF POOR QUALITY

As a reference, the writer might use a Writing Style Guide or another manual. Generally, this was economical and sufficient when most of the work was performed in Military Depots. If the work was unsatisfactory, controls were exercised internally within the military system, thus, the depot had to protect its reputation and there was little need for recourse to the courts should disputes arise.

However, as the depots closed, a trend developed for commercially contracted maintenance and the need for more sophisticated overhaul specifications was obvious.

In surveying the problem, TROSCOM looked at procurement techniques used in buying NEW equipment. Here thousands of industry and government specifications and standards existed. These evolved through years of experience and were developed by a technical staff of engineers and specialists. The overhaul business did not have these advantages. A program was established to close this gap and focused on the smaller issues intentionally. A manufacturer who makes a $10,000 engine will give great detail to the tolerances and limits for wear and replacement of moving parts but there is no mention of an acceptable dent in the gas tank or muffler.

When the proposed MIL-STD is adopted, it will establish a common reference or scale for writers to use when specifying their overhaul requirements. It will reduce the arguments between maintenance overhaul personnel and quality control inspectors. The military customer may have a dent in his radiator but it will be cheaper than a new one. The throw away concept is no longer popular. The standard may have growing pains but it will serve as an important tool to specifying economical overhaul or "Should We Have A New Engine?"

ALBERT HALL, BIS, MA
TROSCOM Equipment Manager
AUTOVON 693-2126

Critique by

Toyo Kogyo Company, Ltd
Rotary Engine Development Division
6047 Fuchu-Machik Aki-Gun
Hiroshima, Japan

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

42

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-202-42

June 29, 1977

Mr. Kenichi Yamomoto
Director and Manager
Rotary Engine Development Division
Toyo Kogyo Company, Ltd.
6047 Fuchu-Machik Aki-Gun
Hiroshima, Japan

Dear Mr. Yamomoto:

SUBJECT: Critiques of the JPL Report SP43-17, "Should We Have a New Engine?"

Your informative letter to Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) on the rotary engine aspects of the subject report has been referred to us for response. The explanation for our responding at this time is explained in the attachment, which also summarizes our restructured program.

The technical data included with your letter indicates that considerable strides have been made by Toyo Kogyo in the development of the rotary engine since publication of the subject study. We were pleased to be made aware of this progress and hope you will share with us the results of further development activities, especially regarding the stratified charge version of the rotary engine.

Regarding the classification of the Wankel engine, we did not designate it as a "mature" configuration because at the time the report was written we did not view it as competitive with the uniform charge Otto Cycle engine. It was selected as an "advanced" configuration because we thought that certain key technological improvements in the Wankel were likely to occur in the future. These improvements are described in pages 3 through 15 of Volume II of the subject report, and I think you will agree that a Wankel engine having these improvements should not be classified as a "current" technology rotary engine.

In conducting automotive technology assessment for ERDA we will include a reevaluation of the rotary engine and will incorporate it in an appropriate

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JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Technical Task Summary (TTS). The several points you made, along with similar ones by other respondees, will be discussed in the TTS. We appreciate your review of the report and look forward to a continued interchange of information.

Sincerely yours,

Harry E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:gpa

Enclosure

TOYO KOGYO CO., LTD.
6047 FUCHU-MACHI, AKI-GUN, HIROSHIMA, JAPAN
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ESTABLISHED: JANUARY 1920

77-40

June 28, 1976

Mr. R. Mercure
U. S. Energy Research and Development
Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N. W.
Washington, D. C. 20545
U. S. A.

Dear Mr. Mercure,

I have received your letter of May 18 requesting my comments on the JPL report entitled " Should We Have a New Engine ? ".

The rotary engined cars are currently mass-produced at our company and research and development work on our rotary engine is still being carried out in order to obtain higher thermal efficiency, lower exhaust emissions, better driveability and lower production cost as a better powerplant while meeting basic requirements for an automotive engine.

We believe that the most essential factors required for future automotive powerplants are compactness, lightness, and lower NO_x emission level which are inherent advantages of the rotary engine, as stated in the said report of Vol. II.

Following are my comments on the said report. Data on our rotary engine are enclosed for your reference.

Comments:

(1) Considering the fact that the rotary engined cars are currently being mass-produced and sold in the world-wide markets, it seems to be unappropriate to classify them in an " Advanced " group as in the said report of Vol. II.

When comparing the rotary engined cars with the conventional engined cars with comparable engine size, power and accellerating performance, the fuel economy figures of the rotary engined cars are on an average level, as shown in Figs. 1,2 and 3.

Figs. 4 and 5 indicate that in comparison with the conventional engined cars with equivalent performance and competitive retail price, the rotary engined car is potentially attractive as a powerplant in terms of its lower interior noise which is an important factor in comfortable driving required of an automobile.

(2) As for the rotary engine's thermal efficiency, our '76 models have been dramatically improved over the models in the past through modifications to the configuration of the combustion chamber and improvements to gas sealing and the ignition system. The level of the improved thermal efficiency has become competitive with that of the conventional engine as indicated in Figs. 1, 2 and 3. We believe that the rotary engine has a potential for further increase in its thermal efficiency by improving the exhaust emission after-treatment device and others.

(3) Toyo Kogyo is carrying out research and development work on the stratified charge rotary engine which makes it possible to operate our rotary engine on a leaner air-fuel mixture. In case of the stratified charge rotary engine, therefore, the lean misfire limit is expected to be extended by nearly 2 - 3 in terms of the A/F ratio as compared with that of the conventional carburetor rotary engine, thus, it will be possible to further improve its fuel economy and driveability and to further reduce its NO_x emissions through the use of the EGR.

Sincerely yours,

K. Yamamoto

Kenichi Yamamoto
Director and Manager
Rotary Engine Development Div.

Encls.

Critique by

Richard G. Johnson
2611 West N-12
Palmdale, CA 93550

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

43

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-197-43

June 29, 1977

Mr. Richard G. Johnson
2611 West N-12
Palmdale, CA 93550

Dear Mr. Johnson:

SUBJECT: Critiques of JPL Report 43-17, "Should We Have a New Engine?"

We were pleased to learn of your interest in alternative engines as expressed in your letter to Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA). In accordance with our restructured program under ERDA direction, as described in the enclosure, we were asked to respond to your letter. In the follow-on study, as summarized in the enclosure, we will address your conceptual design as a candidate alternative engine.

In studying the data enclosed with your letter a number of questions arose. We are concerned whether the present mechanical design will accommodate the high RPM's which are required in order for the engine to be competitive with the Otto engine. The piston seals, piston pin, and drive appear to be the most critical elements. To our knowledge, the only positive displacement Brayton cycle ever developed was an auxiliary power unit (APU) manufactured by the Fairchild Company in the late 1950's. It utilized a Lysholm positive displacement compressor with a conventional axial turbine on the hot side. We are not aware of a successful positive displacement hot expander having been built, due to limitations in materials technology.

We hope you will keep us informed of your progress toward solution of these problems. Your interest in our work and your effort in reviewing it are appreciated.

Sincerely,

H. E. Cotrill

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:jms

Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

July 3, 1976

Energy Research and Development Administration
Heat Engine Systems Branch
Div. of Transportation Energy Conservation
20 Massachusetts Ave., N. W.
Washington, D. C. 20545

Dear Mr. Mercure,

This material is being submitted in response to a solicitation appearing in the May 1976 issue of Automotive Engineering. All of the following including enclosures may be published as the Government sees fit.

In December 1975 I submitted material concerning an improved internal combustion engine to the National Bureau of Standards under the terms of the Non-nuclear Energy Research and Development Act of 1974. I have not received a reply from NBS as of this writing. I have reviewed certain chapters of the JPL report, as well as considerable other material in this field and consider the JPL report to be the most complete and accurate work now available. It is listed in the bibliography to the material previously submitted to NBS.

The primary objective of the present submission is to bring my engine concept to the attention of the JPL authors and others and to point out that the concept agrees with or is not in conflict with certain portions of the JPL report, particularly in the area of fundamental considerations of heat engines.

Enclosed is a copy of a report which describes my concept.

Sincerely,

Richard G. Johnson
2611 W. N-12,
Palmdale, Ca. 93550

Critique by

Massachusetts Institute of Technology
Department of Mechanical Engineering
Swan Laboratory, Building 31
Cambridge, MA 02139

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

44

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-209-44

June 29, 1977

Professor C. Fayette Taylor
Massachusetts Institute of Technology
Department of Mechanical Engineering
Swan Laboratory, Building 31
Cambridge, Massachusetts 02139

Dear Professor Taylor:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We appreciate the interest that you expressed in your letter regarding the Stirling engine as treated in the subject report. Our automative studies have been restructured, as summarized in the enclosure, which also includes an explanation of the plan for responding to critiques of the subject report. Each of your points will be addressed in our reports dealing with the Stirling engine, and only some of the more pivotal issues you brought out are commented on below.

Your question regarding the 20% difference in the comparative power ratings of the Stirling and Otto engines for an equivalent automobile has been borne out by refinements in our computer simulation program over the past two years along with some pertinent engine experience. This work has been reported by the Ford Motor Company.

Insofar as relative engine weights are concerned, we assumed that the Stirling had an aluminum block while the Otto block remained cast iron. We doubt that another attempt by the industry to use aluminum will be made.

Regarding sliding seals, we understand that seals based upon the United Stirling technology are under active development. They may be used as backups to rollsock seals in the event of primary seal failure. Recent experience indicates that the rollsock seal itself has not been a primary failure source, but that other pressure loss failure modes induce secondary failure in the rollsock seal.

The Stirling safety question is under investigation by the Stanford Research Institute (see their Report P.O. 373928). The early conclusions appear to relegate this safety issue to one of minor concern since the mass of hydrogen is small. The reliability questions you put forth are of serious proportions and not satisfactorily resolved at this time.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

jpl JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

The question of engine size, as treated extensively in your letter, was not addressed in our report. It is an interesting point and one that will require careful consideration on our part. All of the comments put forth so cogently in your letter will be addressed in a Technical Task Summary (TTS).

We are looking forward to a continuing interchange of information with you.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and Projections

HEC:gpa

Enclosure

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
CAMBRIDGE, MASSACHUSETTS 02139

SL / LABORATORY
BUILDING 31

December 12, 1975

Dr. Nicholas R. Moore
c/o Jet Propulsion Laboratory
Californai Institute of Technology
Pasadena, California 91103

ORIGINAL PAGE IS
OF POOR QUALITY

Dear Dr. Moore:

My copy of the J.P.L. report, "Should We Have a New Engine" has arrived. Thank you very much for arranging to have this sent to me.

Perhaps because I once had the duty of operating a Stirling pumping engine, I have given first reading to the material on this type of power plant and have several questions about it.

1. Power rating. The curve of Torque vs. speed is so similar to that of an Otto engine timed to give high torque in the lower speed range that I find it hard to justify the 20% lower power assigned to the Stirling. With optimum transmissions for both types, why should the maximum power ratings be so different?

2. Weight. Apparently the Stirling is given an aluminum block while the Otto is cast iron. Have I misread this one?

3. Friction. I have seen a number of swash-plate engines in my career, and they have all tended to have high friction due to the very heavy loading of the pads. I can't find any reference to, or allowance for, friction in the Stirling analysis.

4. Seals. Quote "Rollstock seals have been demonstrated for hundreds of millions of cycles" - Was this done under temperatures and pressures planned for the Stirling?

5. Variable Swashplate angles. My experience with this type of engine has indicated problems enough without such a complication added to an already complex and highly-stressed mechanism.

6. Safety. No mention is made of the danger of a large white-hot heater with open-flame burner and 3000 psi hydrogen in a crash. I should think these would be very bad company compared to the comparitively cool and inert mass of an Otto engine.

7. Reliability. The high efficiencies assigned to this type require heater elements made of highly specialized materials which are stressed close to their ultimate limits at all loads and speeds. Avoidance of failure will depend on extreme accuracy and reliability of the temperature control system. The Otto engine has nothing comparable. The gas turbine, of course, has such highly stressed parts, but at full load only.

I find no reference in these reports to the question of the profound influence of unit size on machine performance (See Vol. I, Chapter 11 of the I.C.E. in Theory and Practice). For example, substituting a 6-cylinder engine for a four of the same power (same piston area) will reduce the engine weight by 15% and substituting an eight for a four would reduce weight (and volume) by 30%. For the small cars, use of an eight would make the size and weight of engine comparable to that of a Wankel, but without the Wankel's poor fuel economy and durability.

I estimate the improvement in fuel economy by substituting an 8 for a 4 in a typical subcompact would improve the fuel mileage by 12%, on account of the reduced inertia weight and correspondingly smaller power (piston area) required. While it might be objected that this would be a costly change, I would estimate the cost as one or more orders of magnitude less than changing to a new type of power plant.

It was a pleasure meeting you and your associates at the D.O.T. conference.

With kind regards.

Sincerely,

C. Fayette Taylor

CFT:jt

45

Critique by

Volkswagenwerk AG
3180 Wolfsburg
Postfach, West Germany

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

RE: 34LPE-77-199-45

June 29, 1977

Messrs. W. H. Hucho and P. Walzer
Volkswagenwerk AG
3180 Wolfsburg
Postfach
West Germany

Dear Messrs. Hucho and Walzer:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

We appreciate your review and your comments on the subject report. Your observation regarding the European trend toward cars having lightweight Otto engines will be introduced into our follow-on work in which we are making comparisons against gas turbine cars. This work is being done in a restructured program summarized in the attachment.

Your assumption on operating the auxiliaries through continuously variable transmissions is a reasonable one it seems to us, and certainly has the effect of offsetting to some extent the advantage of the 2-shaft gas turbine over the Otto engine. We will also incorporate in our work on the horsepower sizing for alternate engines your suggestions regarding the ten second distance covered criterion.

We agree that scaling the Brayton engines to smaller sizes definitely presents technological problems associated with the relatively larger effects of leakages and manufacturing tolerances. These and related issues brought out in other critiques will be examined in appropriate Technical Task Summaries as mentioned in the enclosure.

We are pleased with the interest you have shown in the study and want to thank you for your valuable comments. We would welcome a continued interchange of information on automotive propulsion.

Sincerely,

H. E. Cotrill

H. E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:jms

Enclosure

Telephone 354-4321 Twx 910-588-3269 Twx 910-588-3294

77-40

VOLKSWAGENWERK

AKTIENGESELLSCHAFT

Volkswagenwerk AG, 3180 Wolfsburg, Postfach

Telefon: Wolfsburg (05361) Sammel Nr. 221 oder bei Durchwahl 22 und Hausapparat

Telex: 09 586 0 vw wd

Telegramme: Volkswagenwerk Wolfsburg

Postscheckkonto: Konto Nr. 1510-301 Hannover

Bankkonten: Commerzbank AG, Wolfsburg · Deutsche Bank AG, Wolfsburg · Dresdner Bank AG, Wolfsburg · Nordd. Landesbank, Braunschweig · Westd. Landesbank, Dusseldorf · Bayerische Vereinsbank, Munchen · Bayer. Hypo- u. Wechs.-Bank, München · Bank fur Gemeinwirtschaft, Wolfsburg · BHF-Bank, Frankfurt/Main

BY AIR MAIL

Mr. G. Nunz
Jet Propulsion Laboratory
California Institute of
Technology

Pasadena, California

U. S. A.

Ihre Zeichen	Ihre Nachricht vom	Unser Hausapparat	Unsere Zeichen	3180 WOLFSBURG
		22-4942	1778/drwa-se	May 25, 1976

Dear Mr. Nunz:

According to your statement at the last ERDA meeting in Ann Arbor, May 4-6, 1976, you want to collect critiques to your APSES report. In general we would like to compliment you for a very comprehensive and basic study. It is certainly a meaningful approach to compare alternative power systems under equivalent performance requirements as you have done.

We refer to the predictions given for the FT-gas turbine cars relative to the Otto engine cars. Although it is not easy to isolate instances where a complete disagreement exists, we want to express our concern about the following points:

1. <u>Car weight:</u>
   In your study Otto engine and FT-gas turbine cars have different weights. This results to a large extent from differences in the engine weights. Perhaps it would be more reasonable when studying the next 10 years to assume that the cars of your study can be powered by lightweight 4, 5, or 6 cylinder Otto engines instead of the present heavy 6 or 8 cylinder engines. This is already done today in Europe without sacrificing car performance. In doing so less weight advantage for the gas turbine car results than predicted in your study.

2. Engine power:

For future Otto engine cars one can assume that the auxiliaries will be driven via continously variable transmissions so that the power advantage from the smaller speed ratio of the FT-gas turbine is greatly offset. In addition if the gas turbine car has to cover the same 10 sec distance as the Otto engine car, the torque advantage of the FT-gas turbine is greatly offset by the initial response delay. From both results that equivalent car weights will need about the same engine powers with gas turbines and with Otto engines.

3. Fuel economy:

Getting good component efficiencies will be more difficult with smaller engine sizes and with larger tolerances which one has to visualize in a mass production. In this light we are concerned that some of your efficiency and loss assumptions cannot be obtained with the small engines considered. Such assumptions are the turbine efficiencies, the leackages of heat exchanger and labyrinths, the heat exchanger part load efficiency, and the heat losses through the engine housing and in the oil. We do not know how you have taken into account the auxiliaries, which become relatively more important with smaller engine sizes. Considering this, your predictions for the fuel economy especially in Urban driving cycles seem to be too optimistic.

In closing we want once more to express our appreciation for your report. We hope that by mentioning these points of concern we could be of some help for further refinement.

Sincerely yours
i.V. i.A.

Hucho Walzer

W.-H. Hucho P. Walzer

Critique by

Hydragon Corporation
1326 S. Killian Drive
Lake Park, FL 33403

and

Response by

46

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-194-46

June 29, 1977

Mr. Daniel J. W. McCarthy
Vice President, Administration
Hydragon Corporation
1326 S. Killian Drive
Lake Park, FL 33403

Dear Mr. McCarthy:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA) requested that we respond to your letter in accordance with the restructured JPL program described in the enclosure. At the time our study was in progress, we were unfortunately not aware of your research program of the Integrated Brayton-Rankine (IBR) engine. We appreciate the goals of your research program, and hope we may keep abreast of your progress to the maximum extent proprietary considerations permit. The applicability of the concept to automotive use is a primary interest, but we view the 2500°F uncooled ceramic turbine as a late 1980's development corresponding to "advanced" technology, as the term is used in the subject report.

Assessment of the Brayton-Rankine concept will be included in the follow-on program on alternative engine evaluation which is summarized as to content and schedule in the enclosure. We were pleased to receive your excellent paper on the IBE, and look forward to further discussions of its automotive applications.

Sincerely yours,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:jms

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

HYDRAGON CORPORATION

May 28, 1976

US Energy Research & Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N. W.
Washington, D. C. 20545

ATTN: Mr. R. Mercure

Dear Sir:

This is in response to your published request for input from industry and others to comment upon and update the "JPL Report" (SHOULD WE HAVE A NEW ENGINE, Jet Propulsion Laboratory, August 1975).

Hydragon Corporation has had an ongoing research program in small combined cycle technology in progress for the past five years which, until the present time, has not been publicized due to proprietary and patent considerations. The Company feels that its program may lead to a viable candidate for future automotive power, but was presumably not known to JPL investigators at the time of data compilation.

Therefore, in support of updating the JPL Report, enclosure (1), THE INTEGRATED BRAYTON-RANKINE ENGINE, is submitted as being of possible interest. Authorization to publish enclosure (1) is hereby granted, as requested.

Yours sincerely,

Daniel J. W. McCarthy
Vice President - Administration

Enc: (1) THE INTEGRATED BRAYTON-RANKINE ENGINE
Copy No. 3

1326 South Killian Drive • Lake Park, Florida 33403 • Phone 305 / 848-1066

Critique by

Ethyl Corporation
Automotive Research Division
1600 W. Eight Miles Road
Ferndale, MI 48220

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

47

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-191-47

June 29, 1977

Mr. W.E. Adams, Director
Automotive Research and Application
Ethyl Corporation
1600 W. Eight Miles Road
Ferndale, MI 48220

Dear Mr. Adams:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R. A. Mercure of the U.S. Energy Research and Development Administration (ERDA) requested that we reply to your letter in accordance with our restructured program as described in the enclosure. Regarding your lean burn work, your success in improving the fuel economy while reducing undesirable emissions and maintaining driveability and durability, demonstrates the potential value of this approach. We were aware of your work on lean burn systems and are familiar with the papers quoted in your letter. For the past four years JPL has performed research in lean-burn systems using gasoline-only and hydrogen supplemented gasoline fuel systems. Certain combinations of emission and fuel constraints could make lean-burn systems very attractive. The key issue is the NO_x standard, since 0.4 g/mi is not possible today with simple gasoline-only systems.

The several points that you brought up in your letter will be addressed in an appropriate Technical Task Summary. The enclosure summarizes the general content and schedule of our ERDA work. Your interest in the questions raised in the subject report is greatly appreciated. Work such as yours should help to make the ICE a long-term "alternate". We are looking forward to a continued interchange of information and ideas and thank you for your valuable comments.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:gpa

Enclosure

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

ETHYL CORPORATION
RESEARCH AND DEVELOPMENT DEPARTMENT · RESEARCH LABORATORIES
1600 WEST EIGHT MILE ROAD · FERNDALE, MICHIGAN 48220 · (313) 564-6940

May 27, 1976

U.S. Energy Research and Development Administration
Heat Engine Systems Branch
Division of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Attn: R. Mercure

We have noted that the U.S. Energy Research and Development Administration is soliciting information in order to update, expand, and correct the report, "Should We Have a New Engine?" We would like to bring to your attention the work we have been doing lately on a lean burn emission control system. To help describe the system and its operation, two technical papers are enclosed.

Our lean burn work began over ten years ago. This effort has involved the development of new carburetors, intake manifolds and various emission control devices but, in its present state, consists of relatively simple modifications of the conventional engine. The Turbulent Flow System includes a standard carburetor that is adjusted to furnish lean mixtures, the Turbulent Flow Manifold, and modified ignition timing for improved fuel economy and driveability. Exhaust gas recirculation may or may not be used, depending on the type of car and emission levels desired. For very low levels of hydrocarbons and carbon monoxide emissions, exhaust port liners and thermal reactors can also be added.

The paper, "Emissions, Fuel Economy, and Durability of Lean Burn Systems" describes the general system as applied to all size cars with emphasis on meeting present U.S. emission standards. The paper, "Emissions and Fuel Economy of the Turbulent Flow System for European 4-Cylinder Engines" describes work primarily performed on the smaller, European-type engines. Both papers were delivered before the Society of Automotive Engineers this year.

The advantages of this system are its simplicity and its compatibility with gasoline containing tetraethyllead. Because of this, higher compression ratios and/or greater amounts of spark advance may be used to take advantage of the higher octane number quality of leaded gasolines. This results in better fuel economy and more miles per barrel of crude oil than can be obtained using systems requiring nonleaded gasoline.

The system has been applied to 28 different cars of various sizes and makes. It has been possible to adjust emission levels to those desired for any particular location, including those of the European Economic Community and the very stringent standards of the state of California. Fuel economy of all vehicles has been excellent.

Of high importance has been the good durability of the system and the consistent control of emissions over long mileage. This is shown by the data obtained during a 50,000-mile durability test of a car equipped with the Turbulent Flow System plus exhaust port liners and thermal reactors which resulted in emissions well below the level of the 1976 standards for California. This test is reported in the paper, "Emissions, Fuel Economy and Durability of Lean Burn Systems." The test has continued and the emissions have remained remarkably consistent for over 85,000 miles. The car is continuing to accumulate mileage.

I hope you will find these technical papers of interest. If you have any questions or comments after reviewing this material, please contact us.

Sincerely,

W E Adams

W. E. Adams, Director
Automotive Research and Application

WEA:js
Enclosures

cc: (w/o Encs.)
Messrs. H. J. Gibson
H. E. Hesselberg

Provides good mixture distribution with good driveability — with good fuel economy.
Biggest advantage (assuming 1.5 NOx on a production basis; 0.7 NOx low end of tolerance) is the durability without the catalyst and using leaded gas.

Critique by

A. C. Sampietro
PO Box 2482
Delray Beach, FL 33444

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

48

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-195-48

June 29, 1977

Mr. A. C. Sampietro
Consulting Engineer
P.O. Box 2482
Delray Beach, FL 33444

Dear Mr. Sampietro:

SUBJECT: Critiques of JPL Report SP43-17, "Should We Have a New Engine?".

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded your letter to us for reply as explained in the attachment. During preparation of the subject report we were not aware of your interesting work regarding modifying the standard compression ignition engine in order to improve efficiency while reducing exhaust pollutants. We would like to consider your ideas in follow-on evaluations of alternative engines that we are conducting for ERDA as summarized in the enclosure. We would appreciate receiving from you as much non-proprietary detail on the engine modification as possible.

We appreciate the interest in the subject report and your desire to contribute a solution to the problems of automotive engine performance, economy, and emissions.

Sincerely,

Harry E. Cotrill, Project Manager
Automotive Technology Status and
Projections

HEC:gpa

Enclosure (1)

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

A. C. SAMPIETRO
Consulting Engineer

P. O. BOX 2484
DELRAY BEACH, FLORIDA
33444

May 20, 1976.

To the
U.S.Energy Research and Development Administration,
Heat Engine Systems Branch,
Division of Transportation
Energy Conservation
20 Massachusetts Ave.,N.W
Washington D.C. 20 545   attn. Mr. R. Mercure.

Gentlemen,

With reference to your note at page 60 of the May 1976 issue of Automotive Engineering, you may be interested in the following infor mation, as it may help you evaluate future possibilities.

Before retiring at 65, I was running power train research at Ford,s, and a few months prior to leaving my position I had the germ of an idea on how to civilize the compression ignition engine, by smoothing it out, doing away with the Diesel knock, controlling and possibly preven ting the formation of the NOx. Pressure of day-to-day work, we were developping the catalytic convertor, and the unfurtunate fact that I had to have eyes surgery prevented me from doing anything about this project at the time. After retirement, and frr from daily worries, I worked out the project in some details, suggesting how to modify the Ford 460 c.ins. engine, so that when fitted into the Lincoln, the fuel consumption would be of the order of 22MPG., with practically no exhausteemissions, and a performace as good as it was in 1968, except for top speed that would be decreased to 90-100 MPH. Most of this is described in patent applica tion 43 179/73 (int. conv.) If you are interested you could ask the Ford Motor CO., for copy of this specification. I have the original, but as I promised to assign it to Ford, I feel it would be more courteous for you to ask the Company.

Working on this project, I started to consider what happens to the working fluid in a heat engine, what limits the efficien cy, and what causes pollution, and I came up with a second, different and more radical, and applicable to many forms of heat engines. Finally after years of work I can suggest how to design engines that will:

* Give much higher efficiencies than current.My calculations show that efficiencies of the order of 50% are feasible, and as high as 58% in turbo charged compression ignition engines. This represent a conside rable potential, and would help solve our oil problems.

* Control the NOx and other pollutant to whatever level is desired.

* The modified engines can be built on existing facilities.

* The engines will be no heavier, and more compact than current prectice.

These modifications are specially attractive when applied to large power units, including gas turbines because of the considerable fuel saving afforded.

* As far as I know these modifications are the only method that will permit large cars to be built when the stringent fuel consumption limits of the 80s come in force, and the production of large cars may be neces sary to the economical well being of our Nation.

Some of my friends arranged for a separate consulting group to analyse the key-sub system,and as the report was favourable they are arranging to have the sub-system built.

I have applied for patent protection under the internati onal convention, and you are welcome to a copy of the specification if you are interested: later I would be happy to give you copy of various reports on the subject.

Very truly yours

A. C. Sampietro

A.C.Sampietro

Critique by

Erwin Automotive Plant
Advanced Engine Components Department
Corning Glass Works
Corning, NY 14830

and

Response by

Jet Propulsion Laboratory
Pasadena, CA 91103

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

RE: 34LPE-77-200-49

June 29, 1977

Mr. John G. Lanning, Manager
Advanced Engine Components Department
Erwin Automotive Plant
Corning Glass Works
Corning, N.Y. 14830

Dear Mr. Lanning:

Subject: Critiques of JPL Report SP43-17, "Should We Have a New Engine?"

Mr. R.A. Mercure of the U.S. Energy Research and Development Administration (ERDA) forwarded your letter on Corning's CERCOR ceramic regenerator core prices to us for response. This is in accord with our work statement and follow-on program as described in the attachment.

The point that we intended to make in the subject report was that for a variety of reasons, the unit cost of equipping a fleet of long-haul trucks with turbines was about double the original estimate. Furthermore, the warranty problems were severe enough to cause the Ford Motor Company to replace the turbines with diesel engines. This example was used to illustrate a likely consequence of inadequate assessment of the readiness of new technology. Clearly, a realistic evaluation is essential, along with a well planned long-term development program that includes contingency planning.

We regret that our brief reference to the cost-rise situation may allow the reader to infer that Corning was responsible for the cost increase of the ceramic regenerator cores. To put us in a position to take appropriate corrective action, Mr. R. Heft of this Laboratory is planning to resolve this cost question directly with Corning. At the appropriate point in our recently initiated work for ERDA, we plan to clarify gas turbine costs in a Technical Task Summary, and we hope to include substantive information from Corning and other sources. Our current work for ERDA, including the generation of Technical Task Summaries, is summarized in the enclosure.

Telephone 354-4321 *Twx 910-588-3269* *Twx 910-588-3294*

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

We appreciate the interest you have shown in the subject study, and we are looking forward to a continuing interchange of information relating to automotive technology.

Sincerely,

H.E. Cotrill, Project Manager
Automotive Technology Status
and Projections

HEC:cr

Enclosure

CORNING

Ceramic Products Division
Automotive Products Dept.
Corning Glass Works
Corning, New York 14830
Tel 607-974-9000

July 23, 1976

Mr. R. Mercure
U. S. Energy Research & Dev. Adm.
Heat Engine Systems Branch
Div. of Transportation Energy Conservation
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

Dear Mr. Mercure:

I am writing with regard to the JPL report "Should We Have A New Engine" Volume II Technical Reports.

Page 15-8 Section 15.4 states: "Major cost items that were vended included the two large ceramic rotating regenerator discs that Corning Glass quoted for low volume production at $700-$800 apiece..." - and - "During the production" run, there were significant problems in the yield of the regenerator discs, and as a result Corning raised the price from $700 to $1400.".

I assume this information came from Ford. It certainly did not come from Corning, and to my knowledge there was no contact between JPL and Corning.

CERCOR® ceramic regenerator core prices quoted by Corning to Ford or other customer are predicated on volume, delivery time span and initial delivery date requirements. The actual prices paid for Corning cores by Ford during 1971-1973 reflect changes made by Ford in specifications and reductions in volume requirements versus delivery time spans.

The documents covering pricing are available for discussion with JPL personnel should they desire to pursue the question.

I do feel that Corning was unjustly cast in an unfavorable light on Page 15-8. I would like to have this corrected based on the facts.

Thank you for your interest.

Sincerely yours,

John G. Lanning, Manager
Advanced Engine Components Dept.
Erwin Automotive Plant

jl:rh

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