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# AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

Quarterly Technical Progress Report  
October 1977 — December 1977

Ford Motor Company  
Dearborn, Michigan 48121

Prepared for the  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Lewis Research Center  
Cleveland, Ohio 44135

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As a part of the

**DEPARTMENT OF ENERGY**  
Division of Transportation Energy Conservation  
Heat Engine Highway Vehicle Systems Program

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ADDENDUM

The second Stirling Engine Quarterly Report (January-March 1978) was incorrectly numbered. The old number, CONS/4396-1 NASA CR-135331, should be changed to:

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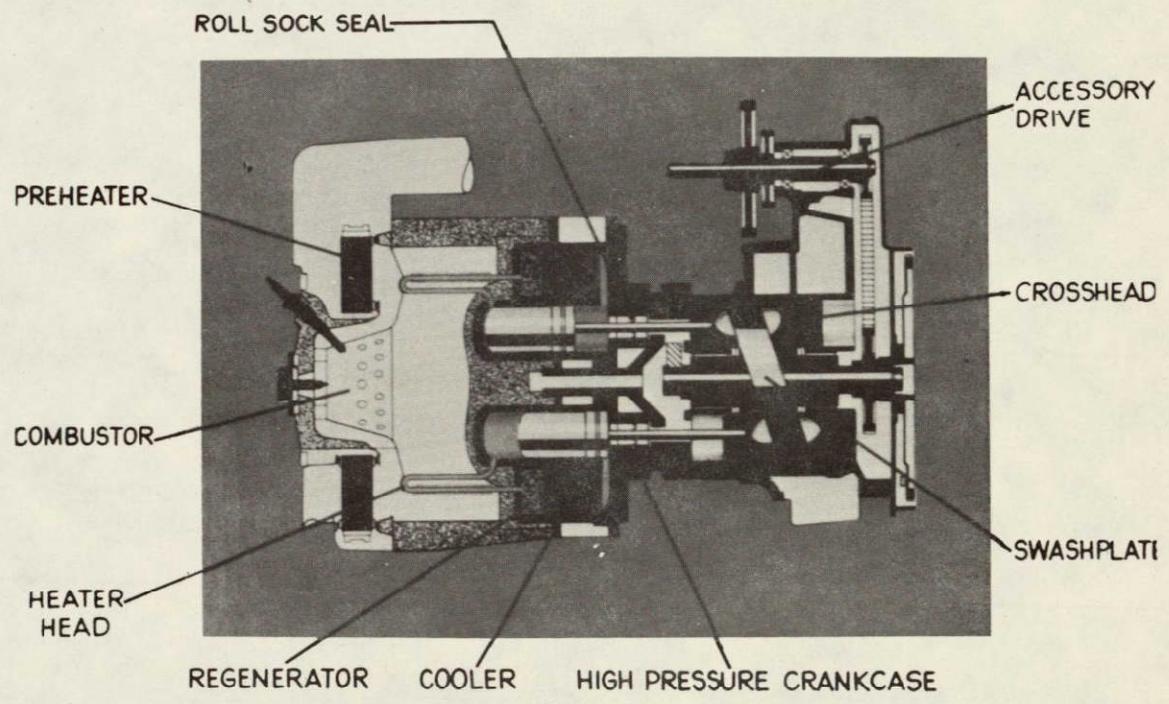
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# 4-215 STIRLING ENGINE



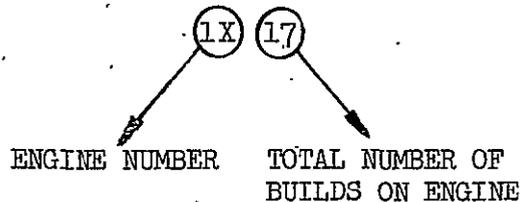
## SECTION 1

### EXECUTIVE SUMMARY AND INTRODUCTION

#### I. EXECUTIVE SUMMARY

This report covers the first 3 months effort of the Ford/DOE Automotive Stirling Engine Development Program, specifically Task I of that program which is Fuel Economy Assessment. At the beginning of this contract effort (September 19, 1977) the projected fuel economy of the 4-215 Stirling engine was 21.16 MPG with a confidence level of 29%. Since that date, the fuel economy improvement projection of the 4-215 Stirling engine has been increased to 22.11 MPG, with a confidence level of 29% (refer to the Fuel Economy Assessment Chart located in sub-task 06, Fuel Economy Analysis).

Collection of fuel economy improvement data is directly related to engine durability. During the first 3 months of this program, engine durability has been limited (refer to Engine Durability Upgrading, sub-task 07). Since September 19, 1977 a total of 47.7 hours of engine running time has been accumulated using two engine builds, engine 1X17 and 3X16. These numbers represent the following:



Engines may be disassembled and reassembled for various reasons such as inspection purposes, installation of instrumentation equipment, protection equipment, failures, etc. Whenever an engine is reassembled, the second two digits are increased by one, signifying a new engine build. Thus, engine 1X17 will become 1X18.

The following is a summary of the individual sub-tasks of Task I, Fuel Economy Assessment. Sub-tasks in this summary are grouped into two categories. The first category consists of those sub-tasks which are directly related to fuel economy. The fuel economy improvement contributions of each individual sub-task are measured against the original estimates established at contract start. The second category consists of those sub-tasks which are not directly related to fuel economy but are an integral part of the Task I effort.

#### CATEGORY 1

##### Mapping and Optimization - Sub-task 01.

Engine 1X17 was installed on the dynamometer for the purpose of establishing repeatability and baseline data. A total of 23.5 hours was accumulated on this engine before the failure of #3 crosshead at the rear retaining groove. Nine data points were taken before the failure.

Engine 3X16 was then installed in the test cell and has run a total of 24.2 hours. Problems developed preventing significant data collection.

The assessed fuel economy improvement contribution of Mapping and Optimization, sub-task 01, remained unchanged at 0.38 MPG (gasoline).

#### Burner System - Sub-task 02

Hardware for the two test rigs (Engine Simulator and Atmospheric Burner) has been ordered.

Fabrication of the impingement jet burner has been completed.

The assessed fuel economy improvement contribution of Burner System, sub-task 02, remained unchanged at 0.15 MPG (gasoline).

#### Preheater Development - Sub-task 03

The engine driven preheater design has been completed. Another preheater design has been completed which includes changes that will increase the flow area to the swirler of the burner, thereby improving combustion. This preheater has been assembled and the reworked burner carrier has been installed.

The preheater test rig has been designed and built. After rig checkout was completed, the original preheater was installed. Torque measurements and temperature readings were taken to assure that the rig was simulating "real" operating conditions.

The assessed fuel economy improvement contribution of Preheater Development, sub-task 03, remained unchanged at 0.16 MPG (gasoline).

#### Engine Drive Study - Sub-task 04

A computer program was written which calculates the bearing loads in a crankshaft type Stirling engine as a function of crank angle. This program allows for the differential gas pressure acting on the engine pistons, reciprocating mass inertia, and the rotating inertia of the connecting rods, calculating the resulting forces on the wrist pin, journal, and main bearings.

An analysis evaluating the fuel economy improvement resulting from mechanically driving the fuel and air atomizing pumps was completed. The improvement was approximately 0.27 MPG in the metro-highway cycle.

A piston ring test rig was designed and built which will determine the friction drag on the piston rings currently being used in the 4-215 Stirling engine. This rig was found to produce excessive vibration within the engine's speed range. Measures have been initiated to correct this situation.

The assessed fuel economy improvement contribution of Engine Drive Study, sub-task 04, has been increased from 0.39 MPG to 0.66 MPG (gasoline).

#### External Heat and Blower System - Sub-task 05

Blower airflow requirements for the reference engine (4-247) have been established. A consultant was retained to assist in designing a blower best suited to those requirements.

Several types of blower drives have been considered. These drives will result in total blower power savings because the resulting blower speed is closer to the maximum required speed.

A preliminary design for a variable speed blower has been completed. This blower requires an electric motor which serves the dual purpose of driving the blower during start-up and working in conjunction with the engine belt drive to the blower, increasing the blower/engine speed ratio at low engine speeds.

The assessed fuel economy improvement contribution of External Heat and Blower System, sub-task 05, remained unchanged at 0.19 MPG (gasoline).

#### Power Control - Sub-task 08

The test run on the hydrogen control valve indicates the suitability for another type of valve in this application. The hydrogen control valve will be redesigned to increase reliability.

Work on the hydrogen compressors will consist mainly of evaluating the power required to drive these compressors. A test rig, as well as dynamometer testing, will be used for this evaluation. Hardware for test rig installation has been ordered.

The assessed fuel economy improvement contribution of Power Control, sub-task 08, remained unchanged at 1.20 MPG (gasoline).

#### Air/Fuel Control - Sub-task 09

The fuel metering computation circuit of the dynamometer air/fuel control was updated by adding non-linear gain computation. The circuit will now compensate for the non-linear response characteristics of the Vortair air flow sensor.

A logic circuit for automatically positioning the exhaust gas recirculation (EGR) valve was added to the dynamometer cell engine cooling system.

The assessed fuel economy improvement contribution of Air/Fuel Control, sub-task 09, remained unchanged at 0.23 MPG (gasoline).

#### Cycle Analysis - Sub-task 10

A number of reduced power optimizations were run using the programs written by N. V. Philips. These optimization runs resulted in engines designated the 4-270, with a design speed of 2525 RPM, and the 4-204, with a design speed of 4000 RPM (same as the baseline 4-215).

These programs were also used for part-load calculations. Beginning with essentially the same starting conditions as the previous reduced power optimization attempts, new designs were initiated which required indicated efficiency to be maximized at either the maximum torque (MP) point or the metro-highway (M-H) composite point. The "best" engine to date, using this procedure, is the 4-247.

Tests were conducted to determine the potential fuel economy improvements if thermal losses were reduced. This was accomplished by reducing the thickness of the cylinder and regenerator-cooler walls. No stress analysis tests are being run, however, at this time.

The assessed fuel economy improvement of Cycle Analysis, sub-task 10, remained unchanged at 2.38 MPG (gasoline).

#### Other Fuel Economy Improvements - Sub-task 14

A new sub-sub-task, "Deceleration Fuel Shut-Off," has been added to this sub-task since the original proposal of May, 1977.

A study of "Methods to Reduce Conduction Losses" was initiated (refer to sub-task 10, Cycle Analysis).

The assessed fuel economy improvement contribution of Other Fuel Economy Improvements, sub-task 14, has been increased from 0.39 MPG to 1.00 MPG (gasoline). This increase is due to the addition to Deceleration Fuel Shut-Off.

It should be noted that the assessed fuel economy improvement of this sub-task is based strictly on estimates that have not been investigated. When a proposed idea is considered ready for investigation, it will be moved to its applicable sub-task. At this point the assessed fuel economy improvement will also be transferred to the applicable sub-task, lowering the fuel economy improvement estimate of this sub-task. Accordingly, when new items are added to this sub-task, the fuel economy improvement estimate of this sub-task will increase.

#### Cooling System Analysis - Sub-task 15

Two transparent flow models of the internal cooling system have been designed. The first model, which will replicate the cooling system in the vicinity of the cylinder and regenerator-cooler walls, is being fabricated. Quotes are being received on the second model which will replicate an area of the cooling system in the vicinity of the piston rod seals.

The assessed fuel economy improvement contribution of Cooling System Analysis, sub-task 15, remained unchanged at 0.06 MPG (gasoline).

#### Fuel Economy Analysis - Sub-task 06

Computations of dynamometer engine constant volume sampling hot (CVS-H) and Environmental Protection Agency - Highway (EPA-HWY) time weighting at selected speed/load (mapping) points were completed using the chassis dynamometer road load equations, with and without allowances for air conditioning. This information will permit fuel economy projections of vehicle chassis roll tests using engine dynamometer test data.

#### Total Fuel Economy Assessment:

The assessed fuel economy improvement contribution of the fuel economy related sub-tasks is 6.41 MPG (gasoline). The total fourth generation fuel economy projection is 22.1 MPG (gasoline) with a confidence level of 29% (see figure 1).

#### CATEGORY 2

#### Engine Durability Upgrading - Sub-task 07

Presently, engine durability has been limited. The main contributor to engine failure has been the sealing system. An accelerated sealing system program is under way.

Installation of the crank drive sliding seal test rig is 80% complete. Additional personnel have been assigned to the piston rod seal program in an effort to reach an early solution.

Work on the sealing system is concentrating on both the rollsock seal and sliding seal system. Two test rigs for the piston rod rollsock sealing system, one crank drive and one swashplate drive, have been designed. Parts for both rigs have been ordered and some of the rollsock test rig parts have been received.

Two protection devices were installed on engine 1X17. The first device was a continuous reading smoke detector for exhaust gas monitoring. The second device was a feature which was added to the rollsock protection device. This device is designed to protect against surges in pressure differential across the rollsock.

A total of 23.5 hours was accumulated on engine 1X17 before the failure of #3 crosshead. Nine data points were taken before the failure occurred.

Engine 3X16 was then installed in the test cell and has run a total of 24.2 hours. However, the CO emissions measuring equipment created several problems. These problems have prevented the accumulation of a significant number of data points.

#### Responsive Support - Sub-task 11

A publication was prepared for the Highway Vehicle Systems Contractors' Coordination Meeting which was held at the Hyatt Regency Dearborn Hotel in Dearborn, Michigan on October 4, 5, and 6, 1977.

#### Contract Support - Sub-task 12

Three Monthly Technical Progress Narrative Reports have been prepared and distributed to date.

#### Reference Engine - Sub-task 13

No progress was made on this sub-task during this reporting period.

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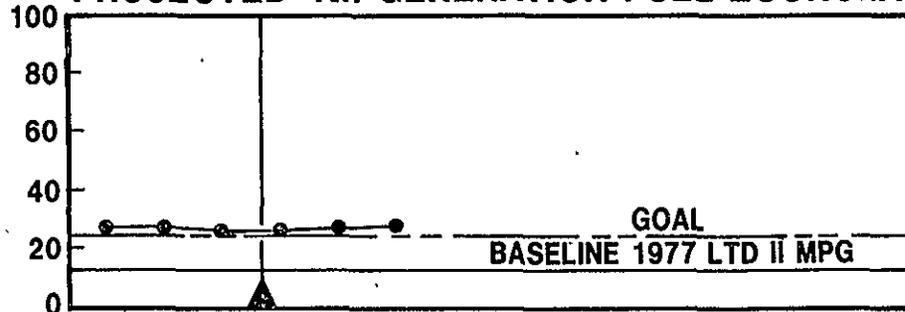


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# ACHIEVEMENTS — FORD IMPROVED STIRLING PROGRESS

## PROJECTED 4th GENERATION FUEL ECONOMY

FUEL ECONOMY MPG  
METRO HIGHWAY FROM  
CVS-CH GOV. TEST  
TEST PROCEDURE  
4500 LB.  
INERTIAL WEIGHT



## CONFIDENCE LEVEL FOR ACHIEVING 20.6 MPH GOAL

CONFIDENCE  
LEVEL  
%

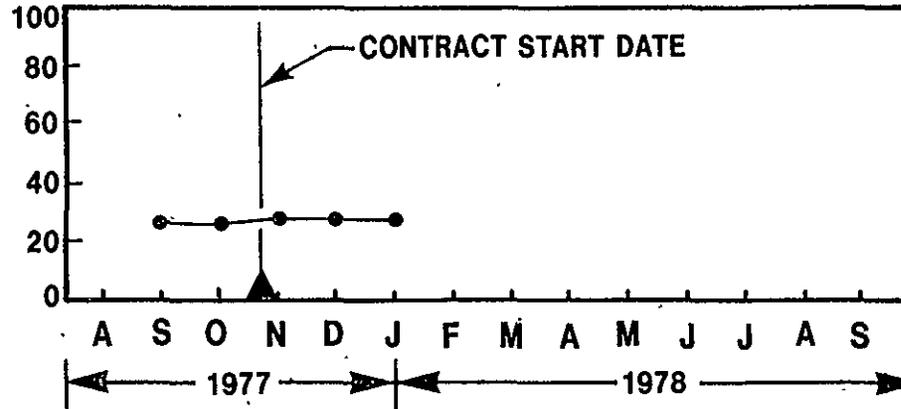


FIGURE-1

## II. INTRODUCTION

This report is the first in a series of quarterly reports designed to detail the progress of the Ford/DOE Automotive Stirling Engine Development Program. Therefore, some of the information contained in this report such as Background and Present Contract will not reappear in future quarterly reports. This program is funded jointly by Ford Motor Company and the United States Department of Energy (DOE) under contract number EC-77-C-02-4396 which was effective September 19, 1977. The Department of Energy has delegated project management responsibility for this contract to the NASA-Lewis Research Center in Cleveland, Ohio.

The Automotive Stirling Engine Program is directed toward establishing the technological and developmental base that would enable a decision on whether an engineering program should be directed at Stirling engine production. Such engines are believed to provide an attractive alternative for meeting national needs related to fuel consumption and environmental protection. For example, the fuel economy of a Stirling powered automobile is estimated to be nominally 30% greater than that of a 1977 spark ignition engine powered automobile of equivalent size, weight, and performance. It is estimated that the Stirling engine powered automobile will also meet the 1976 standards set forth in the Clean Air Amendments of 1970.

The program is divided into twelve overlapping Tasks which are shown in figure 2. Four of these Tasks are directed toward the iterative development of the Stirling Engine System via a series of engine "generations".

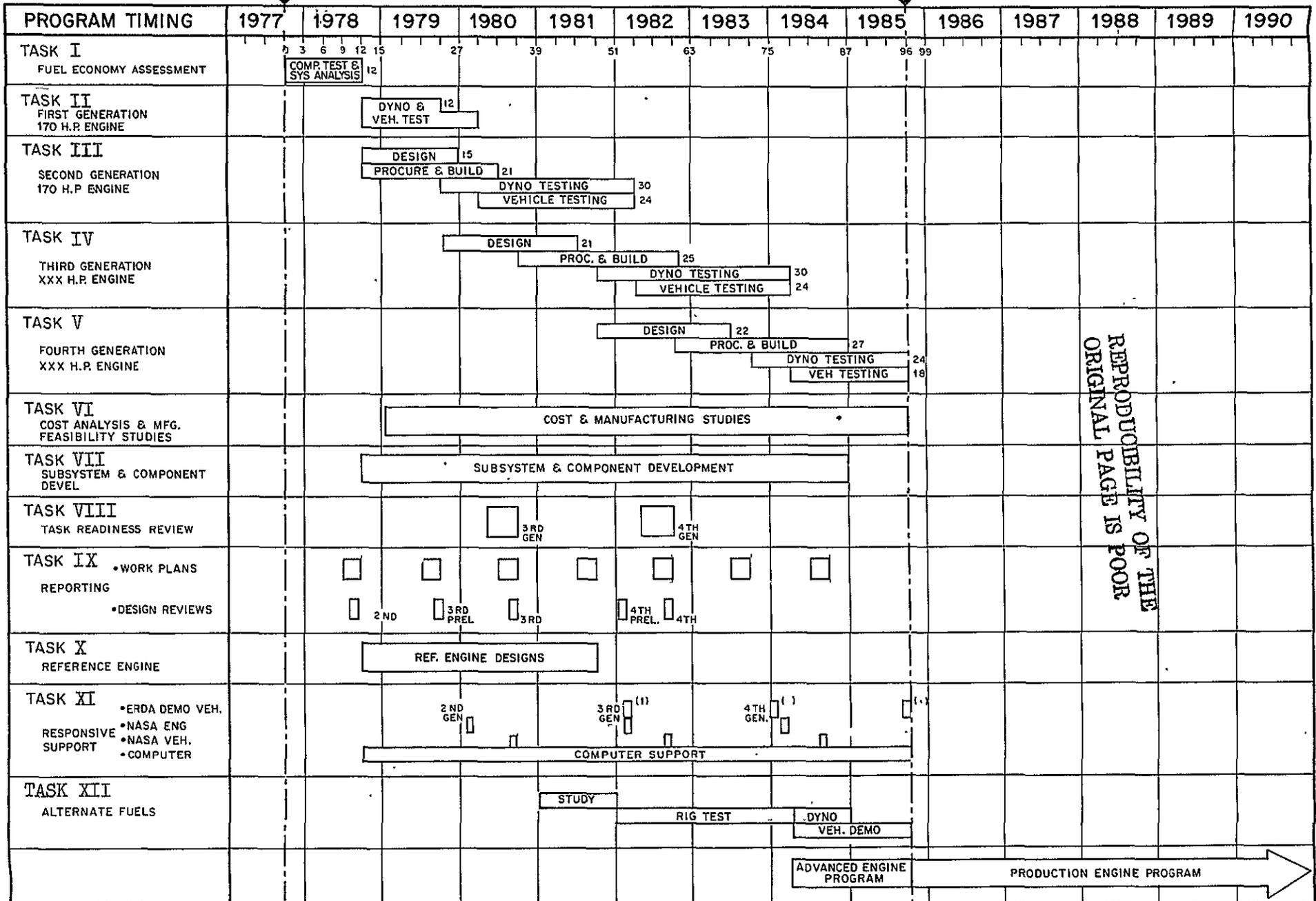
Task I covers the first year's effort of the program. The objective of this Task is to perform certain analyses and component development work for the purpose of determining whether the fuel economy objective established for the Fourth Generation Stirling engine (30% improvement) can be achieved. To accomplish this objective durability upgrading of the current Stirling engine is required.

Specifically, Task I, Fuel Economy Assessment, is directed at achieving, with a high degree of confidence, the May 12, 1977 ERDA proposal estimate of 20.6 MPG (gasoline) for a 4500 lb. IWC Stirling engine powered passenger car. The current M-H fuel economy projection for the 170 HP Stirling engine is 15.7 MPG (gasoline). The confidence level for this projection today is 32%. A confidence level of 29% is projected for a 22.1 MPG (gasoline) estimate. If, at the end of the one year effort all of the planned analyses and test work is accomplished, and the projected improvements are substantiated, the confidence levels would rise to 59% for the 20.6 MPG projection and 54% for the 22.1 MPG estimate. The progress thus far achieved during this fuel economy assessment task is shown in figure 1.

# AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

OCT. 1, '77  
START

STOP SEP. 30, '85



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DATES LISTED ARE CALENDAR YEARS

FIGURE - 2  
1-8

## SECTION 2

### BACKGROUND

#### I. GENERAL

For many years Ford Motor Company has been active in a variety of programs to investigate the potential of using engines other than conventional internal combustion (IC) engines in automotive applications. In late 1970 a meeting was held with N. V. Philips Gloeilampenfabrieken of the Netherlands to discuss their progress in the development of Stirling cycle engines. Philips is a major producer of electrical and electronic equipment. Philips originally started work on the Stirling engine as a power source for electrical generator sets in 1938. The development of Stirling engines has continued since that time with a variety of applications ranging from torpedo propulsion to space power.

The Stirling engine has certain inherent qualities which make it an attractive candidate for automobile application. It is an external combustion engine and therefore has multi-fuel capability. Because of its controlled continuous combustion, the Stirling engine lends itself to improved fuel economy, a goal Ford Motor Company had been actively pursuing prior to 1973 when the need for energy conservation became evident. However, it appeared that a Stirling cycle engine was too heavy and complex for passenger car application and that nitrogen oxide (NOx) emissions were excessive. N. V. Philips Laboratories had been working actively to solve these problems and at their meeting with Ford in 1970 provided evidence to show that solutions were possible.

#### II. FORD-PHILIPS PROGRAM

With the possibility of solving the problems of size, weight, complexity, and emissions, Ford Motor Company entered and funded a program with N. V. Philips to investigate the applicability of a Stirling engine designed specifically to replace the 351 CID IC piston engine in the Ford Torino intermediate size passenger car. The objectives of this program were:

- . To demonstrate Stirling engine emission capabilities
- . To determine packageability in a vehicle
- . To predict vehicle performance and fuel economy
- . To identify major problems as a basis for further efforts

Two versions of the Stirling engine were investigated at the start of the program, a one-cylinder Rhombic drive engine, and a four-cylinder double acting swash-plate drive engine. Both engine configurations were subjected to a detailed design study to determine the most suitable Stirling engine for passenger car propulsion.

When Ford and Philips began the Stirling program in 1971, each company assumed specific tasks:

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FORD:

- . Provide specifications for engine design
- . Conduct vehicle package studies
- . Project vehicle performance and fuel economy
- . Design accessory systems
- . Provide customer acceptance criteria

PHILLIPS:

- . Design and build engines
- . Provide engine drawings to Ford
- . Conduct simulated CVS emission tests
- . Provide basic engine performance and specific fuel consumption data
- . Furnish information on general engine operating characteristics.

Performance and fuel economy projections were made using Ford Motor Company computer programs and fuel consumption maps furnished by Phillips. The maps included all losses for auxiliaries, accessories, fans, etc. The baseline car was a 1972 Ford Torino with a 351 CID engine without emission controls. Both cars were equipped with automatic transmission, power steering, power brakes, air conditioning, and radio. The test weight of the baseline car included an allowance for future safety, damageability, and emission equipment.

The performance of the Stirling car was essentially equal to that of the baseline car, illustrating the similarity between the performance characteristics of the Stirling and conventional IC engines.

During this program, two 1975 Ford Torinos were selected for Stirling engine installation. Because the Stirling engine was considerably longer than the 351 CID engine it replaced, some vehicle modifications were required. These modifications consisted of the following:

- . Some modification of the underbody was made at the dash panel for transmission and exhaust system clearance.
- . Major front-end revisions were made to accept the larger radiator.

- . Cooling louvers were added to the hood and holes were placed in the bumper to allow air flow through the radiator.
- . Three frame crossmembers were modified.
- . A new radiator was designed and installed which would provide twice the coolant volume of the original baseline vehicle radiator.
- . A new high output water pump was installed.
- . A variable thermostat for heating the passenger compartment was developed and installed.
- . The front suspension was slightly modified to provide clearance for the revised frame crossmembers.
- . The driveshaft was shortened and the axle pinion angle changed.
- . A vacuum pump was added to the vehicle to power some accessories (heating and air conditioning system). (The Stirling engine provides no engine vacuum).
- . A hydroboost (hydraulic power) brake system was added to replace the vacuum powered brake system.
- . A revised mechanical shift linkage was used on the transmission.
- . A single exhaust pipe (without muffler or catalytic converter) was installed.
- . Modified sending units and an electric fuel pump were added to the fuel system.
- . The power steering pump was revised to supply power to the hydroboost power brake system.
- . A 94 Ampere hour battery and a 105 Ampere alternator were installed.
- . A completely automatic electronic control system was added.

At the same time that Ford was modifying these vehicles, N. V. Philips was testing several 4-215 engines; two of which would ultimately be installed in the two vehicles. The Torinos were sent to Holland and the engines were installed. One of the two Stirling engine powered Torinos was returned to Ford Motor Company on October 10, 1975. In addition, one complete engine for dynamometer testing and assorted spare parts were received.

Fuel economy of the Stirling car was compared with the baseline Torino under two conditions: the baseline engine at 1970 emission levels, i.e., no loss in fuel economy due to emission treatment; and the baseline engine at future emission levels, with an estimated loss in fuel economy of 15%.

At a cruising speed of 70 MPH, the Stirling economy was projected to be 9% better than the 1970 baseline economy, and 28% better than the derated baseline economy. Customer average projections showed a 16% advantage in the economy of the Stirling engine over the 1970 engine and 37% over the derated baseline engine.

### III. ERDA 80-100 HORSEPOWER FEASIBILITY STUDY

Because of the knowledge and experience Ford gained during this program, a contract between Ford Motor Company and the U. S. Energy Research and Development Agency (ERDA) was initiated to conduct studies of an automotive Stirling engine. The contract included two tasks. Task I was to report information obtained from the Ford funded development program of a 170 horsepower Stirling engine-powered intermediate size vehicle; and Task II was an initial design study of an 80-100 HP Stirling engine for a compact vehicle. Task II of this contract was funded by ERDA, under contract number EY-76-C-02-2631.001M.

The objectives of Task II were those listed in Table 2-1.

TABLE 2-1

#### 80-100 HP STIRLING ENGINE POWERED VEHICLE OBJECTIVES AND PROJECTIONS

<u>Criteria</u>	<u>Baseline*</u>	<u>Objective</u>	<u>Projection</u>
Emissions (HC/CO/NOx)	.9/9.0/2.0	0.2/1.7/0.2	0.1/1.7/0.3g/mile**
Fuel Economy (Metro-Hwy.)	25.1	30.1	25.5 MPG***
Fuel Economy (30-70 MPH avg.)	29.4	-	33.0 MPG
Performance (0-60 MPH)	15.2	16.5	16.3 seconds
Noise Level (SAE J986a)	80	70	70 decibels
Cold Engine Start-up Time	1	15	15 seconds

\* The baseline car was a 1976 Ford Pinto with a California emission package, powered by a 2.3 liter engine with automatic transmission.

\*\* At low mileage.

\*\*\* Proposed design changes were being considered for the 170 HP Stirling engine that were expected to result in a 30% fuel economy improvement for that engine. The extent to which these changes could be applied to the smaller Stirling engines was unknown. Our best estimate was that a 20-25% improvement over the baseline Pinto would result.

A report (G00/2631-22) covering this program is now available from the National Technical Information Service, U.S. Department of Commerce.

The results of Task II of this contract were as follows:

- a. The Stirling engine could be downsized from the 4-215 size for smaller automobiles such as the Pinto, but the swashplate drive concept tended to result in an engine that was longer in dimension than an IC engine of equivalent power.
- b. The 4-98 (four-cylinder, 98 cc per cylinder) Stirling engine could be packaged into a 1976 Pinto if changes were made to the sheet metal. However, no major changes to the front suspension, steering, or drivetrain were required.
- c. Other drive concepts (crank type), although only explored on a preliminary basis, seemed to offer packaging advantages over the swashplate design.
- d. The projected weight of the 4-98 Stirling engine installation would have been approximately 76 pounds heavier than the 2.3 liter IC engine installation. It is believed that this difference could have been reduced through a weight reduction program.
- e. Low mileage emissions of one half of the level specified in the 1970 Clean Air Amendments (0.20 g/mile HC, 1.7 g/mile CO, 0.20 g/mile NOx) were projected.
- f. The projected performance (0-60 MPH acceleration time) was equivalent to the IC engine vehicle performance.
- g. The projected metro-highway fuel economy, with the state of art design restraints for the Stirling engine which existed at that time, was the same or approximately 3% better than the 1976 2.3 liter Pinto, depending upon the emission calibration. However, this equivalent fuel economy was, of course, at a much lower emission level.

## SECTION 3

### TASK I, FUEL ECONOMY ANALYSIS

#### I. GENERAL

Task I of the Automotive Stirling Engine Development Program has been divided into fifteen sub-tasks. Twelve of these sub-tasks are directly related to fuel economy. The remaining three sub-tasks are: sub-task 11, Responsive Support; sub-task 12, Contract Support; and sub-task 14, Other Fuel Economy Improvements. Each of the 15 sub-tasks will be reported on individually.

#### II. REPORT FORMAT

Each sub-task consists of several separate but related operations which are listed as sub-sub-tasks. The report for each sub-task is as follows:

- a. A timing chart of the sub-task which contains the following information (see Example Timing Chart).
  1. A horizontal bar(s) which appears to the right of the respective sub-sub-task.
  2. Target deadlines which are represented by circles and located along the bar. The dates of these deadlines are shown by the calendrical scale which appears at the top of each chart. At the end of each quarter, the bars are shaded according to the amount of progress made during that quarter.
  3. At strategic locations along these bars circles appear which contain one of the letters E, A, C, or D. The letters represent the following:
    - a) E = Estimate. This estimate represents the fuel economy improvement estimate which existed for that particular sub-sub-task at the beginning of the contract (September 19, 1977).
    - b) A = Theoretical Analysis. A theoretical analysis will be assigned to selected sub-sub-tasks during the Task I effort.
    - c) C = Component Test. Certain sub-sub-tasks interpret into actual component parts of the Stirling engine system (SES). In this case, after a theoretical analysis is performed and results indicate a measurable improvement in fuel economy, this component will be bench or rig tested. If these results reinforce the results of the theoretical analysis, then the component will eventually be tested on the dynamometer.
    - d) D = Dynamometer Engine Test. This is the last phase of component testing in regard to fuel economy improvement. At this point, the component will be ready for installation on the reference engine.

These letters are used in conjunction with the individual fuel economy assessment charts which appear at the bottom of each timing chart. The individual fuel economy assessment charts are explained in this section.

4. A box(s) may also appear along the horizontal bar(s) which contains a double digit number. The number represents the number of the sub-task from which data is being received or to which data is being sent (depending on the direction of the arrow). This interface also falls within the time frame depicted by the calendrical scale.
- b. A Fuel Economy Assessment (MPG) chart, where applicable, which has been extracted from the master Fuel Economy Assessment chart (sub-task 06, Fuel Economy Analysis). The individual charts show the Fuel Economy Assessment (MPG) of the sub-sub-tasks as follows:
1. The original estimate which was included in the ERDA Proposal of May 12, 1977.
  2. The estimate as of September 19, 1977 (contract start date). This estimate underwent reassessment and differs from the original estimate proposed to ERDA on May 12, 1977.
  3. The estimate of each individual sub-sub-task after Theoretical Analysis, Component, and Dynamometer Testing.
- A shaded area in one or more of the columns adjacent to the sub-sub-task indicates that the sub-sub-task is not scheduled for the respective test at this time.
4. The column to the right indicates the projected Fuel Economy Assessment (MPG) of a 4-215 sized fourth generation Stirling engine in the baseline vehicle. The individual charts do not include the confidence level of these projections. Confidence level information is located on the master Fuel Economy Assessment chart which is attached to sub-task 06, Fuel Economy Analysis.
- c. A written report detailing the progress of each sub-sub-task. This page will contain, when applicable, a concise description of the work performed, problems encountered, the "fix" to the problems, and the work planned for the next reporting period. In the event that a particular item requires additional explanation, an attachment(s) will be referenced on this page and included in the report.

### III. PROGRESS OF INDIVIDUAL SUB-TASKS

The following reports will cover the progress of each individual sub-task. Instead of listing the sub-tasks in numeric order (01 through 15), the sub-tasks were placed into two categories as follows.

### Category 1

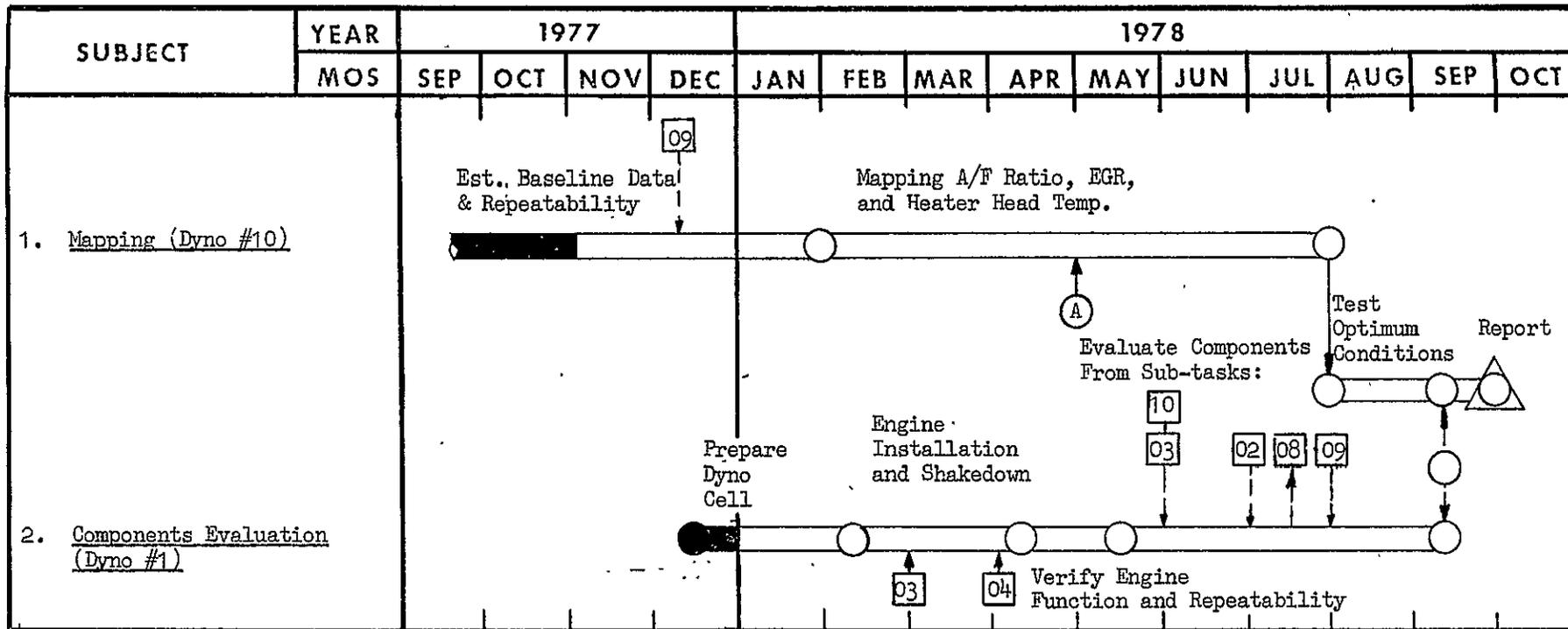
- . Mapping and Optimization - sub-task 01
- . Burner System - sub-task 02
- . Preheater Development - sub-task 03
- . Engine Drive Study - sub-task 04
- . External Heat and Blower System - sub-task 05
- . Power Control - sub-task 08
- . Air/Fuel Control - sub-task 09
- . Cycle Analysis - sub-task 10
- . Other Fuel Economy Improvements - sub-task 14
- . Cooling System Analysis - sub-task 15
- . Fuel Economy Analysis - sub-task 06

Category 1 consists of those sub-tasks which are directly related to fuel economy. Fuel Economy Analysis - sub-task 06, is placed at the end of this category because a portion of this sub-task is dedicated to coordinating all the fuel economy improvement contributions from the other sub-tasks in Category 1 and listing them on the master Fuel Economy Assessment chart located in sub-task 06. Concurrent with coordinating the fuel economy improvement contributions, a confidence level for these fuel economy improvement numbers is also assigned.

### Category 2

- . Engine Durability Upgrading - sub-task 07
- . Responsive Support - sub-task 11
- . Contract Support - sub-task 12
- . Reference Engine - sub-task 13

Category 2 consists of those sub-tasks not directly related to fuel economy but are nevertheless an integral part of the Task I effort.



FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E)	(A)	(C)	(D)	Vehicle Projection
			Estimate	Theoretical Analysis	Component Test	Dyno. Engine Test	
01	MAPPING & OPTIMIZATION (ERVIN)	.4					.38
	.Reduced EGR requirements	.04	.04				
	.Reduced exhaust back-pressure	.03					
	.Minimize air flow reqmts.	.04					
	.Temperature scheduling	.27					

MAPPING AND OPTIMIZATION, SUB-TASK 01

The objective of this sub-task is to determine the effect on fuel economy through optimization of air flow, fuel flow, exhaust gas recirculation (EGR) flow, and heater heat temperature of the current Stirling engine and for engines having components developed as a result of the Task I sub-tasks. The technique of engine mapping developed by Ford Motor Company is used to evaluate the effect of changes in various parameters. Ford will also develop warm-up modes of the engine so as to optimize starting characteristics with minimum fuel usage and emissions. At the end of this sub-task effort a Stirling engine will be assembled which contains the developed components and a final mapping and optimization evaluation will be made. Information from this evaluation will be included in a final report to be prepared for the entire Task I effort.

Mapping is a technique by which vehicle fuel economy is optimized through use of dynamometer testing and computer analysis. For a complete description of mapping refer to the following SAE papers:

"Powertrain Simulation: A Tool for the Design and Evaluation of Engine Control Strategies in Vehicles", number 760158, Paul D. Blumberg

"Engine Mapping Methodology", number 770077, R. E. Baker and E. E. Daby

At the time of contract start (September 19, 1977) engine 1XL7 was installed on the dynamometer for the purpose of establishing repeatability and baseline data. A total of 23.5 hours was accumulated on engine 1XL7 before the engine experienced a failure. Nine data points were taken before the failure occurred.

Engine 3XL6 was then installed in the test cell and has run a total of 24.2 hours since its installation at the end of November, 1977. However, problems developed in the emissions measuring equipment and the collection of a significant number of data points was prevented.

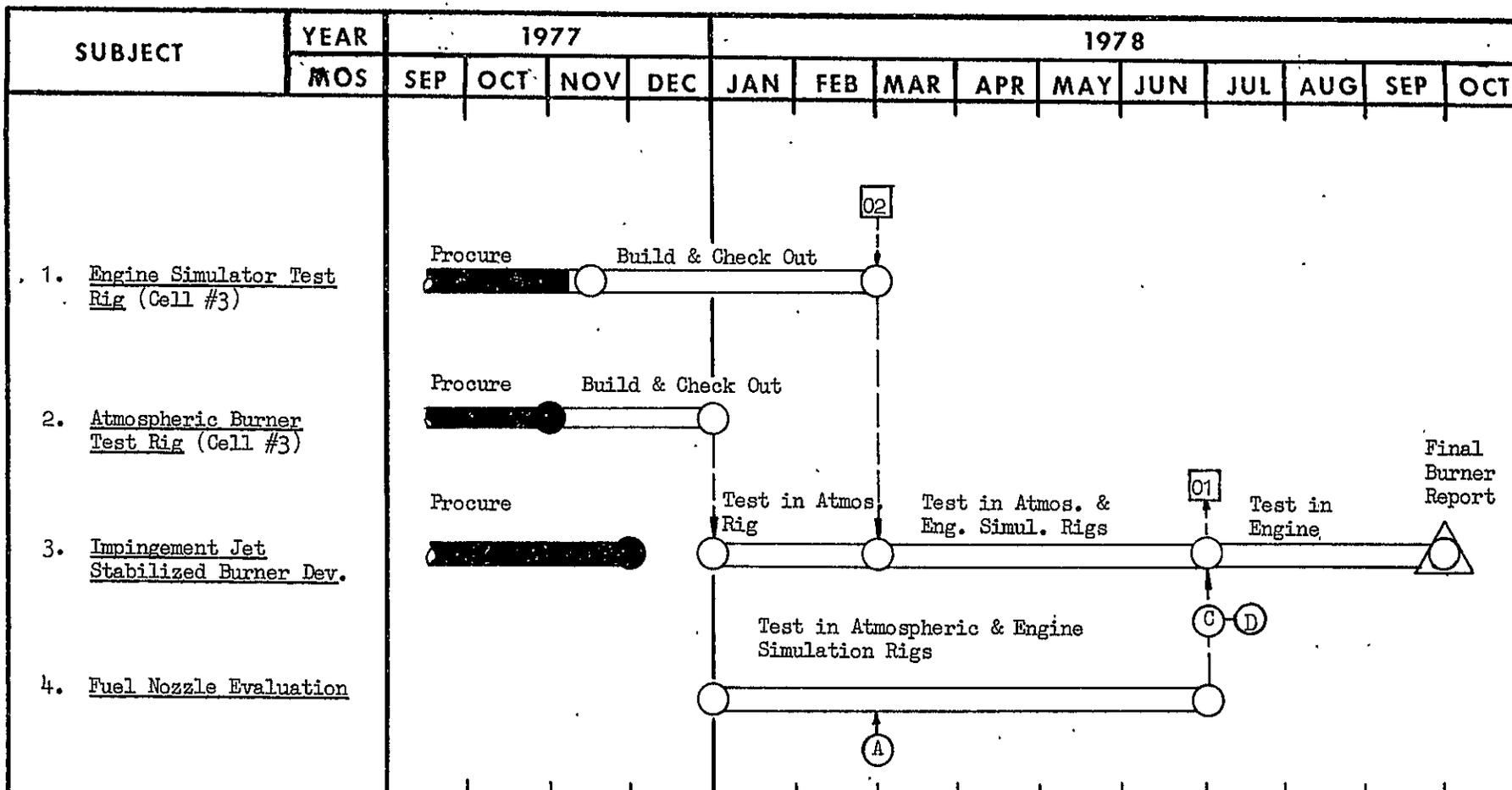
To date, 47.7 hours of mapping have been accumulated using two engine builds (1XL7 and 3XL6). Engine durability has been a major obstacle in the accumulation of additional data. Efforts to increase engine durability are under way. For a detailed explanation of these efforts refer to Engine Durability Upgrading, sub-task 07.

Mapping and Optimization, Sub-task OL

FUEL ECONOMY ASSESSMENT

The assessed fuel economy improvement contribution of Mapping and Optimization remained unchanged at 0.38 MPG (gasoline).

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FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
02	BURNER SYSTEM (REAMS)	.2					
	.Low pressure drop burner	.02	.02				
	.Improved heater head temperature distribution	.13	.13				.15

## BURNER SYSTEM, SUB-TASK 02

The objective of this sub-task is to determine the fuel economy improvements associated with minimizing the gas pressure drop through the burner, reducing the emission levels to achieve Clean Air Amendment levels, and achieve a combustion gas flow pattern such that temperature variation in the heater head is minimized. A redesigned burner system will be tested on an atmospheric burner test rig and an engine simulator rig together with other required system components in an attempt to meet the burner system objectives. After acceptable functional characteristics are achieved, the burner system will be installed on a Stirling engine for dynamometer mapping and evaluation.

Fabrication of the first impingement jet burner has been completed (figure 3-1). The fuel for this burner enters the chamber via a fuel nozzle. The air supply to the chamber is divided into two parts; primary and secondary. The primary supply enters the chamber through passages located between the burner can and the outside insulation (see figure 3-2). This air passes through a mechanism called a swirler. This swirler creates a turbulence inside the burner which causes the incoming air and fuel to be mixed. The secondary air supply enters the chamber by way of the impingement jets which are holes in the wall of the chamber approximately 1" in diameter. These holes allow air to enter perpendicular to the flame causing further turbulence. This causes the air and fuel already in the chamber to be further mixed. Because the flame in the chamber is continuous, combustion products are continuously sent through the flame, resulting in a cleaner burn.

During the next reporting period it is anticipated that both the engine simulator test rig and the atmospheric burner test rig will have been assembled and checked out. Impingement jet stabilized burner development and fuel nozzle evaluations will also be initiated using the two test rigs.

### FUEL ECONOMY ASSESSMENT

The assessed fuel economy improvement contribution of Burner System, sub-task 02, remained unchanged at 0.15 MPG (gasoline).

# IMPINGEMENT JET STABILIZED BURNER

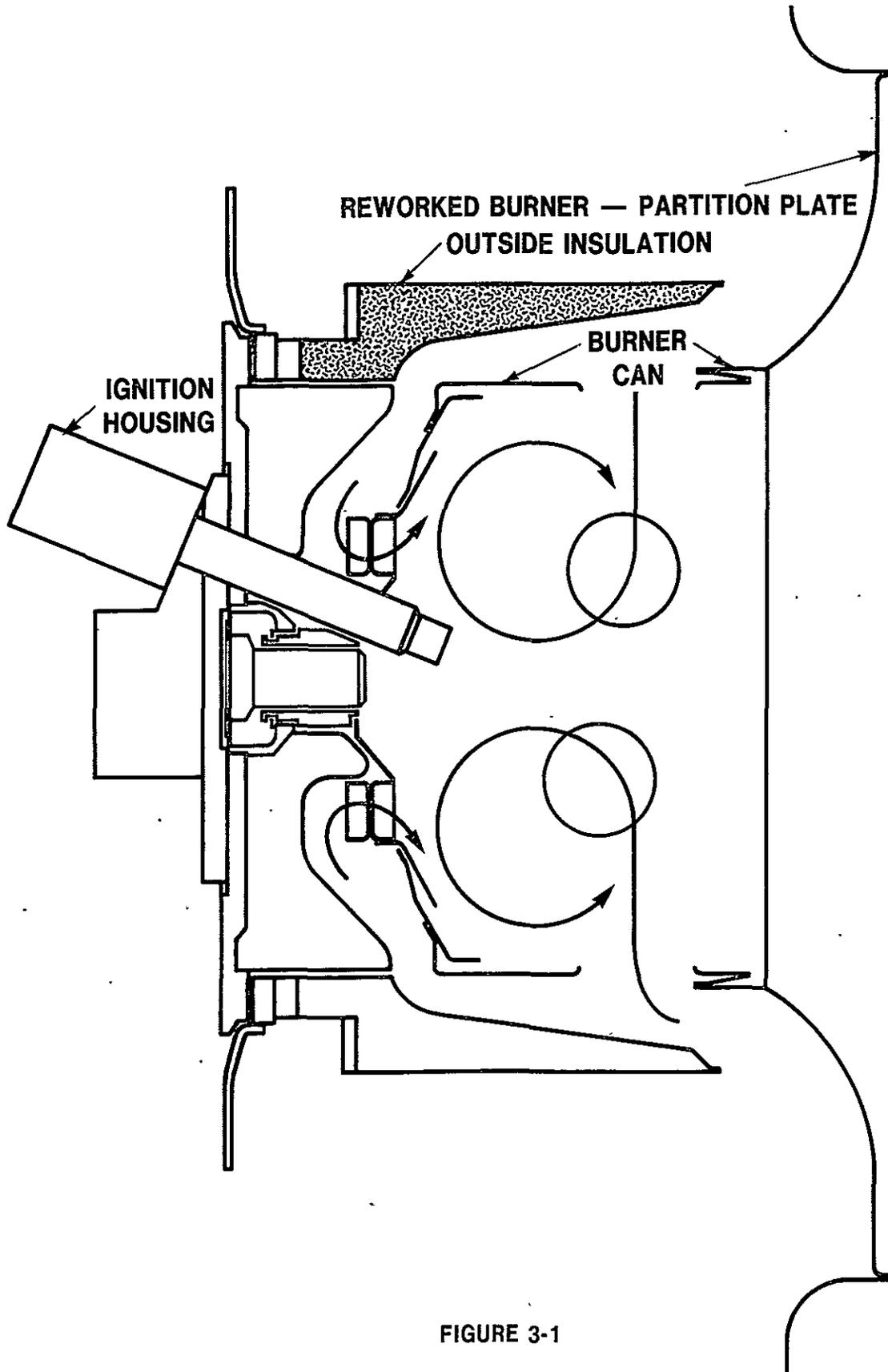


FIGURE 3-1

# REDESIGNED PREHEATER

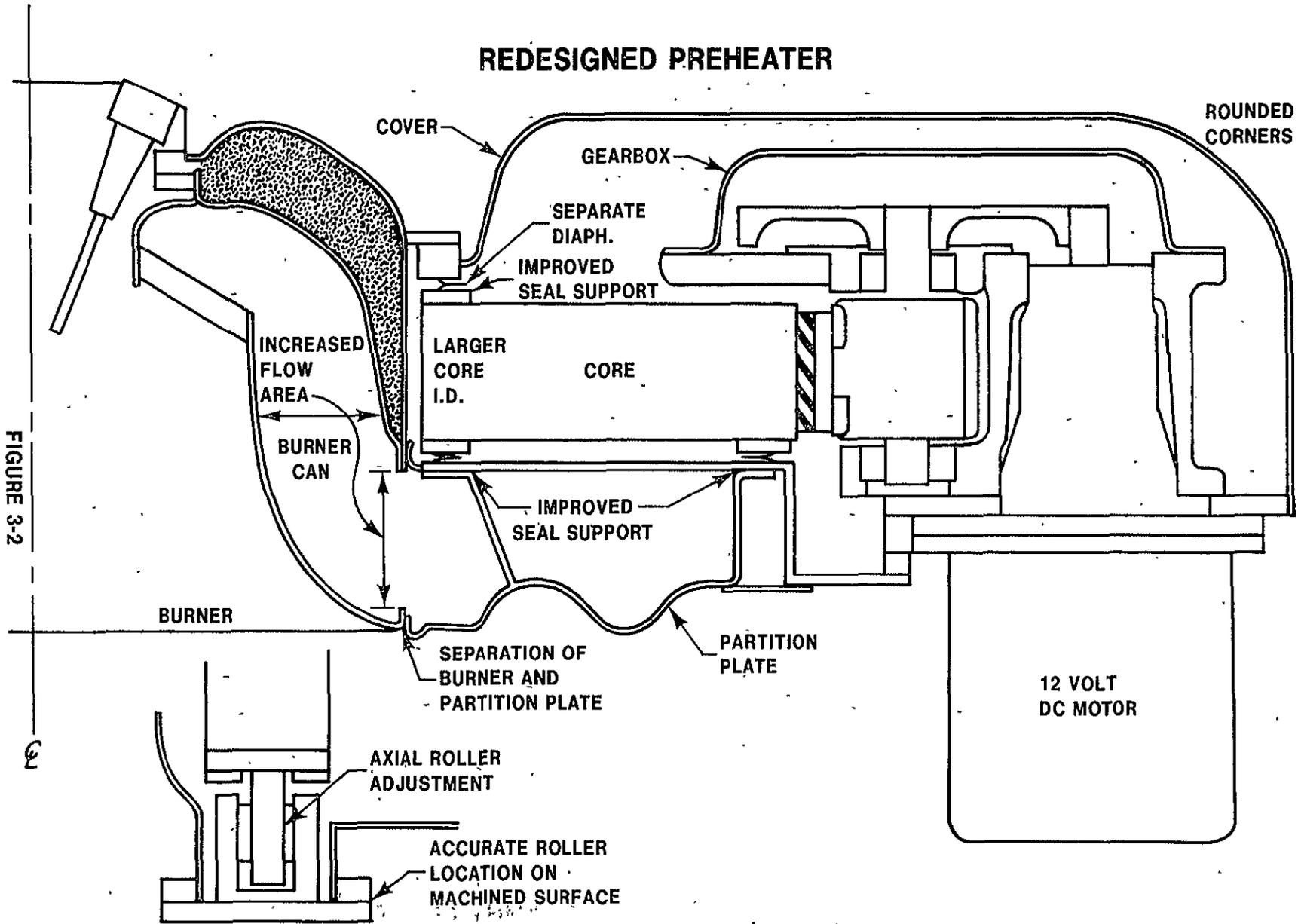
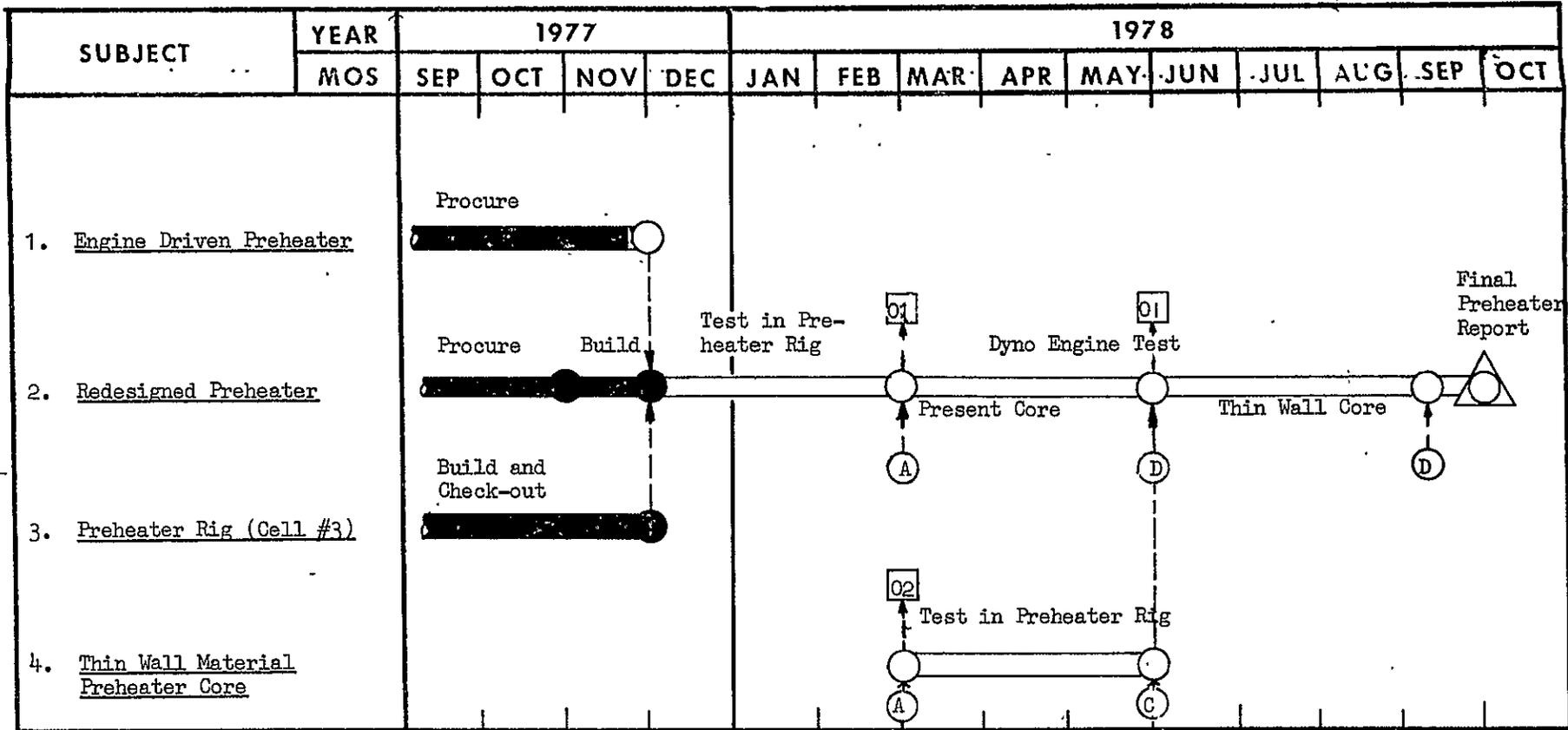


FIGURE 3-2



FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
03	PREHEATER (REAMS)	.3					.16
	.Engine driven preheater	.14	.14				
	.Thin wall material preheater core	.14	- (2)				
	.Seal friction reduction	.01	.00				
	.Reduced preheater leakage	.02	.02				

(2) Estimate included in the Total of Cycle Analysis, Sub-task 10

### PREHEATER DEVELOPMENT, SUB-TASK 03

The objective of this sub-task is to determine the fuel economy improvement which will result from a redesign of the Stirling engine preheater. An evaluation of the preheater's functional capability when driven directly from the engine accessory power shaft, rather than by the currently used electric motor drive will also be performed. In addition, the preheater will be modified to use the latest preheater ceramic core technology, and efforts will be made to reduce seal leakage and friction. The entire redesigned preheater system will be tested and developed on a preheater test rig and, after acceptable functional characteristics have been achieved, the preheater system will be installed into a Stirling engine for dynamometer mapping, evaluation, and optimization.

The engine driven preheater design has been completed. Since the preheater must operate at the same time the burner does, a 12 volt D.C. motor to drive the preheater during ignition and engine cranking. Once the engine is running, the core is driven by the engine via a overrunning clutch on the motor shaft (see figure 3-3). The parts for this preheater assembly have been received. The shaft on the D.C. motor was too short. The motor has been returned to the vendor and a new, longer shaft will be installed.

In addition to the engine driven preheater, another preheater has been designed (see figure 3-2). This redesigned preheater includes changes which will increase the flow area to the swirler of the burner, improving combustion. The changes include:

- a. Increased flow area to swirler. This was accomplished by increasing the inside diameter of the ceramic core. Although the heat transfer area was decreased, the effect was insignificant.
- b. Separation of burner from the preheater partition plate. This was done so that burner development would not require removal and replacement of the entire preheater assembly.
- c. Improved seal support with the hot side seal supported on one surface by the partition plate rather than three surfaces as with previous design.
- d. Increased seal support for 360 degree contact on the inner cold side seal.
- e. Increased flexibility in repair by separating the cold side diaphragm from the seal. The original design was a one piece seal diaphragm assembly that required a complete replacement when either the seal or diaphragm had failed.

### Preheater Development, Sub-task 03

- f. Location of rollers from a machined surface.
- g. Provision for axial adjustment of rollers to center them in the ring-gear groove.
- h. Rounded corners to decrease flow resistance of the cooling fan.

The original and redesigned preheater are shown on figure 3-4.

The redesigned preheater has been assembled and the reworked burner carrier has been installed. When tested, the preheater operated smoothly and quietly.

After modifications on the air piping in the test cell, the redesigned preheater will be ready for testing.

The preheater test rig has been designed and built (see figure 3-5). This rig will simulate engine operating conditions. The rig can be used to evaluate the following:

- a. Torque required to drive the core.
- b. Gear or roller noise.
- c. Seal noise.
- d. Durability of core, seals, and diaphragms.

This test rig cannot be used to evaluate the following:

- a. Leakage.
- b. Emission levels.
- c. Burner design.
- d. Effect on EGR.

After the rig was assembled and check-out was completed the original preheater was installed. Torque measurements and temperature readings were taken to assure that the rig was simulating the "real" operating conditions for which it was designed. Changes were necessary in order to stabilize the torque required to drive the core.

Preheater Development, Sub-task 03

During the next reporting period it is anticipated that testing of the redesigned preheater in the preheater rig will be completed. It is also anticipated that the redesigned preheater will be installed on the dynamometer engine.

FUEL ECONOMY ASSESSMENT

The assessed fuel economy improvement contribution of Preheater Development, remained unchanged at 0.16 MPG (gasoline).

# ENGINE DRIVE PREHEATER

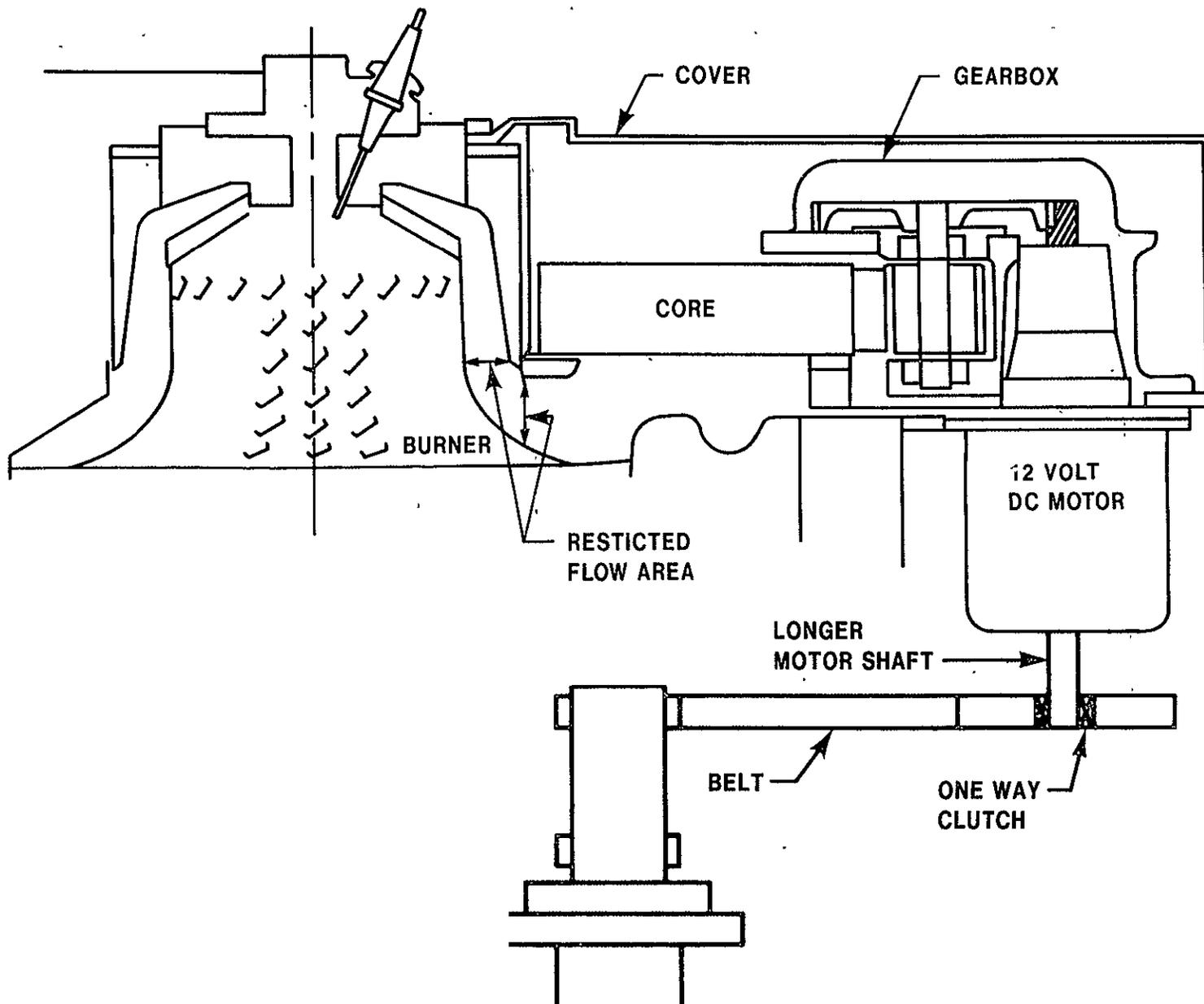
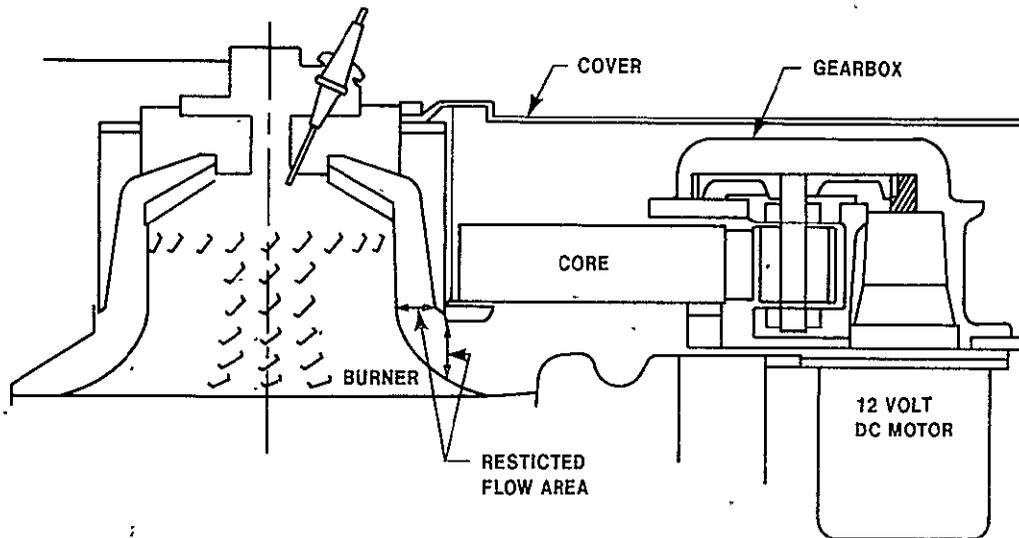


FIGURE 3-3

# PREHEATER VARIATIONS

## ORIGINAL PREHEATER



## REDESIGNED PREHEATER

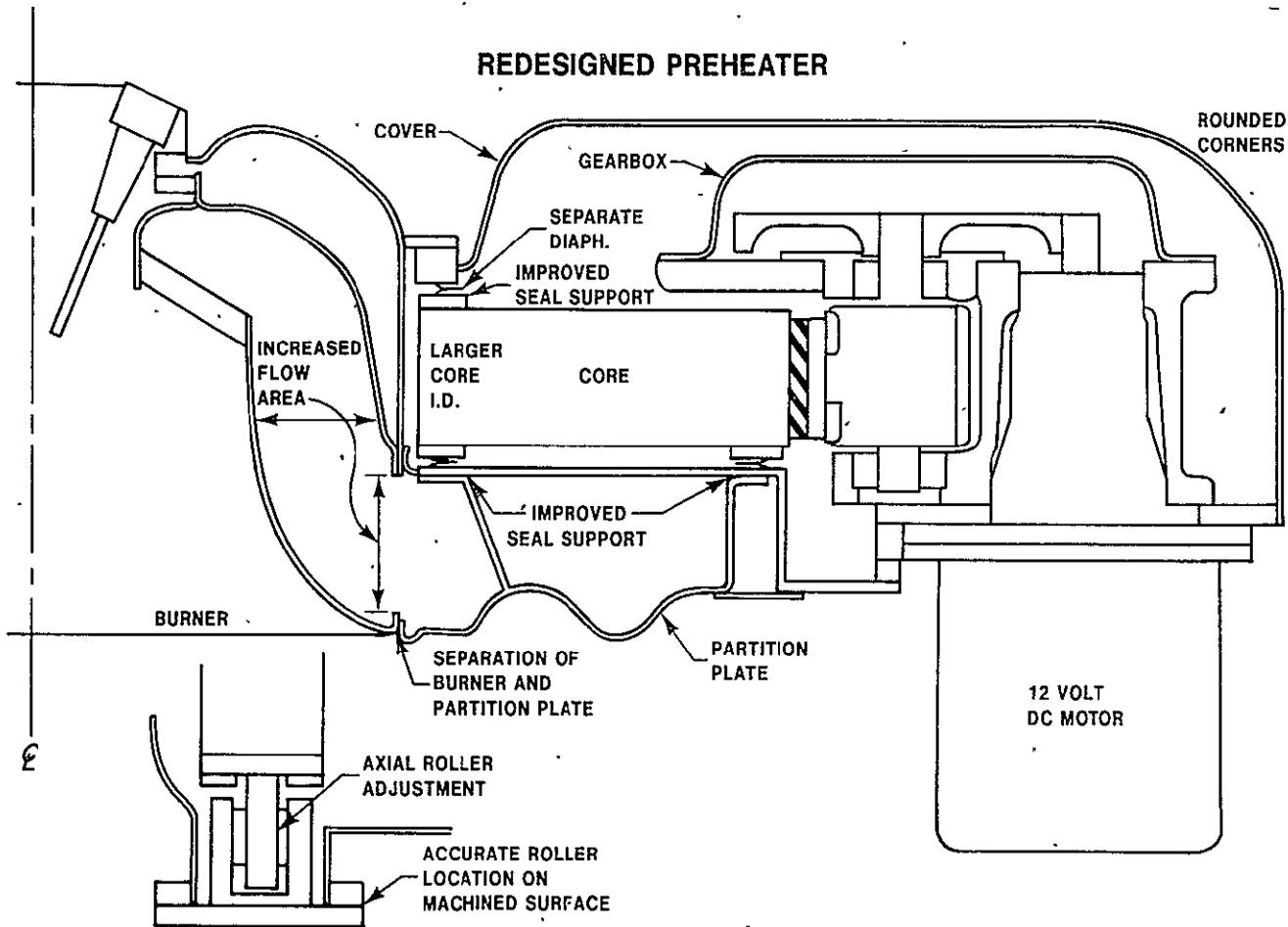


FIGURE 3-4

# PREHEATER RIG

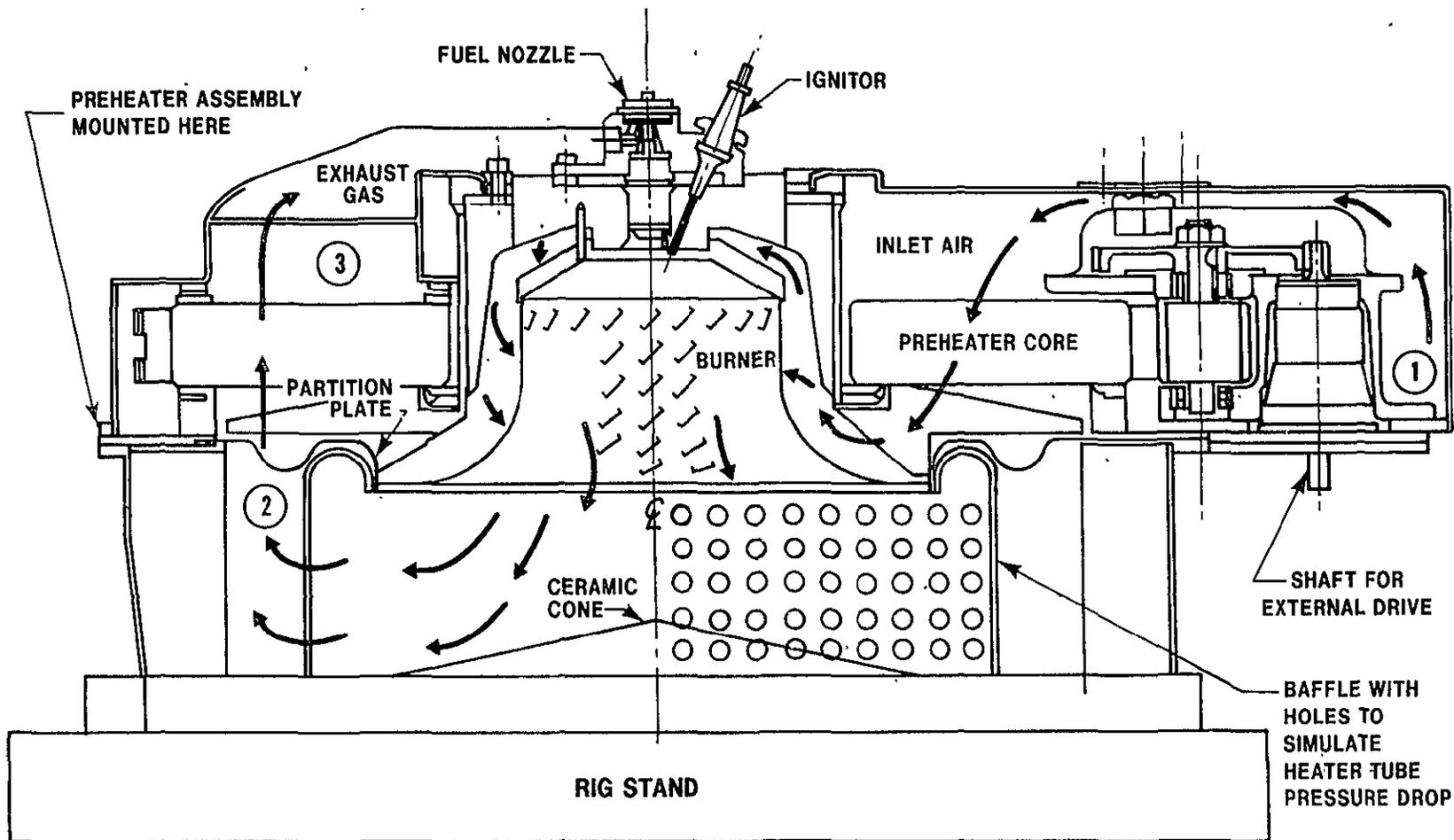
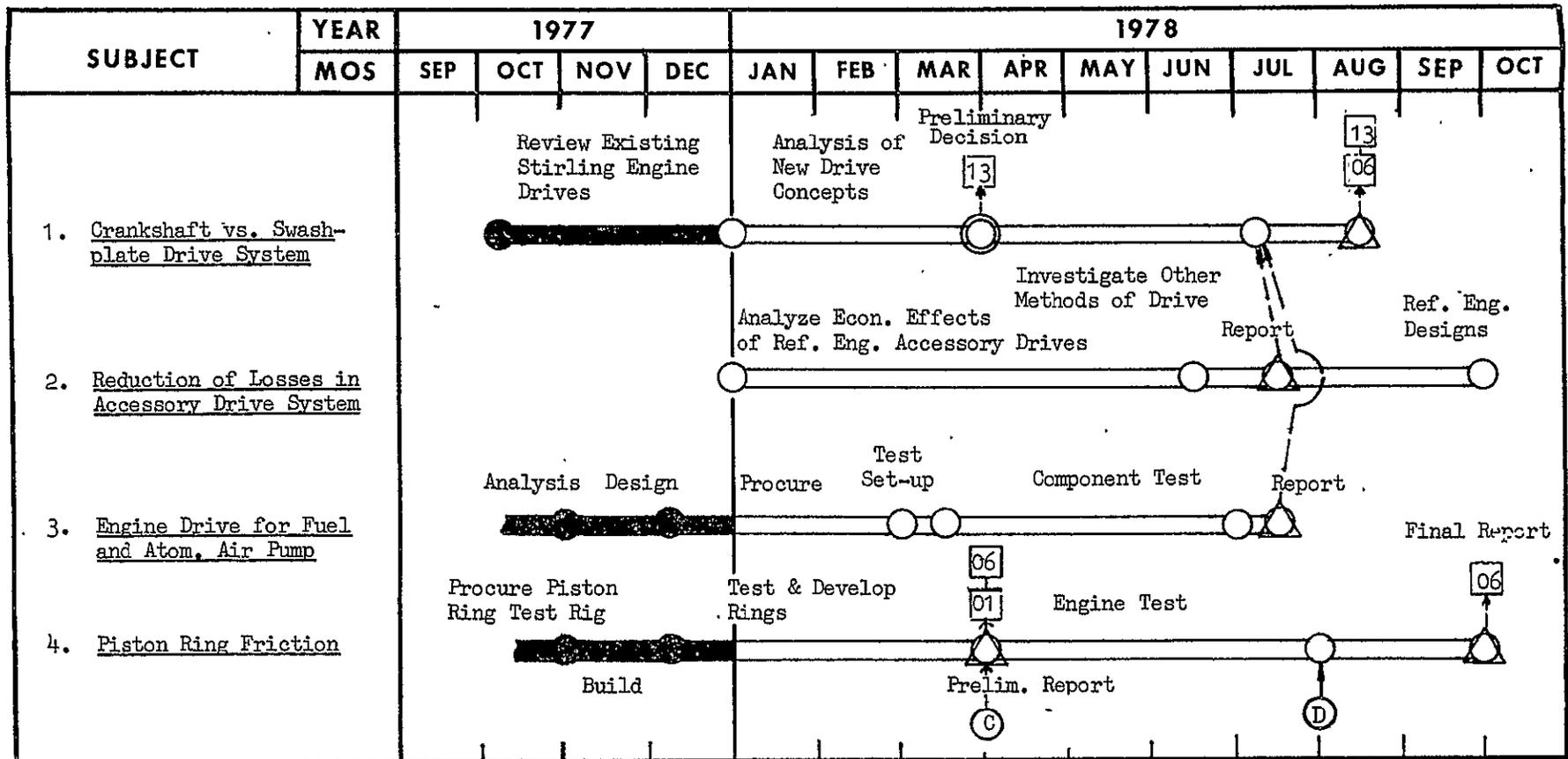


FIGURE 3-5

## INSTRUMENTATION

1. AIR FLOW, TEMPERATURE, AND PRESSURE AT INLET TO RIG
2. TEMPERATURE INLET TO PEHEATER ON EXHAUST SIDE
3. TEMPERATURE AND PRESSURE ON EXHAUST FROM RIG
4. PREHEATER DRIVE TORQUE AND SPEED

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FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
04	ENGINE DRIVE STUDY (KANTZ)	.2					.66
	. Crankshaft vs Swashplate	.10	.10				
	. Accessory drive	.05	.05				
	. Engine drive for fuel and atom. air pump	-		+ .27			
	. Piston ring friction	-		.24			

#### ENGINE DRIVE STUDY, SUB-TASK 04

The objective of this sub-task is to determine fuel economy improvements possible in the engine drive system by providing the designs and analyses necessary to compare the mechanical efficiency of the swashplate drive system with one or more crank and connecting rod types of drive systems. For each of the drive systems to be evaluated, a concept engine assembly drawing will be prepared as part of sub-task 13, Reference Engine, and the feasibility of packaging this concept engine within an automobile engine compartment will be assessed. The drive system analyses will include alternative methods for powering accessories and auxiliaries including the air atomizing compressor and fuel pump. Contributors to engine friction such as sliding seals and piston rings will also be analyzed.

A computer program was written which calculates the bearing loads in a crankshaft type Stirling engine as a function of crank angle. This program allows for the differential gas pressure acting on the engine pistons, reciprocating mass inertia, and the totaling inertia of the connecting rods, calculating the resulting forces on the wrist pin, journal and main bearings. This program was later expanded to include a method of calculating the size of the wrist pin, crank pin, and main bearing required in a crankshaft type engine and also the functional losses of these bearings. These calculations were made taking into consideration such parameters as length/diameter ratio, eccentricity ratio, lubricant viscosity, bearing clearance, characteristic number, and load. Figures 3-6 and 3-7 illustrate polar plots of the front main bearing and crank pin forces in a typical crankshaft drive Stirling engine at the operating condition. Once the optimum bearing parameters have been established, the frictional power losses can then be calculated.

An analysis evaluating the fuel economy improvement resulting from mechanically driving the fuel and air atomizing pumps was completed. The improvement was approximately 0.27 MPG in the metro-highway cycle. A schematic of the electrical and mechanical pump drives is provided (see figure 3-8).

Package studies were performed which indicate that belt driven air atomizer and fuel pumps are packagable in the baseline vehicle and can be driven by the blower motor during start-up or the engine during normal running. One of the possible package layouts is shown in figure 3-9.

A piston ring test rig was designed and built which would determine the friction drag on the piston rings currently being used in the 4-215 Stirling engine. Also, the test rig will evaluate modified versions of the rings to ascertain the optimum design for a piston ring which would be used in future Stirling engines.

#### Engine Drive Study, Sub-task 04

The piston ring test rig was found to have excessive vibration within the engine's speed range. Initially, the vibration was believed due to the inherent unbalance of a single piston reciprocating drive. A weight was added to the rig in an effort to isolate the source of the vibration from the strain gage columns. The position of the weight is shown in figure 3-10. The weight was beneficial in that it increased the range of testing from 1000 RPM to 1500 RPM.

The natural frequency of the piston ring test rig was measured and shown to be approximately 500 cps. The measurement was accomplished by averaging the vibration frequencies shown on oscilloscope traces for various operating conditions (see figure 3-11). The calculated natural frequency of the piston ring test rig is approximately 1400 cps. This calculation is based upon the spring rate of four strain gage columns supporting the stationary mass of the cylinder assembly and assumes all columns are loaded equally. A portion of the calculated higher frequency is due to the fact that some of the sprung mass (connecting hoses and water) was not included.

It was decided that to move the natural frequency of the rig out of the range of testing is impractical and therefore data will only be taken below 1500 RPM.

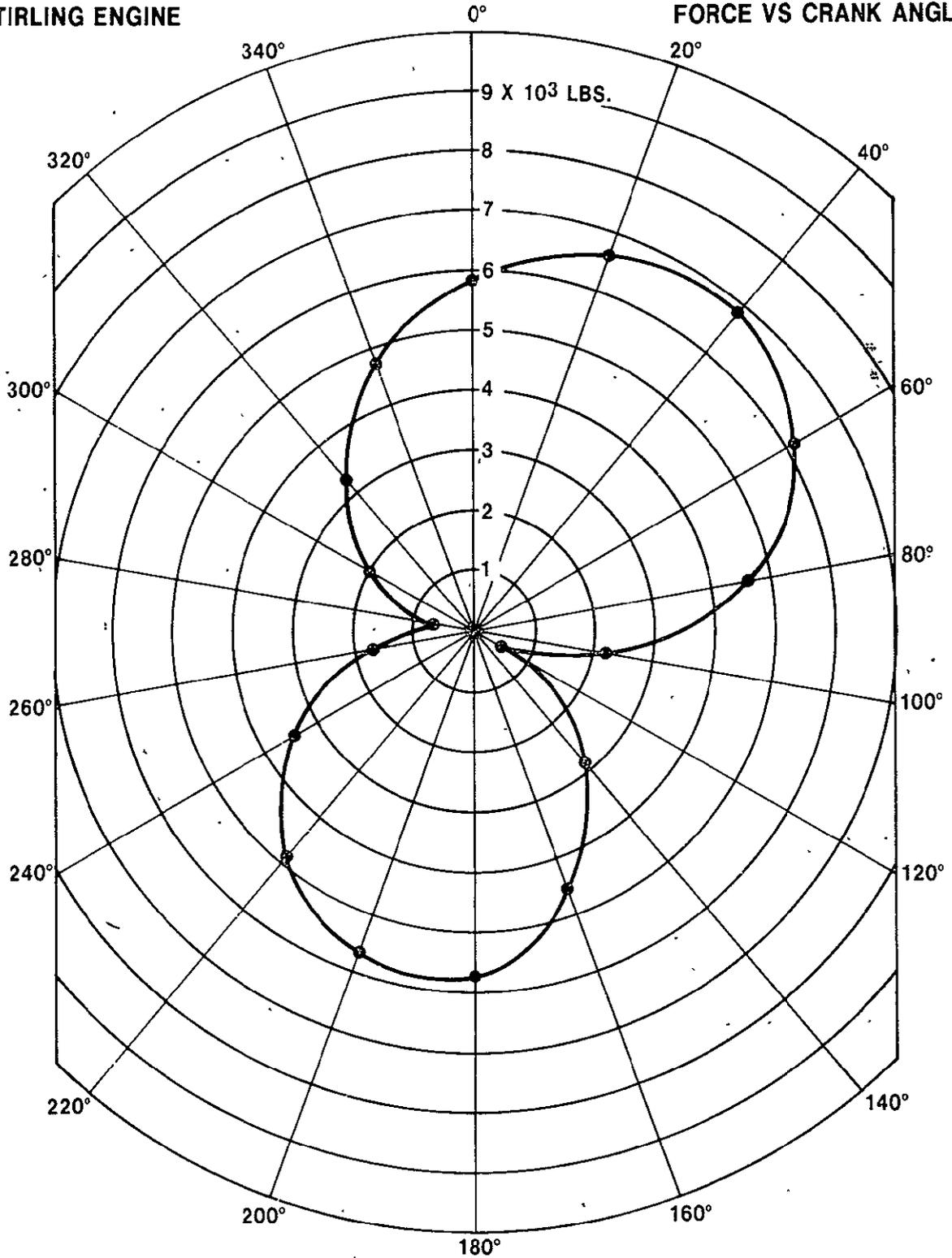
During the next reporting period it is anticipated that an analysis of the economy effects of reference engine accessory drives will begin. It is also anticipated that procurement and test set up of components for the fuel and atomizing air pump study will be completed. Testing and development of new piston rings will continue.

#### FUEL ECONOMY ASSESSMENT

The assessed fuel economy improvement contribution of Engine Drive Study, sub-task 04, has been increased from 0.39 MPG to 0.66 MPG (gasoline). This change results from the theoretical analysis of the engine drive for the air atomizer and fuel pump which yielded a 0.27 MPG improvement. There was no original ERDA estimate on this item (refer to Fuel Economy Assessment chart, sub-task 06).

**DUAL CRANKSHAFT  
STIRLING ENGINE**

**FRONT MAIN BEARING  
FORCE VS CRANK ANGLE**

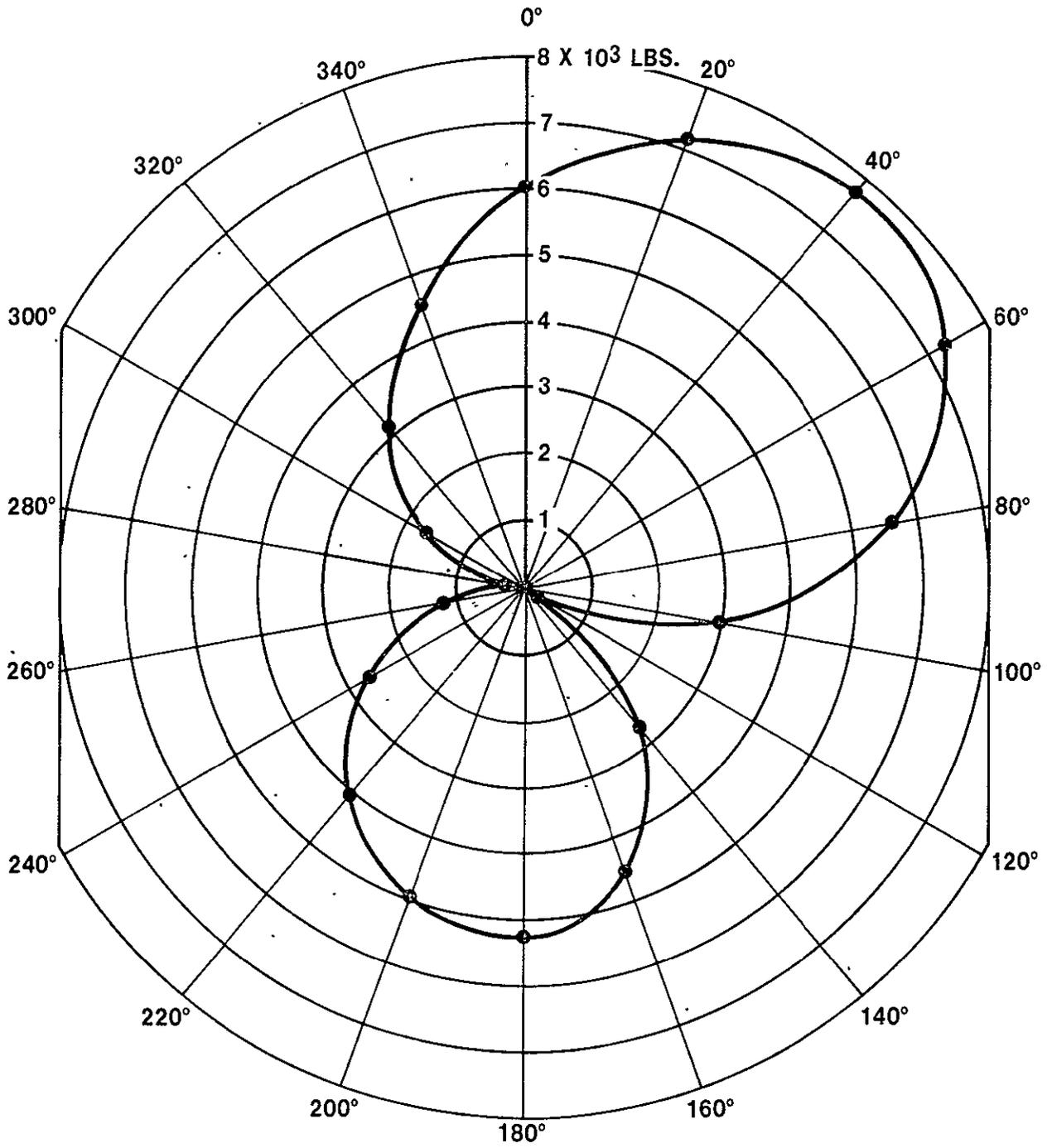


**ENGINE SPEED = 2000 RPM  
MEAN PRESSURE = 200 ATM**

**FIGURE 3-6**

**DUAL CRANKSHAFT  
STIRLING ENGINE**

**CRANKPIN BEARING  
FORCE VS CRANK ANGLE**

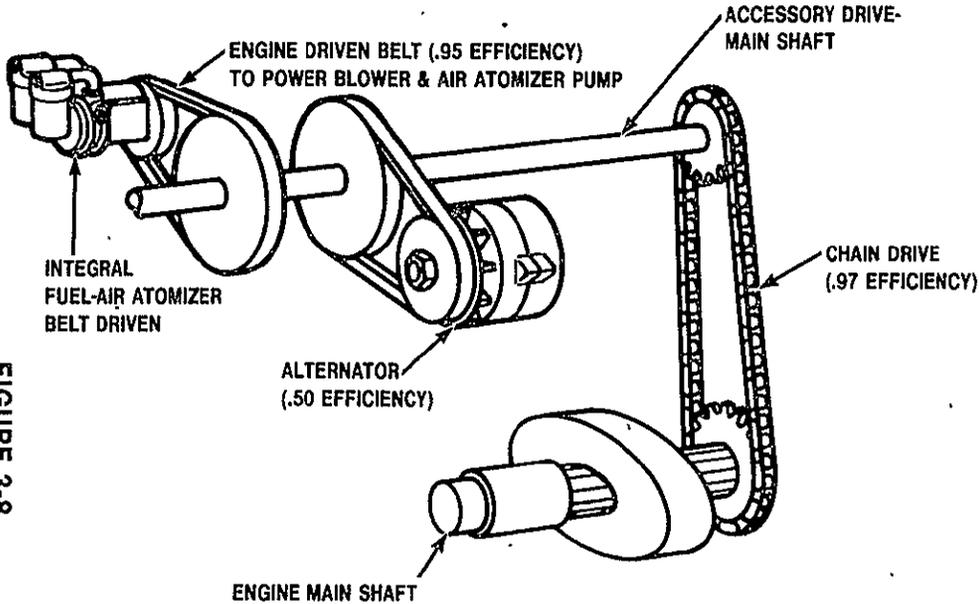


**ENGINE SPEED = 2000 RPM  
MEAN PRESSURE = 200 ATM**

**FIGURE 3-7**

**DRIVE SYSTEM-FUEL AND AIR ATOMIZER PUMPS**

**PROPOSED SYSTEM**  
**BELT DRIVE**



**CURRENT SYSTEM**  
**ELECTRICALLY POWERED**

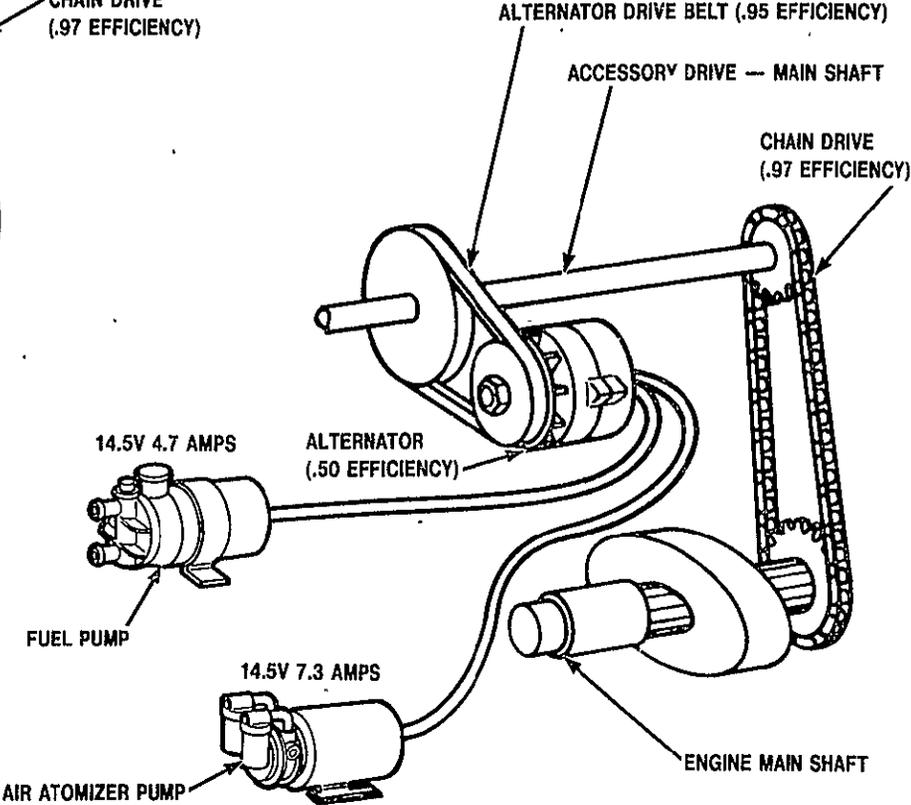


FIGURE 3-8

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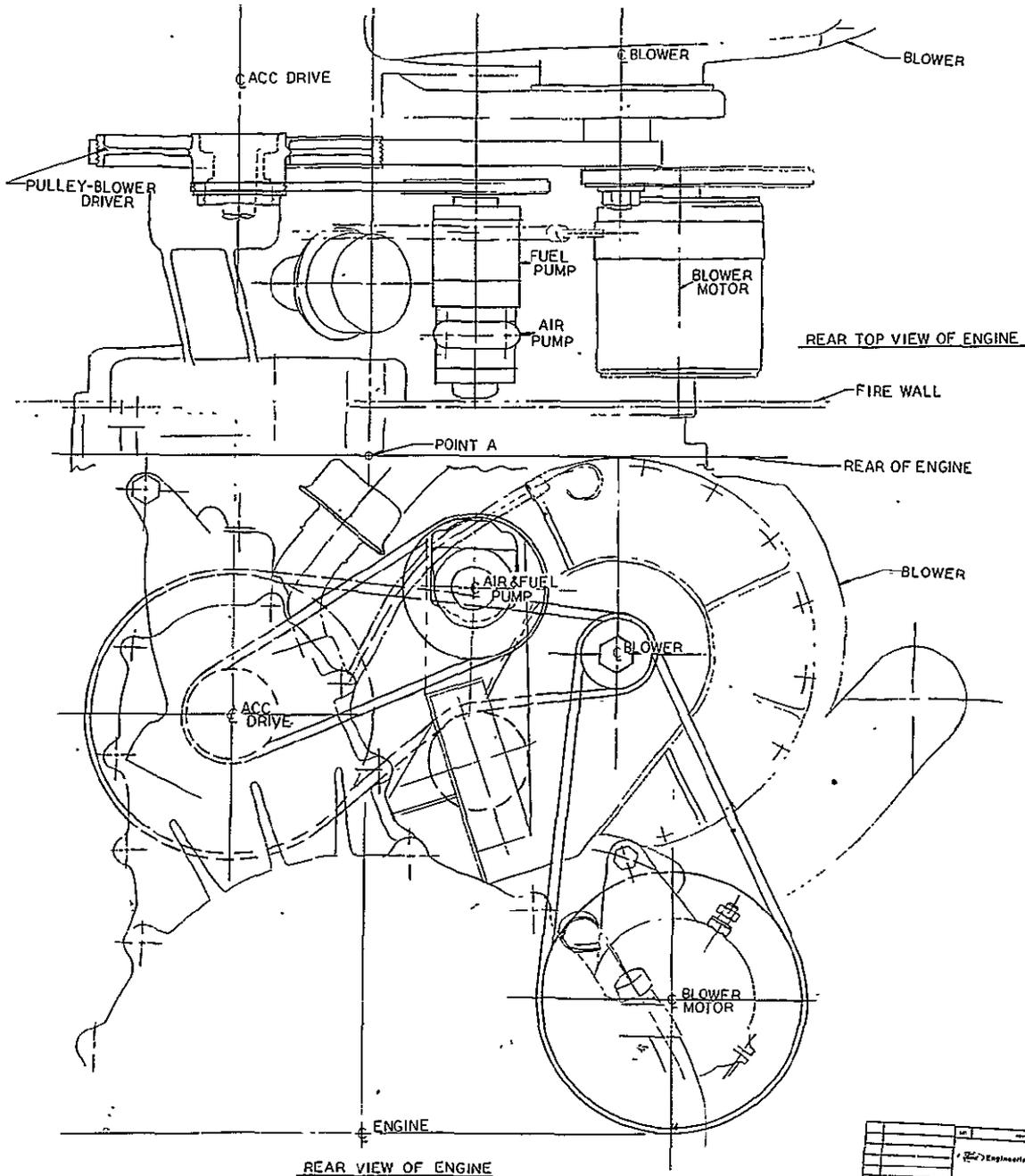


FIGURE 3-9

DATE	BY	REVISION	NO.
Engineering & Research Staff			
PROPOSAL - AIR/FUEL PUMP LOCATION			
LAP-0321			

# PISTON RING FRICTION TEST RIG SCHEMATIC

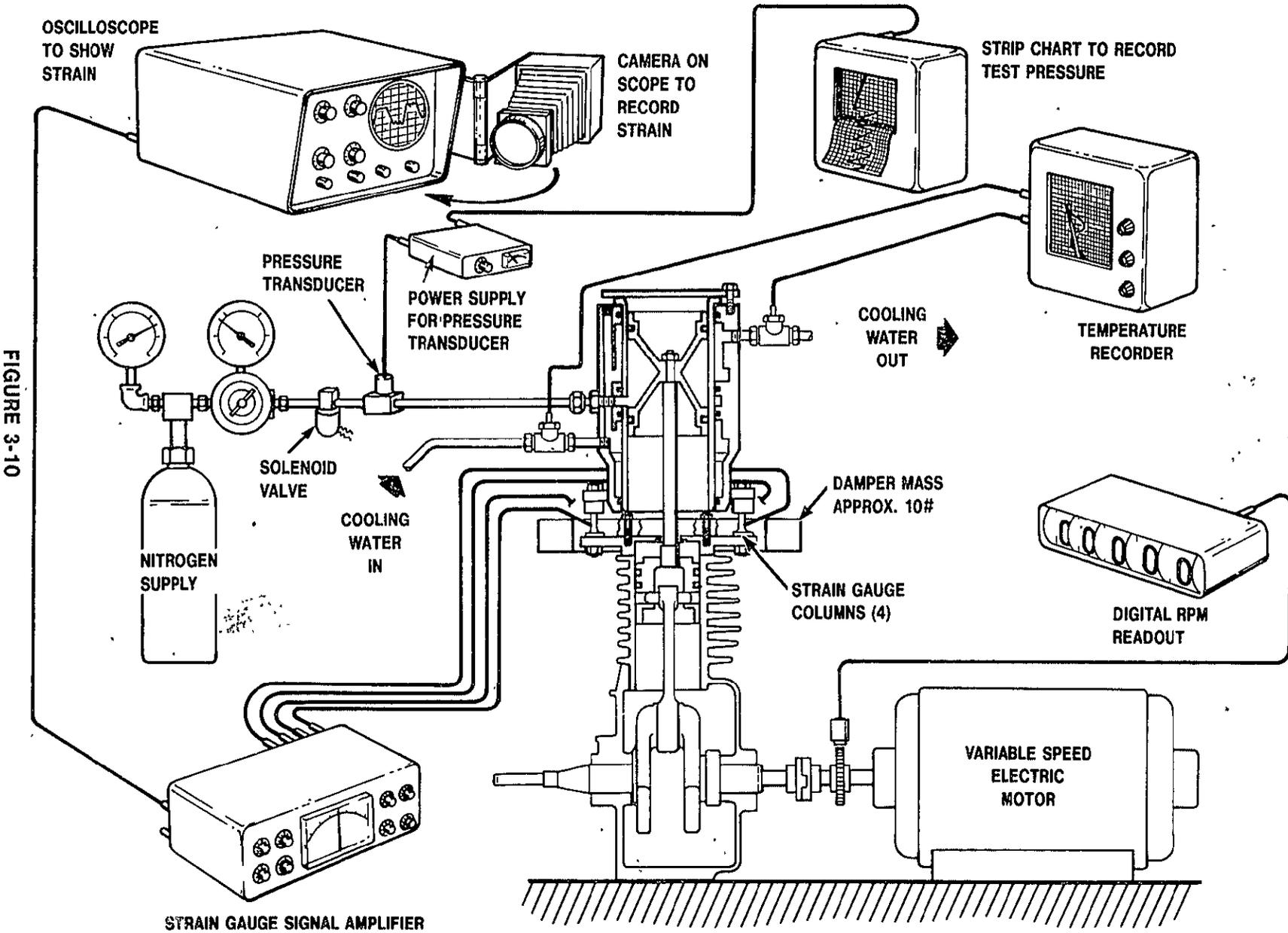
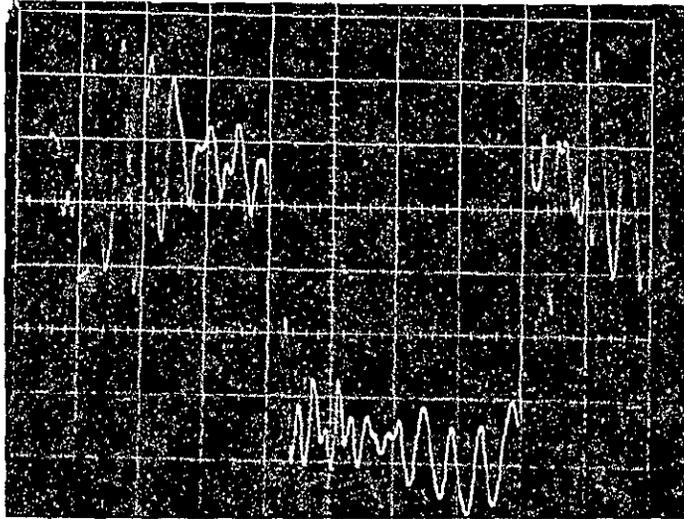


FIGURE 3-10

PISTON RING TEST RIG  
NATURAL FREQUENCY

Experimental Determination

Analytical Determination



3-28  
FIGURE 3-11



$$\text{FREQUENCY (f)} = \frac{\text{RPM}}{60 \frac{\text{sec.}}{\text{min.}}} \times \frac{\text{cm}}{\text{rev.}} \times \frac{\text{Oscillation}}{\text{cm}}$$

$$f = \frac{1500}{60} \times 8 \times 2.5$$

$$f = 500 \text{ cps}$$

$$f = \frac{1}{T} = \frac{1}{2} \frac{\text{kg}}{W}$$

W = Spring weight = 9.1 lbs.

k = Spring rate of strain gage columns

$$k = \frac{A \times E}{l} \quad 4 \quad \frac{\text{lb.}}{\text{in.}}$$

Where: A = Column cross section area

l = Length of column

E = Young's Modulus (Brass)

$$k = \frac{.0246 \times 15.9 \times 10^6}{0.83} \quad 4 = 1.884 \times 10^6$$

$$f = \frac{1}{2} \frac{1.884 \times 10^6 \times 386}{9.1}$$

$$f = 1424 \text{ cps}$$

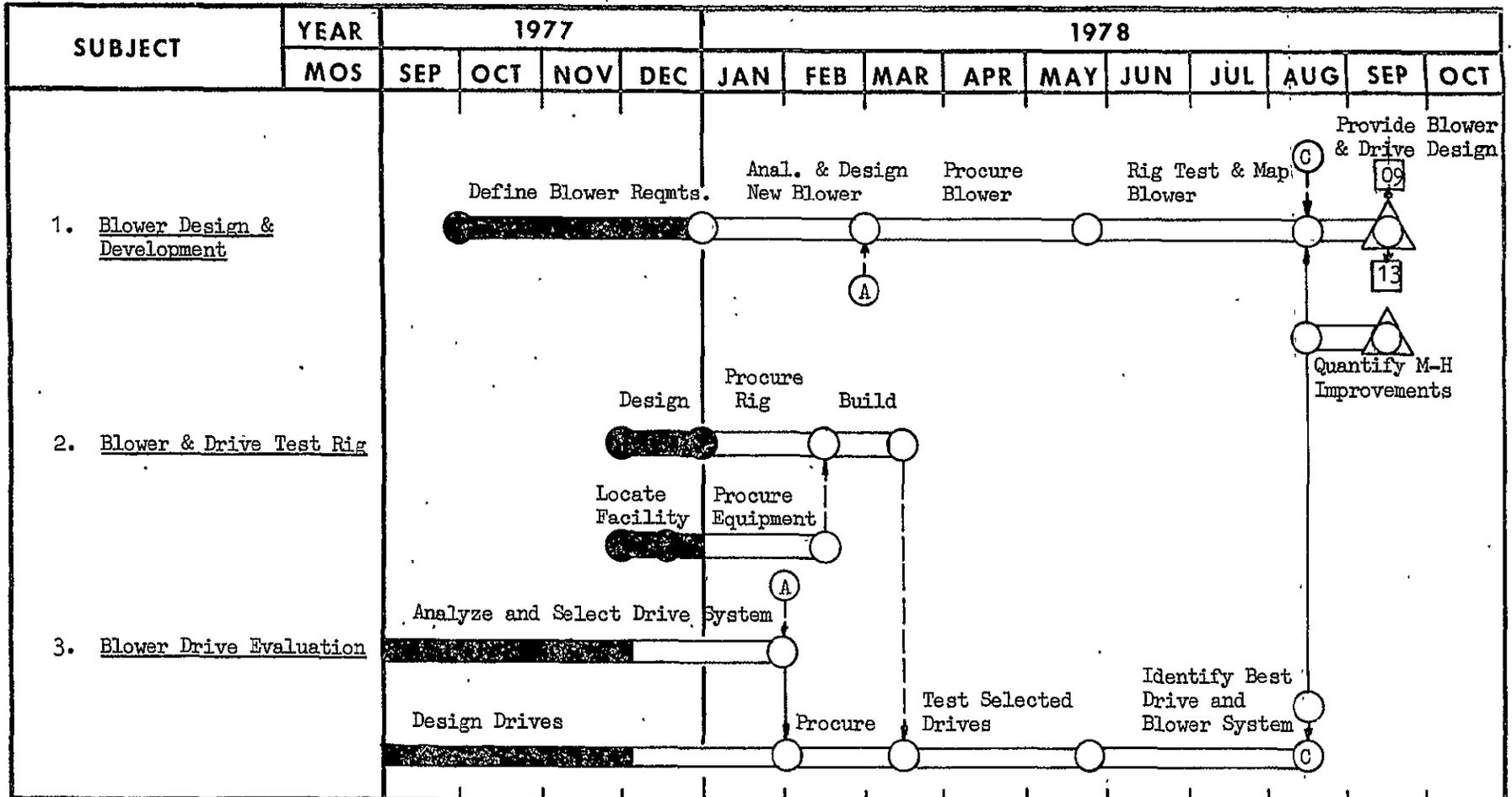
DRIVE SYSTEM

SCHEMATIC

CHARACTERISTICS

<p>1. BELT &amp; CHAIN</p>	<p>ROLLING CONTACT BEARINGS</p> <p>*O.W.C.</p> <p>POLY "V" BELT</p> <p>HyVO CHAIN</p> <p>ENGINE MAIN SHAFT</p> <p>BLOWER MOTOR</p> <p>O.W.C.</p> <p>BLOWER</p> <p>*O.W.C. (ONE WAY CLUTCH)</p>	<p>BLOWER SPEED</p> <p>ENGINE SPEED</p> <p>ACTUAL</p> <p>REQUIRED</p>
<p>2. CHAIN, VISCOUS CLUTCH AND BELT</p>	<p>VISCOUS CLUTCH</p> <p>O.W.C.</p> <p>BELTS</p> <p>BLOWER MOTOR</p> <p>BLOWER</p>	<p>BLOWER SPEED</p> <p>ENGINE SPEED</p> <p>ACTUAL</p> <p>REQUIRED</p>
<p>3. VARIABLE SPEED</p>	<p>M V O CHAIN</p> <p>BELT</p> <p>PLANETARY GEARSET</p> <p>MOTOR</p> <p>O.W.C.</p> <p>BLOWER MOTOR</p> <p>BLOWER</p>	<p>BLOWER SPEED</p> <p>ENGINE SPEED</p> <p>ACTUAL</p> <p>REQUIRED</p>

FIGURE 3-12



FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
05	EXTERNAL HEAT AND BLOWER SYSTEM (KANTZ)	.1					.19
	.Improved blower design	.04	.04				
	.Improved blower drive	.05	.05				
	.Reduce air flow reqmts. (Ref. Sub-task 10)	-	.10				

## EXTERNAL HEAT AND BLOWER SYSTEM, SUB-TASK 05

The purpose of this sub-task is to determine the fuel economy improvements that can be obtained through a redesign of the entire external heat system. The improved fuel economy will result from reducing the gas pressure drop through the system. (See also sub-tasks 02, 03 and 10.) Subsequently, the blower characteristics will be analyzed, together with newly developed mapping techniques so as to minimize blower power requirements. The resulting blower and external heat system will be rig tested and developed.

Blower airflow requirements for the reference engine (4-247) have been established. The results are shown in Table 3-1. A consultant was retained to assist in designing a blower best suited to those requirements. The consultant submitted a report which outlines several preliminary blower designs. However, there was apparently a misunderstanding of our goals as the consultant's designs were directed at eliminating excessive power consumption at high engine speeds while sacrificing adequate capacity at low engine speeds. The consultant also recommended that two control modes, inlet throttling and bypass of discharge into the inlet, would be needed to provide the low flows encountered at part load operation. Two meetings were held to discuss these problems; it was resolved that adequate blower capacity at engine speeds under 2000 RPM, with minimum power consumption, is the primary goal. It was also decided that a blower design based upon a constant ratio drive was desirable and that, at present, only inlet throttling will be considered for controlling blower flow.

A cell, located in the Mechanical Components Testing Laboratory is available for testing the blower. A laminar air flow meter and five manometers were ordered for the tests. The manometers have been received. This instrumentation will be used on the Blower and Drive Test Rig.

Several types of blower drives have been considered (see figure 3-12). Drives numbered 2 and 3 will result in total blower power savings over design 1 because the resulting blower speed is closer to the maximum required speed. The power saving will be derived from less inlet throttling resulting in a more efficient blower operation. A preliminary design for a variable speed blower drive has been completed. This design is similar to design 3, figure 3-12. The design requires an electric motor which serves the dual purpose of driving the blower during start-up and working in conjunction with the engine belt drive to the blower, increasing the blower/engine speed ratio at low engine speeds.

During the next reporting period it is anticipated that a new blower design will be completed and some hardware will be ordered. Also, all hardware for the blower and drive test rig will be received and the rig assembled. During the next reporting period a blower drive selection will be made.

External Heat and Blower System, Sub-task 05

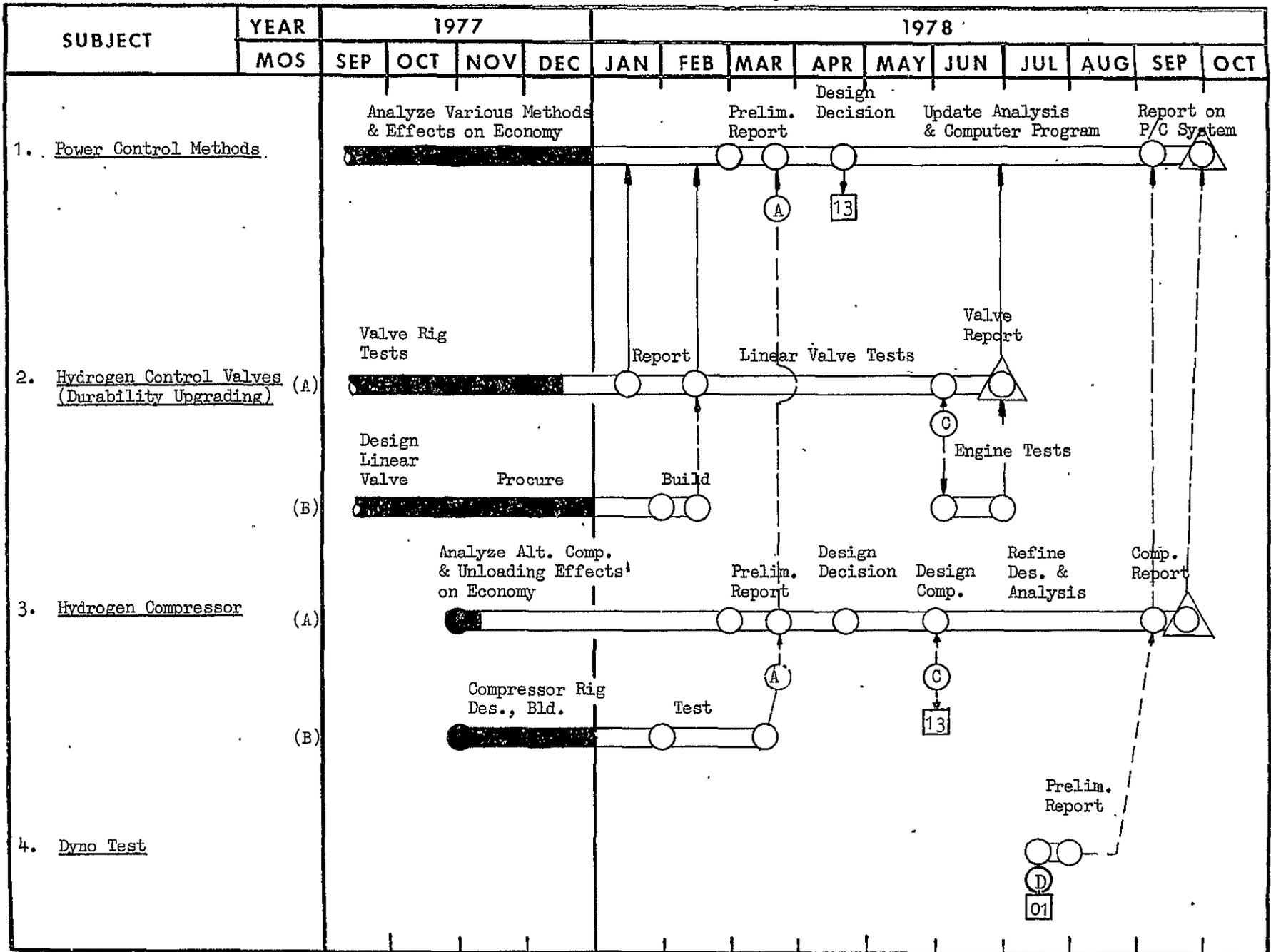
FUEL ECONOMY ASSESSMENT

The assessed fuel economy contribution of the External Heat and Blower System, sub-task 05, remained unchanged at 0.19 MPG (gasoline).

TABLE 3-1

Maximum Blower Airflow Requirements  
Reference Engine

<u>Engine Speed</u> (RPM)	<u>EGR</u> (%)	<u>Inlet</u>			<u>Pressure Rise Across Blower</u> (CmH <sub>2</sub> O)
		<u>Temp.</u> (°C)	<u>Pressure</u> (CmH <sub>2</sub> O)	<u>Volume Flow</u> (M <sup>3</sup> /sec)	
600	114	66.6	- 0.3	.0186	4.66
1000	143	87.7	- 1.5	.0509	14.48
1500	75	88.0	- 6.0	.1026	43.58
1725	10	31.4	- 5.5	.0799	40.08
1800	0	20.0	- 4.7	.0725	36.50
2000	0	20.0	- 5.5	.0771	40.80
2500	0	20.0	- 8.5	.0943	58.95
3000	0	20.0	-10.2	.1004	67.04
3500	0	20.0	-18.5	.1263	108.71
4000	0	20.0	-24.5	.1407	139.14
4500	0	20.0	-32.0	.1539	173.87



Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Eng. Test	Vehicle Projection
08	POWER CONTROL SYSTEM (KOSACHEFF)	.9					1.20
	.Alternate power control	-	.20				
	.Reduce power losses of power control actuator needed for fast transient response	-	.02				
	.Hydrogen compressor losses	.85	.85				
	.Eliminate "short circuiting" power losses during decelerations	-	.03				
	.Hydrogen distributor friction	.05	.05				
	.Sealed piston dome	.05 (2)	.05				

(2) Estimate included in the Total of Cycle Analysis, Sub-task 10

## POWER CONTROL, SUB-TASK 08

The purpose of this sub-task is to determine the fuel economy improvements that can be achieved through modifications to the hydrogen compressor system components, the hydrogen distribution system, and other power control components. The modified power control system will be evaluated on a test rig and, if necessary, on a dynamometer engine.

In this sub-task, computer programs supplied by N. V. Philips and United Stirling of Sweden are being utilized to develop a more effective method of power control. The present power control system is a mean pressure control system which increases or decreases engine power by increasing or decreasing the hydrogen supply in the engine. Computer simulations have indicated a maximum M-H fuel economy improvement of 0.94 MPG (using gasoline as the combustionable fuel) with a hybrid power control. The hybrid control is a combination of dead volume and mean pressure control. Maximum fuel economy is obtained with a maximum control volume of 300% of the swept volume displacement. A significant fuel economy improvement can also be realized with smaller amounts of control dead volume (see figure 3-13).

This sub-task will also concentrate on two of the component parts of the power control system; the hydrogen control valve and the hydrogen compressor.

The tests run on the hydrogen control valve indicates the suitability for another type of valve in this application. The hydrogen control valve will be redesigned to increase reliability. Unavailability of a hydraulic oil flow control valve has delayed tests which will determine minimum oil flow and pressure requirements that will be necessary for the new valve. However, a linear power control valve has delayed tests which will determine minimum oil flow and pressure requirements.

Work on the hydrogen compressors will consist mainly of evaluating the power required to drive these compressors. A test rig, as well as dynamometer testing, will be used for this evaluation. Hardware for test rig installation has been ordered.

Work on eliminating "short circuiting" power losses during deceleration modes of operation will continue. Engine short circuiting reduces engine torque immediately but does not reduce fuel flow so that it is an inefficient control mode. Reducing mean pressure by removing working fluid from the engine is the efficient and preferred method to reduce torque. The compressor size is a significant factor in that, if the compressor capacity is incapable of reducing mean engine pressure fast enough to satisfy a deceleration schedule during a driving cycle, the engine is short circuited.

### Power Control, Sub-task 08

Work will continue on reducing the hydrogen distributor friction. The hydrogen distributor is an engine driven, rotating valve that admits hydrogen to each cycle during the cycle's high pressure phase. The two bearings, seals, and other minor friction producing elements result in a power loss to the engine.

Designs for sealed piston domes will continue to be investigated. A sealed dome piston appreciably reduces the quantity of hydrogen to be transferred to and from the engine cycle during engine torque changes. Reducing the quantity of hydrogen to be transferred could result in reducing the capacity (size) of the compressors. This would result in an attendant fuel economy improvement.

During the next reporting period preliminary reports on power control methods, hydrogen control valves, and hydrogen compressors should be completed.

### FUEL ECONOMY ASSESSMENT

The assessed fuel economy contribution of the Power Control Systems, sub-task 08, remained unchanged at 1.20 MPG (gasoline).

METRO-HIGHWAY FUEL ECONOMY  
VS.  
CONTROL DEAD VOLUME

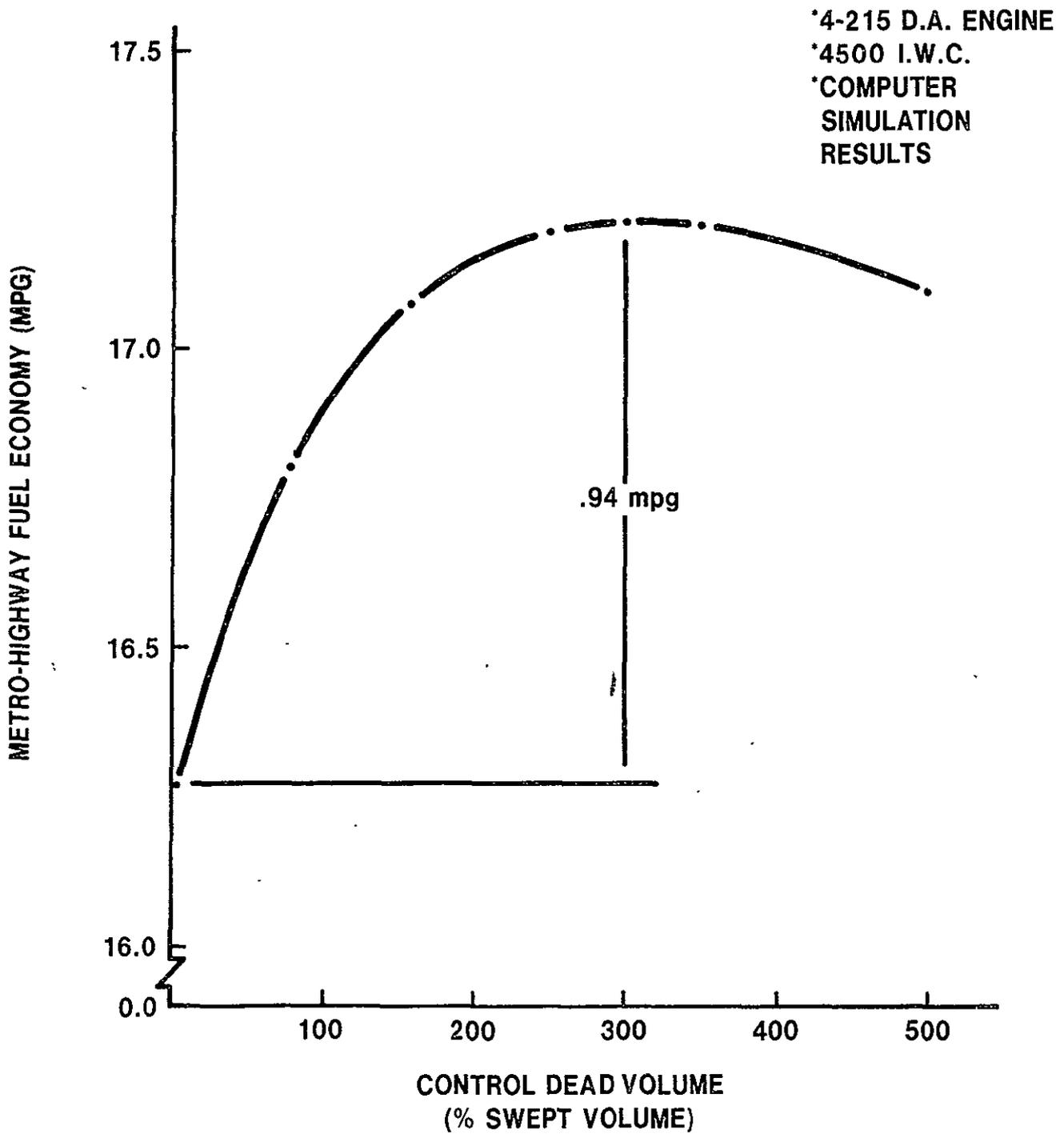
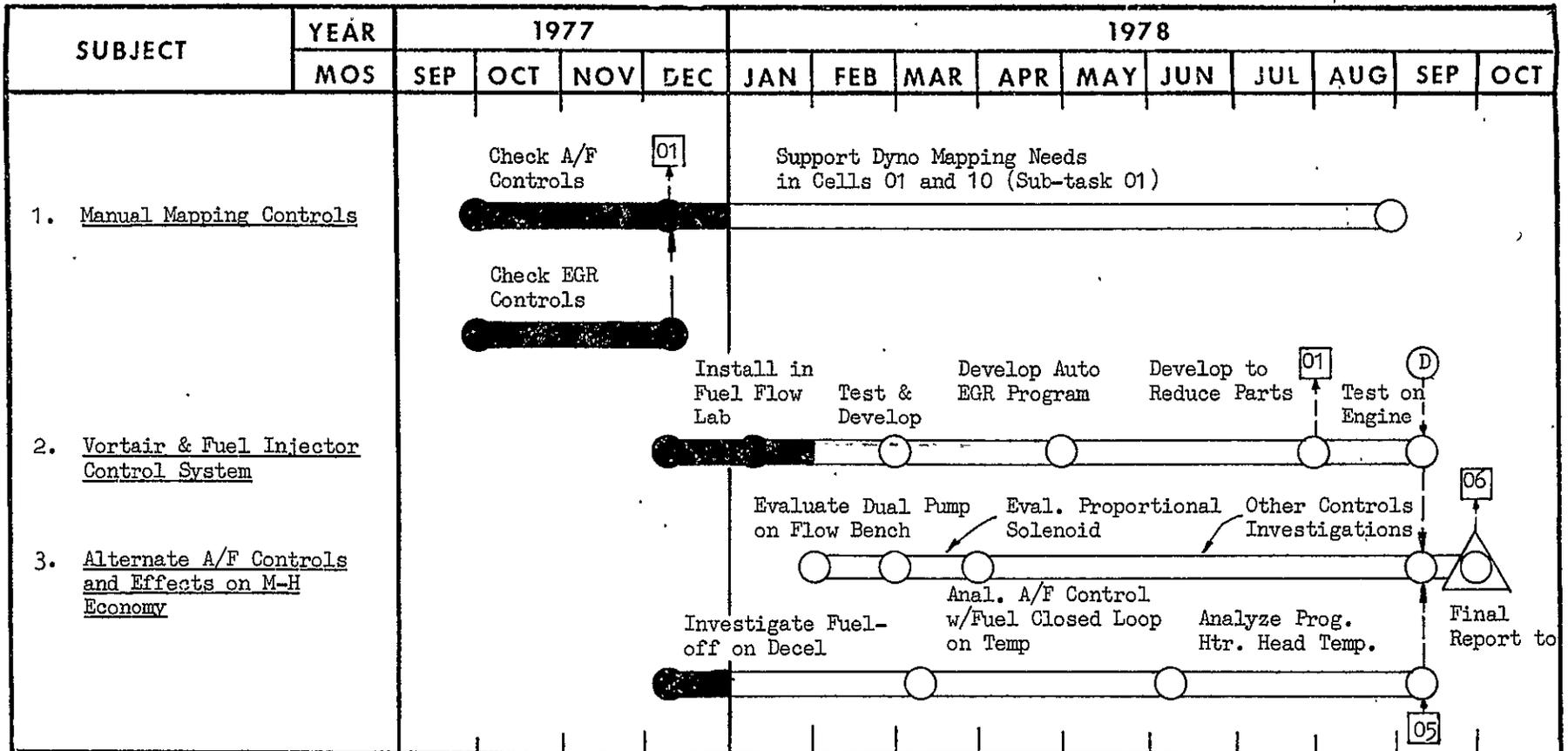


FIGURE 3-13



Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Engine Test	Vehicle Projection
09	AIR/FUEL CONTROL SYSTEM (FENTON)	.2					.23
	.Low pressure drop A/F control	.04		.06			
	.Improve A/F control	.10	.10				
	.Reduce power loss of electronic power and control systems	-		.07			

## AIR/FUEL CONTROL, SUB-TASK 09

The purpose of this sub-task is to determine the fuel economy improvement potential possible with modified or new air/fuel control systems. Based upon the results of vehicle correlation tests in sub-task 06, Ford will determine the extent of air/fuel control development required to complete mapping and optimization studies. At the end of this sub-task, the air/fuel control system will be transferred to the dynamometer engine for the final mapping and optimization effort.

This sub-task is directly related to the Mapping and Optimization and Burner System sub-tasks in that controls used for the engine, burner, and dynamometer during dynamometer testing are supplied by this sub-task.

The fuel metering computation circuit of the dynamometer air/fuel control was updated by adding non-linear gain computation. The circuit will now compensate for the non-linear response characteristics of the vortair air flow sensor so that a nearly constant air/fuel ratio will be maintained over the range of fuel flow requirements of the engine.

A logic circuit for automatically positioning the exhaust gas recirculation (EGR) valve was added to the dynamometer cell engine control system. The logic circuit senses engine conditions which could cause exhaust sooting, and automatically positions the EGR valve, reducing the probability of this situation.

This sub-task will also deal with the further development of the vortair air/fuel control system while investigating alternative air/fuel controls, measuring their effect on fuel economy. The air/fuel control (vortair) now used on the 4-215 Stirling was designed by Ford Motor Company when the controls provided by N. V. Philips were found inadequate for the requirements set by Ford. The Vortair system will, however, be developed further and tested on the dynamometer.

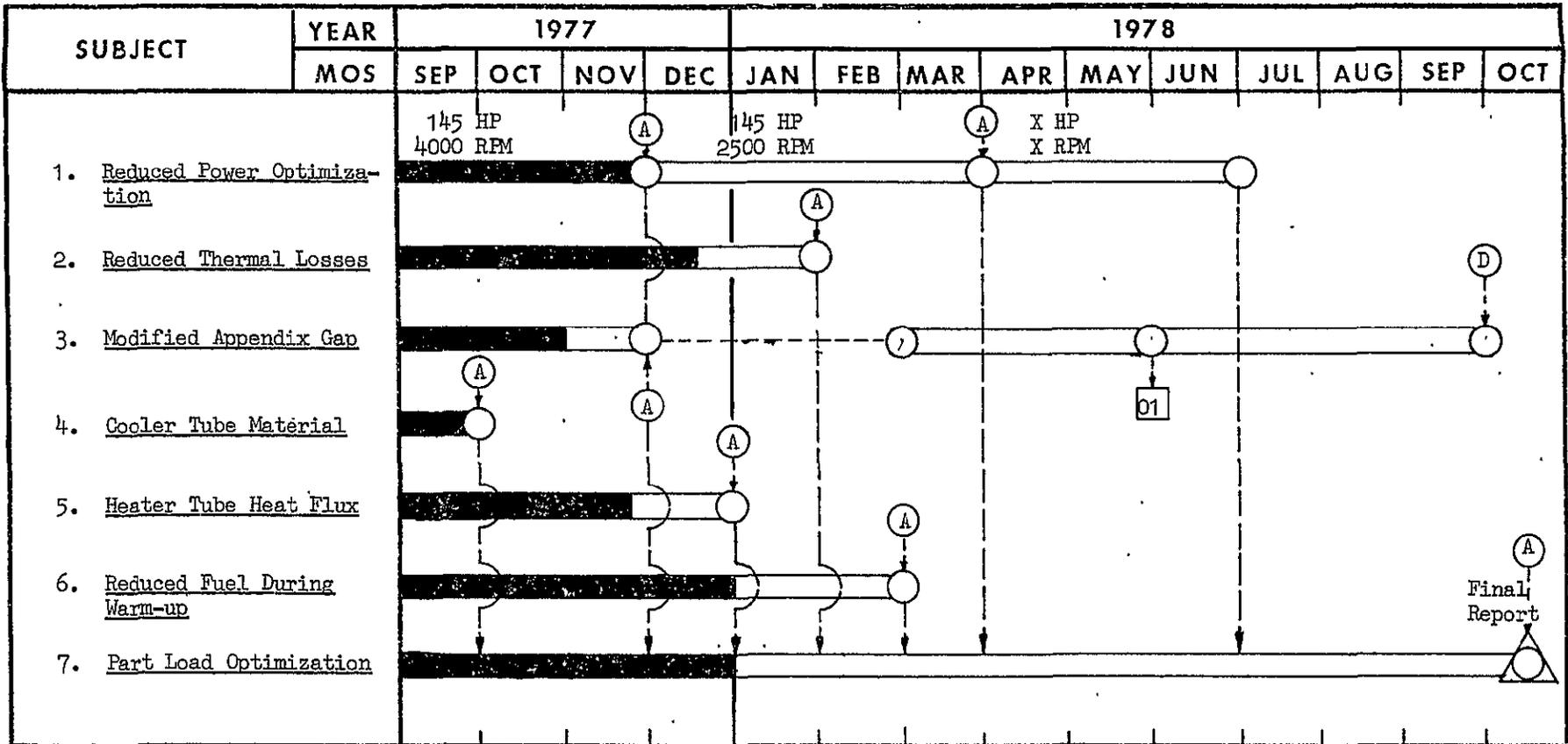
During the next reporting period test and development of the Vortair and fuel injector control system will begin in the fuel flow lab. A program will also begin to develop an automatic EGR program. A flow bench evaluation of a dual pump will be started. Fuel Off on Deceleration investigations will not be completed until personnel from the theoretical analysis group have completed other higher priority assignments.

Air/Fuel Control, Sub-task 09 (Continued)

Fuel Economy Assessment

The assessed fuel economy contribution of Air/Fuel Control, sub-task 09, increased from .16 MPG to .23 MPG (gasoline) during this quarter. A computer analysis of the blower power reduction, resulting from replacing the original Philips 2/3 valve with the Ford Vortair air flow sensor, yielded a 0.06 MPG (gasoline) increase compared to the 0.04 MPG originally estimated.

A first run calculation on the computer engine using a 46 ampere vs. a 50 ampere alternator load during the simulated EPA tests have shown a 0.07 MPG increase compared to the 0.02 originally estimated.



FUEL ECONOMY ASSESSMENT (MPG)

Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(E) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
10	CYCLE ANALYSIS (REAMS)	2.1					2.38
	.Reduced power reoptimization	.63	-	2.20	[Hatched]	[Hatched]	
	.Reduced thermal losses	.16	-				
	.Modified appendix gap	.27	-				
	.H <sub>2</sub> cooler tube material	.12	-				
	.Increased heater head heat flux	.16	.16				
	.Reduce fuel loss used for engine warm-up	-	.02				
	.Part load reoptimization	.63	-				

## CYCLE ANALYSIS, SUB-TASK 10

The purpose of this sub-task is to determine potential fuel economy improvements which would result from changes to the basic Stirling cycle. Cycle analysis will be performed, using developed computer programs, to establish opportunities for providing significant fuel economy improvements. Modifications to the current design, such as engine size, reoptimization, and heat loss reduction will be examined. Information from this sub-task will be used in the Reference Engine, sub-task 13.

A complex of computer programs which was written by N. V. Philips will be the main tool employed during this sub-task. This program allows examination of various aspects of Stirling engine operation such as; reduced power optimization, reduced thermal losses, modified appendix gap, cooler tube material, heater head heat flux, reduced fuel during warm-up, and part-load engine optimization.

With the exception of the 4-215 Stirling engine, all other engines mentioned in this write-up exist only as computer models and not as hardware. The optimization program systematically varies Stirling engine dimensions and searches for maximum efficiency within a given set of constraints such as maximum power, overall engine length etc. The 4-215 Stirling engine was optimized at a higher power range than is necessary to meet the power requirements of the present baseline. Because of this, a reduced power optimization exercise was performed in an effort to reduce power output of the engine and perhaps increase the fuel economy of the Stirling engine.

A number of reduced power optimization runs were made since the initiation of this sub-task. All of these runs were made at the full-load design point of 145 HP net. The attempts included various combinations of heater-head heat flux, engine speed, engine length and O.D., and heater tube heat ratio.

One of the optimizations resulted in an engine designated the 4-270, with a design speed of 2525 RPM, and another attempt resulted in the 4-204 with a design speed of 4000 RPM, the same as the baseline 4-215 engine. Complete engine maps for both of these engines were generated, and fuel economy calculations were carried out. The 4-270 engine gave a 1.4 MPG improvement over baseline and the 4-204 engine gave a 1.5 MPG increase. Sample outputs from our fuel economy calculation program are included showing the M-H fuel economy for the 4-215, 4-270, and 4-204 engines. (Refer to Tables 3-2, 3-3, and 3-4 respectively.)

This program was also used for a part-load calculation. The objective of part-load optimization is to determine the gains in engine performance which would result from designing an engine at the same intermediate operating point while still satisfying the full load design conditions. Figure 3-14 illustrates a hypothetical engine speed/torque map indicating those points which are of interest in a part-load optimization.

Cycle Analysis, Sub-task 10 (Continued)

Beginning with essentially the same starting conditions used in the previous reduced power optimization attempts, new designs were initiated which required indicated efficiency to be maximized at either the maximum torque (MT) point or the metro-highway (M-H) composite point. The "best" engine to date, using this procedure, is the 4-247. This engine gives an improvement of 2.2 MPG over the baseline 4-215. These results are listed in Table 3-5.

It should be noted that the part-load optimization procedure includes elements of reduced power optimization (previously discussed) reduced thermal losses, modified appendix gap, and cooler tube material.

Thermal losses in this application, are defined as the heat that is conducted from the hot side to the cold side of the engine. Analysis has been initiated on the 4-247 in an effort to assess the fuel economy improvement which would result from reducing the thickness of the cylinder and regenerator housing walls by one half their present thickness. By reducing the thickness of the cylinder and regenerator walls, the path of heat conduction will be reduced, thus reducing the heat transferred to the cold side of the engine. Due to the fact that the Stirling engine is a heat engine (requires heat to run the Stirling cycle), heat lost to the cool side of the engine must be replaced by burning additional fuel. However, no stress analysis is being performed at this time; therefore, the confidence level of the fuel economy resulting from reducing thermal losses will be low.

The appendix gap is an annular volume defined by the clearance between the piston dome and the cylinder, and the length of the dome itself (see figure 3-15). By changing the dimensions of this gap, changes in engine performance can be achieved. To date, the only analysis performed is based on the effect of increasing and decreasing the gap length of the optimized 4-247 engine and observing the effect on M-H fuel economy. Because the engine was optimized with "floating" dome dimensions, in both cases M-H fuel economy decreased.

The choices for cooler tube material have centered around steel and aluminum. Using the 4-215 engine, complete engine maps were generated using first steel and then aluminum for the cooler tubes, both at a constant radiator top water temperature of 50°C. The results revealed a 0.014 increase in fuel economy improvement when aluminum was substituted for steel.

Heater Tube Heat Flux is defined as the heat transferred through the heater tube to the hydrogen divided by the inside tube wall area measured in kilowatt per centimeter squared. An attempt was made to predict the effect of variations in heater head heat flux on the projected M-H fuel economy of a Stirling engine powered vehicle.

### Cycle Analysis, Sub-task 10 (Continued)

Initial attempts at running the optimization program at fluxes other than the baseline value of  $125 \text{ w/cm}^2$  were unsuccessful. The CONDIT sub-routine was then modified to increase the chances of obtaining convergent optimization runs.

Eventually, convergent runs were obtained at approximately 100, 150, and  $200 \text{ w/cm}^2$ . However, some of these runs were (and are) of questionable value since the various tube dimensions and numbers of tubes calculated are such that the indicated number of tubes cannot be placed on the heater head of an actual engine, at least with practical tube wall thicknesses. In this situation, fin dimensions cannot be established nor can the burner program be run to obtain the fuel flows required in the engine map.

For these reasons, the effect of heat flux on fuel economy has not yet been established and additional optimization runs will be required.

Due to the significant effect on fuel economy of the fuel burned to heat the engine during a cold start, an improved computer analysis program has been developed. The computer program incorporates the .43 cold start fuel economy penalty. A typical sample output from this program is attached (refer to table 3-6).

A preheater optimization program has been under development for use in conjunction with the part-load engine optimization techniques as used in the Stirling engine optimization, but with the burner program as the analytical sub-routine. This program will eventually be used to size heater tube fins and preheater core, taking into consideration system efficiency, air system pressure drop, and maximum preheater inlet temperature.

During the next reporting period, it is anticipated that studies on Reduced Thermal Losses, Modified Appendix Gap, Heater Tube Heat Flux, and Reduced Fuel During Warm-up will be completed. Work on Reduced Power Optimization will continue.

### FUEL ECONOMY ASSESSMENT

The assessed fuel economy improvement contribution for Cycle Analysis, sub-task 10, remained unchanged at 2.38 MPG (gasoline).

TABLE 3-2

METRO-HIGHWAY FUEL ECONOMY SUMMARY FOR 4-215 ENGINE PREPARED ON 2 DEC 1977  
 BASED ON ENGINE MAP DATA FILE W215.10 AND N-H DATA FILE NH215.45 (4500 LB. IVC VEN.)

THESE RESULTS ARE BASED ON A DYNAMOMETER ENGINE WITH STEERING AND FAN LOSSES EQUAL TO ZERO

\*\*\*\*\*  
 N-H PT    SPEED    TORQUE    POWER    PRESS    FUEL    CITY    CITY    % TOT    HIWAY    HIWAY    % TOT    ICASE  
           RPH        NM        KW        ATM       G/G    SEC    GRAM    CITY    SEC        BRAM    HIWAY  
 \*\*\*\*\*

1	600.000	53.180	3.341	32.324	0.538	384.700	206.910	15.959	10.500	5.647	0.420	4
2	800.000	40.700	3.410	27.571	0.583	202.800	118.286	9.124	5.100	2.975	0.221	4
3	900.000	-6.780	-0.639	11.082	0.392	115.000	45.113	3.480	56.000	21.968	1.633	2
4	1000.000	67.840	7.104	36.455	0.818	184.700	151.135	11.657	11.400	9.328	0.693	4
5	1100.000	108.540	12.503	50.597	1.125	202.400	227.734	17.566	13.200	14.852	1.104	4
6	1300.000	156.020	21.240	68.398	1.650	120.600	199.002	15.349	20.300	33.497	2.489	4
7	1600.000	203.510	34.098	87.594	2.464	37.800	93.151	7.185	32.800	80.829	6.007	4
8	1700.000	108.540	19.323	52.227	1.648	58.000	95.597	7.374	311.800	513.919	38.193	4
9	1800.000	217.080	40.919	94.229	2.938	25.300	74.338	5.734	33.600	98.726	7.337	4
10	2000.000	122.110	25.575	58.754	2.094	40.700	85.214	6.573	269.300	563.839	41.903	4

TOTAL CVS-H FUEL CONSUMPTION = 1296.4815 GRAMS  
 CVS-H FUEL ECONOMY = 16.2134 MPG  
 COLD START FUEL PENALTY = 147.7000 GRAMS  
 TOTAL CVS-CH FUEL CONSUMPTION = 1444.1815 GRAMS  
 CVS-CH FUEL ECONOMY = 14.5552 MPG  
 TOTAL EPA HWY FUEL CONSUMPTION = 1345.5797 GRAMS  
 EPA HWY FUEL ECONOMY = 21.3333 MPG

\*\*\*\*\*  
 \*  
 \* TOTAL N-H FUEL ECONOMY = 16.9834 MPG \*  
 \*  
 \*\*\*\*\*

CITY    TOTAL POSITIVE ENGINE WORK = 4.793 HP-HR  
 =====  
 TOTAL NEGATIVE ENGINE WORK = -0.027 HP-HR  
 NET ENGINE WORK = 4.766 HP-HR  
 NET OVERALL EFFICIENCY = 22.437 PCT.

HWAY    TOTAL POSITIVE ENGINE WORK = 6.010 HP-HR  
 =====  
 TOTAL NEGATIVE ENGINE WORK = -0.013 HP-HR  
 NET ENGINE WORK = 5.997 HP-HR  
 NET OVERALL EFFICIENCY = 27.205 PCT.

TABLE 3-3

METRO-HIGHWAY FUEL ECONOMY SUMMARY FOR 4-270 ENGINE PREPARED ON 2 DEC 1977  
 BASED ON ENGINE MAP DATA FILE W270.02 AND M-H DATA FILE NH27045A (4500 LB. IUC VEH.)

THESE RESULTS ARE BASED ON A VEHICLE ENGINE WITH STEERING AND FAN LOSSES INCLUDED

N-H PT	SPEED RPM	TORQUE NM	POWER KW	PRESS ATM	FUEL G/S	CITY SEC	CITY GRAM	Z TOT CITY	HIWAY SEC	HIWAY GRAM	Z TOT HIWAY	ICASE
1	380.000	67.800	2.698	41.163	0.436	292.560	127.696	10.073	3.000	1.309	0.119	4
2	600.000	128.800	8.093	57.756	0.749	215.480	161.493	12.739	12.270	9.196	0.835	4
3	750.000	101.700	7.987	48.767	0.785	491.610	385.832	30.434	51.460	40.388	3.669	4
4	900.000	216.900	20.442	86.533	1.460	169.860	248.050	19.566	32.190	47.008	4.270	4
5	1000.000	-6.800	-0.712	15.739	0.442	43.000	19.017	1.500	93.000	41.130	3.736	4
6	1100.000	155.900	17.958	66.622	1.396	33.880	47.292	3.730	292.890	408.836	37.140	4
7	1200.000	318.600	40.036	123.706	2.640	57.490	151.749	11.970	43.620	115.138	10.459	4
8	1350.000	176.300	24.924	75.199	1.858	68.130	126.619	9.988	235.570	437.806	39.771	4

TOTAL CVS-H FUEL CONSUMPTION = 1267.7481 GRAMS  
 CVS-H FUEL ECONOMY = 16.5809 MPG  
 COLD START FUEL PENALTY = 166.0000 GRAMS  
 TOTAL CVS-CH FUEL CONSUMPTION = 1433.7481 GRAMS  
 CVS-CH FUEL ECONOMY = 14.6612 MPG  
 TOTAL EPA HWY FUEL CONSUMPTION = 1100.8103 GRAMS  
 EPA HWY FUEL ECONOMY = 26.0769 MPG

\*\*\*\*\*  
 \*  
 \* TOTAL M-H FUEL ECONOMY = 18.2579 MPG \*  
 \*  
 \*\*\*\*\*

CITY  
 ===  
 TOTAL POSITIVE ENGINE WORK = 5.416 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.011 HP-HR  
 NET ENGINE WORK = 5.405 HP-HR  
 NET OVERALL EFFICIENCY = 26.024 PCT.

HWAY  
 ====  
 TOTAL POSITIVE ENGINE WORK = 5.235 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.025 HP-HR  
 NET ENGINE WORK = 5.210 HP-HR  
 NET OVERALL EFFICIENCY = 28.892 PCT.

3-19

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TABLE 3-4

METRO-HIGHWAY FUEL ECONOMY SUMMARY FOR 4-204 ENGINE PREPARED ON 2 DEC 1977  
 BASED ON ENGINE MAP DATA FILE U204.01 AND M-H DATA FILE MH215.45 (4500 LB. IWC VEH.)

THESE RESULTS ARE BASED ON A DYNAMOMETER ENGINE WITH STEERING AND FAN LOSSES EQUAL TO ZERO

\*\*\*\*\*  
 M-H PT SPEED TORQUE POWER PRESS FUEL CITY CITY X TOT HIWAY HIWAY X TOT ICASE  
 RPM NH KW ATM G/S SEC GRAM CITY SEC GRAM HIWAY  
 \*\*\*\*\*

1	600.000	53.180	2.341	41.902	0.475	384.700	182.820	15.553	10.500	4.990	0.404	4
2	800.000	40.700	3.410	35.892	0.517	202.800	104.789	8.915	5.100	2.635	0.213	4
3	900.000	-6.780	-0.639	14.102	0.339	115.000	39.032	3.321	56.000	19.007	1.537	2
4	1000.000	67.840	7.104	47.931	0.734	184.700	135.552	11.532	11.400	8.367	0.677	4
5	1100.000	108.540	12.503	67.929	1.027	202.400	207.838	17.682	13.200	13.555	1.096	4
6	1300.000	156.020	21.240	92.875	1.523	120.600	183.640	15.623	20.300	30.911	2.500	4
7	1600.000	203.510	34.098	119.910	2.289	37.800	86.518	7.361	32.800	75.074	6.071	4
8	1700.000	108.540	19.323	70.304	1.512	58.000	87.715	7.462	311.800	471.542	38.133	4
9	1800.000	217.080	40.919	129.119	2.733	25.300	69.136	5.882	33.600	91.817	7.425	4
10	2000.000	122.110	25.575	79.258	1.926	40.700	78.387	6.669	269.300	518.663	41.944	4

TOTAL CVS-H FUEL CONSUMPTION = 1175.4263 GRAMS  
 CVS-H FUEL ECONOMY = 17.8832 MPG  
 COLD START FUEL PENALTY = 161.3000 GRAMS  
 TOTAL CVS-CH FUEL CONSUMPTION = 1336.7263 GRAMS  
 CVS-CH FUEL ECONOMY = 15.7253 MPG  
 TOTAL EPA HWY FUEL CONSUMPTION = 1236.5600 GRAMS  
 EPA HWY FUEL ECONOMY = 23.2141 MPG

\*\*\*\*\*  
 \*  
 \* TOTAL M-H FUEL ECONOMY = 18.3958 MPG \*  
 \*  
 \*\*\*\*\*

CITY  
 ===  
 TOTAL POSITIVE ENGINE WORK = 4.793 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.027 HP-HR  
 NET ENGINE WORK = 4.766 HP-HR  
 NET OVERALL EFFICIENCY = 24.748 PCT.

HWAY  
 ===  
 TOTAL POSITIVE ENGINE WORK = 6.010 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.013 HP-HR  
 NET ENGINE WORK = 5.997 HP-HR  
 NET OVERALL EFFICIENCY = 29.603 PCT.

TABLE 3-5

METRO-HIGHWAY FUEL ECONOMY SUMMARY FOR 4-247 ENGINE PREPARED ON 2 DEC 1977  
 BASED ON ENGINE MAP DATA FILE U247.01 AND M-H DATA FILE MH215.45 (4500 LB. IUC VEH.)

THESE RESULTS ARE BASED ON A DYNAMOMETER ENGINE WITH STEERING AND FAN LOSSES EQUAL TO ZERO

\*\*\*\*\*  
 M-H PT SPEED TORQUE POWER PRESS FUEL CITY CITY Z TOT HIWAY HIWAY Z TOT ICASE  
 RPM NM KW ATH S/S SEC GRAM CITY SEC GRAM HIWAY  
 \*\*\*\*\*

1	600.000	53.180	3.341	39.101	0.432	384.700	166.195	14.949	10.500	4.536	0.378	4
2	800.000	40.700	3.410	33.667	0.475	202.800	96.261	8.658	5.100	2.421	0.202	4
3	900.000	-6.780	-0.639	13.386	0.303	115.000	34.894	3.139	56.000	16.992	1.417	2
4	1000.000	67.840	7.104	45.067	0.688	184.700	127.032	11.426	11.400	7.841	0.654	4
5	1100.000	108.540	12.503	63.587	0.974	202.400	197.205	17.738	13.200	12.861	1.073	4
6	1300.000	156.020	21.240	86.683	1.465	120.600	176.641	15.888	20.300	29.733	2.480	4
7	1600.000	203.510	34.098	111.987	2.233	37.800	84.417	7.593	32.800	73.251	6.109	4
8	1700.000	108.540	19.323	66.134	1.463	58.000	84.874	7.634	311.800	456.272	38.052	4
9	1800.000	217.080	40.919	120.852	2.686	25.300	67.958	6.113	33.600	90.252	7.527	4
10	2000.000	122.110	25.575	74.388	1.875	40.700	76.307	6.863	269.300	504.902	42.108	4

TOTAL CVS-H FUEL CONSUMPTION = 1111.7849 GRAMS  
 CVS-H FUEL ECONOMY = 18.9069 MPG  
 COLD START FUEL PENALTY = 166.1000 GRAMS  
 TOTAL CVS-CH FUEL CONSUMPTION = 1277.8849 GRAMS  
 CVS-CH FUEL ECONOMY = 16.4494 MPG  
 TOTAL EPA HWY FUEL CONSUMPTION = 1199.0608 GRAMS  
 EPA HWY FUEL ECONOMY = 23.9401 MPG

\*\*\*\*\*  
 \*  
 \* TOTAL M-H FUEL ECONOMY = 19.1451 MPG \*  
 \*  
 \*\*\*\*\*

CITY  
 ===  
 TOTAL POSITIVE ENGINE WORK = 4.793 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.027 HP-HR  
 NET ENGINE WORK = 4.766 HP-HR  
 NET OVERALL EFFICIENCY = 26.164 PCT.

HWAY  
 ===  
 TOTAL POSITIVE ENGINE WORK = 6.010 HP-HR  
 TOTAL NEGATIVE ENGINE WORK = -0.013 HP-HR  
 NET ENGINE WORK = 5.997 HP-HR  
 NET OVERALL EFFICIENCY = 30.529 PCT.

3-51

REPRODUCIBILITY OF THE  
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TABLE 3-6

SAMPLE COLD START FUEL CALCULATION  
ENGINE REFERENCE NUMBER --BASELINE

COMPONENT	COLD START FUEL - GRAMS	PERCENT OF TOTAL
FINS	16.22	10.8
TUBES	22.93	15.3
CYLINDER WALLS	19.06	12.7
CYLINDER ENDS	9.59	6.4
REGENERATOR WALLS	12.30	8.2
REGENERATOR ENDS	18.57	12.4
REGENERATOR MATRIX	7.37	4.9
PREHEATER	18.21	12.1
INSULATION	19.16	12.8
MISCELLANEOUS	6.50	4.3
TOTAL	149.91	

# DIAGRAM SHOWING POSSIBLE DESIGN POINTS CONSIDERED IN PART LOAD OPTIMIZATION STUDY

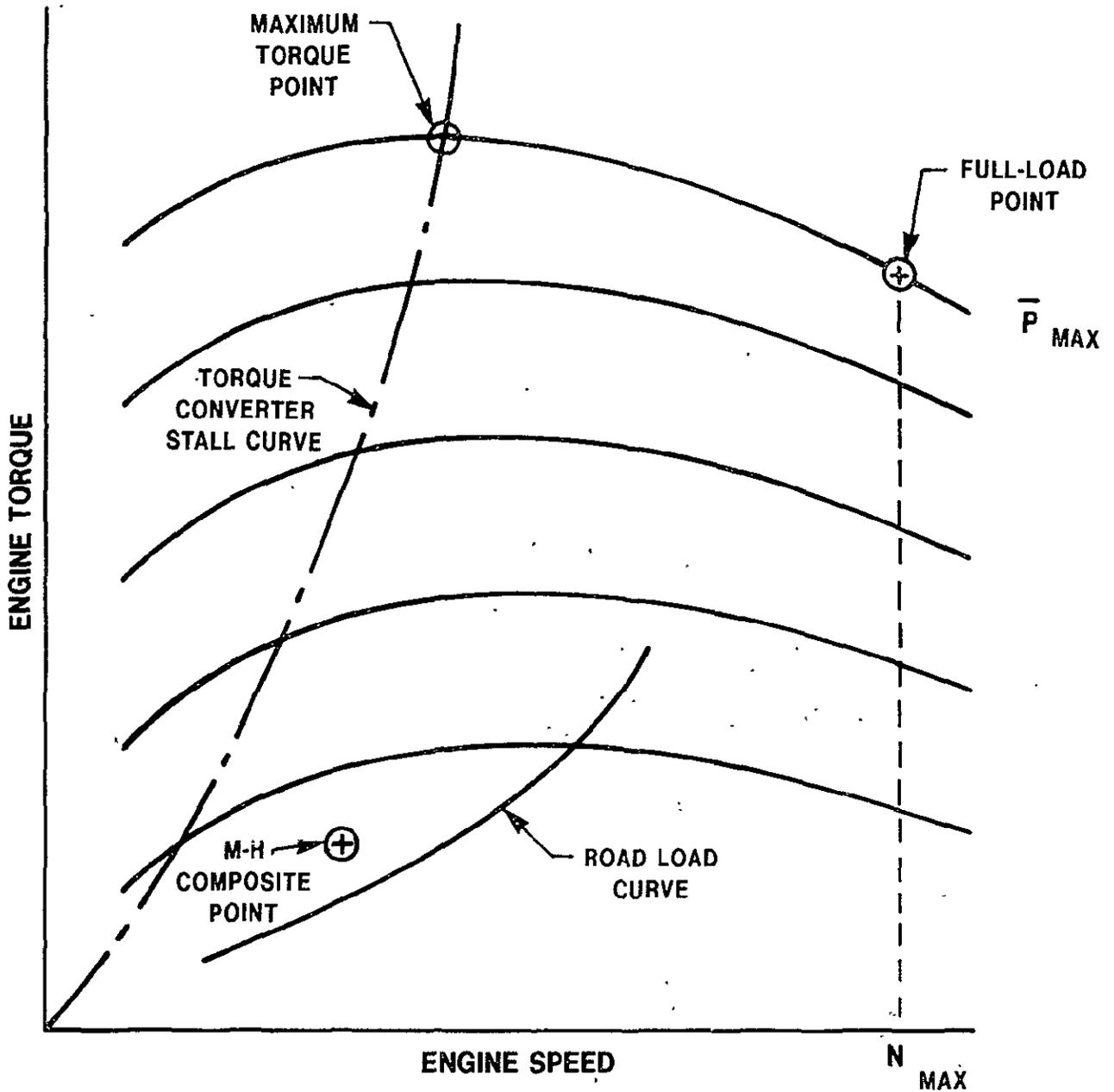


FIGURE 3-14

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LDD1 & LDD2  
ARE APPENDIX  
GAP LENGTHS

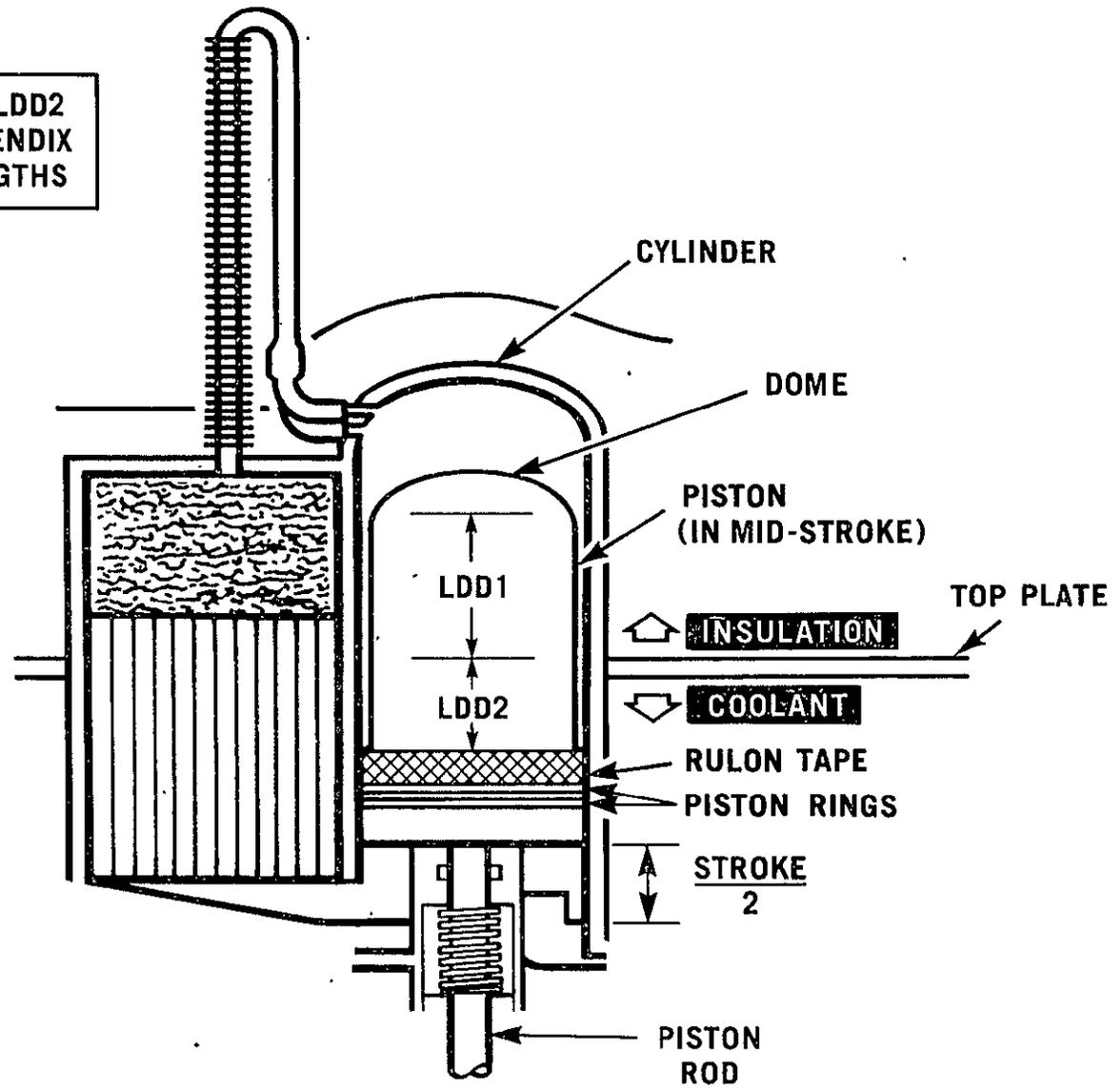


FIGURE 3-15

3-54

APPENDIX GAP LENGTH DIAGRAM

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#### OTHER FUEL ECONOMY IMPROVEMENTS, SUB-TASK 14

The purpose of this sub-task is to identify and assess the magnitude of potential fuel economy improvement areas not previously covered under any of the current program sub-tasks. Undoubtedly, additional opportunities for fuel economy improvements will be identified, especially from the Fuel Economy and Cycle Analysis sub-task efforts. Work required for this sub-task will be specified as the need arises and detailed workplans will be reviewed with DOE and NASA prior to initiation of efforts.

The items listed under this sub-task are not active projects. However, it is estimated that these items would produce improvements in fuel economy and, therefore, will be considered whenever possible, at various points during the Task I effort.

It should be noted that the assessed fuel economy improvement of this sub-task is based strictly on non-investigated estimates. When a proposed idea is considered ready for investigation, it will be moved to its applicable sub-task. At this point the assessed fuel economy improvement will also be transferred to the applicable sub-task, lowering the fuel economy estimate of this sub-task. Accordingly, when new items are added to this sub-task, the fuel economy improvement estimate of this sub-task will increase.

A new sub-sub-task, "Deceleration Fuel Shut-Off", has been added to this sub-task since the original proposal of May, 1977. From a continuous record of heater head  $H_2$  gas temperatures, monitored during vehicle operation over the CVS and EPA-HWY driving cycles, it was determined that  $H_2$  over temperature conditions existed for 190 sec. (CVS) and 40 sec. (EPA-HWY) during deceleration modes of operation. Fuel flow rates during over-temperature conditions were reduced to 0.4 g/s during the chassis dynamometer vehicle tests. If the fuel flow had been shut off during the over-temperature periods, instead of being reduced to 0.4 g/s, there would have been an estimated optimum fuel savings of 76g (CVS) and 16g (EPA-HWY). This savings in fuel has been translated into an estimated fuel economy improvement of 0.61 MPG. A confidence level of 20% has been assigned to this improvement (refer to sub-task 06, Fuel Economy Analysis).

A study of "Methods to Reduce Conduction Losses" with thinner cylinder and regenerator-cooler walls is in progress. A computer model of the 4-247 (fourth generation) Stirling engine with thinner walls (1/2 thickness) is being prepared for this evaluation (refer to sub-task 10, Cycle Analysis).

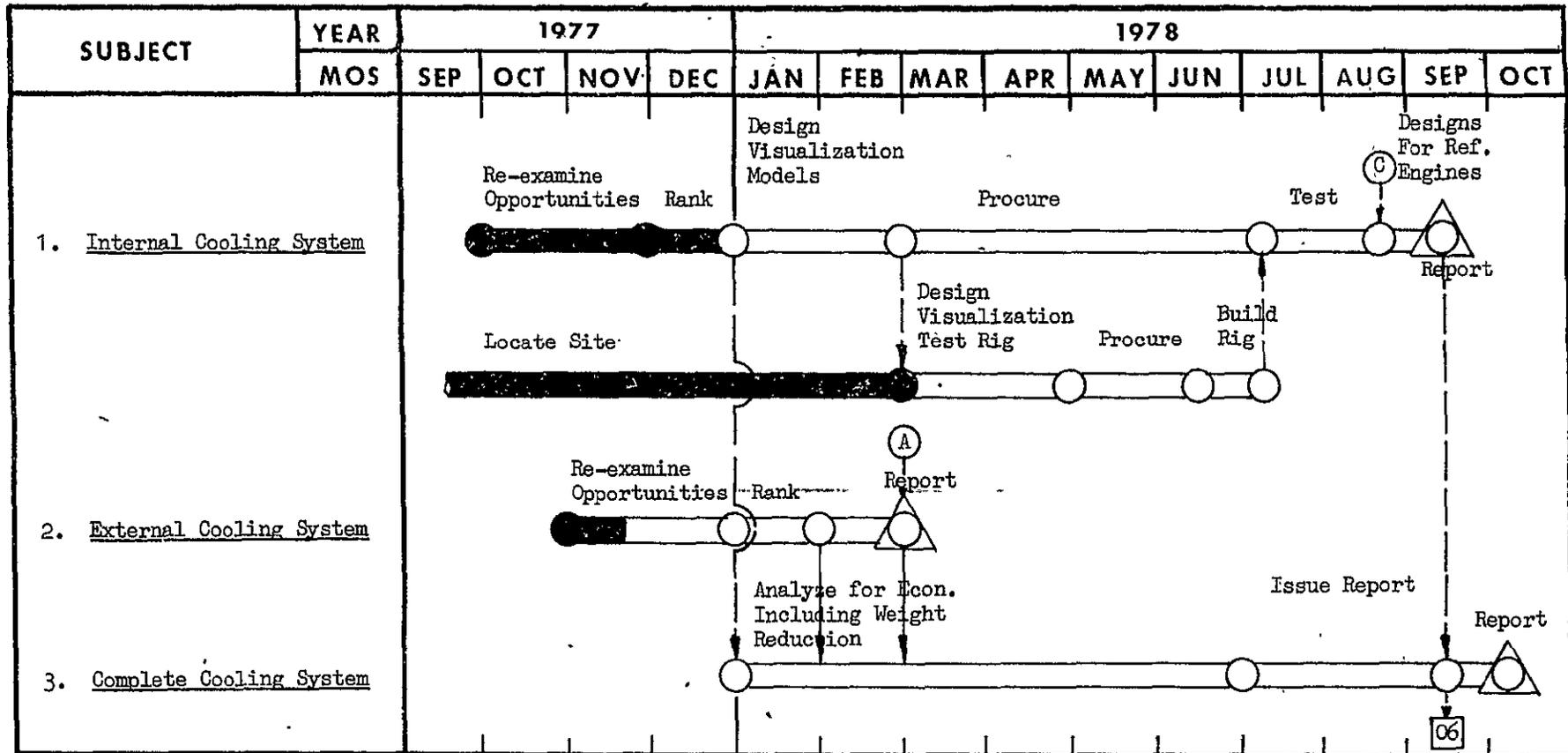
Other Fuel Economy Improvements; Sub-task 14 (Continued)

During the next reporting period a theoretical analysis of M-H fuel economy due to a reduction of engine and accessory inertia, oil pump requirements, and conduction losses will be conducted.

Fuel Economy Assessment

The assessed fuel economy improvement contribution of Other Fuel Economy Improvements has been increased from 0.39 MPG to 1.00 MPG (gasoline) due to the addition of Deceleration Fuel Cut-off.

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Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	(B) Estimate	(A) Theoretical Analysis	(C) Component Test	(D) Dyno. Engine Test	Vehicle Projection
15	COOLING SYSTEM (JONES)	.50					
	.Radiator fin improvement for lower pressure drop	-	.02				.06
	.W/P power reduction	-	.04				

## COOLING SYSTEM DEVELOPMENT, SUB-TASK 15

The purpose of this sub-task is to determine fuel economy improvement by conducting detailed analyses on the Stirling engine cooling system, including the water pump, radiator, fan and cooling water circuit, to identify specific opportunities for improvement and optimization. If required, existing components will be modified to substantiate the analyses.

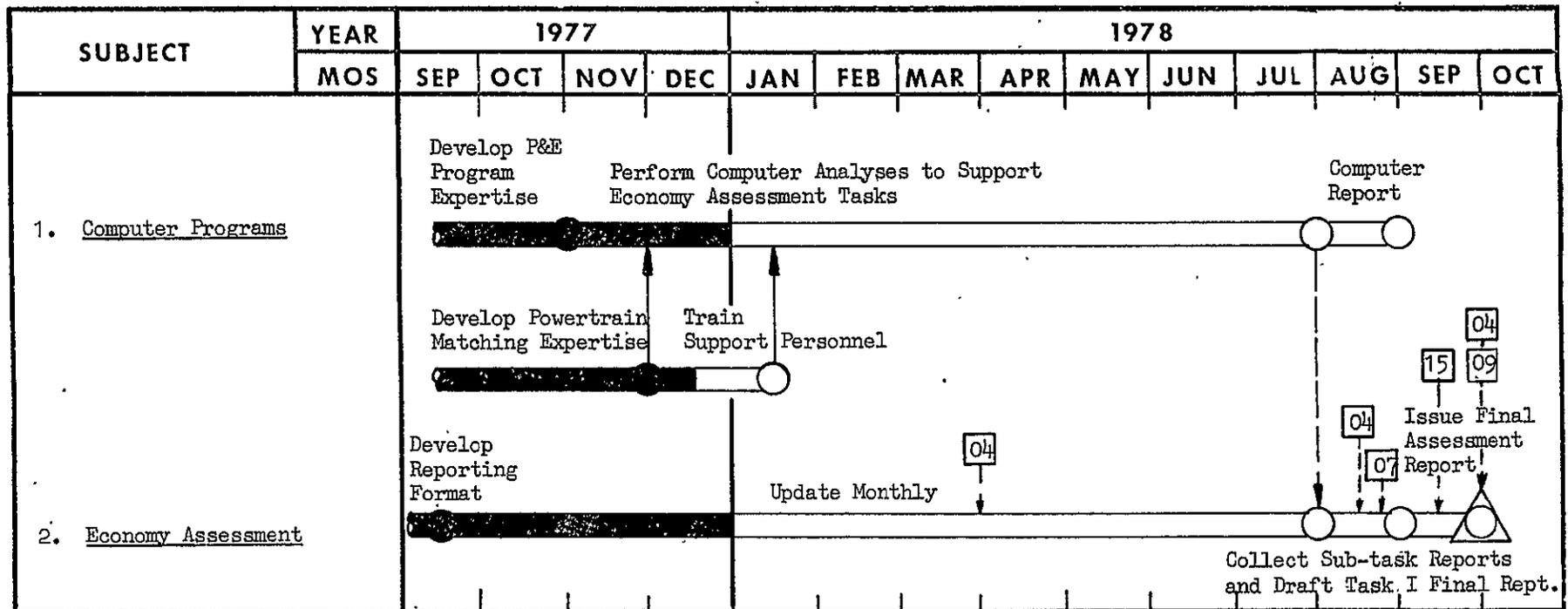
This sub-task will look at both the internal cooling system (the water jacket and water pump), and the external cooling system (radiator). In an effort to investigate the internal cooling system, two transparent models of the water jacket have been designed. The first model replicates the water jacket in the vicinity of the cylinder and regenerator-cooler walls and the second replicates the water jacket in the vicinity of the piston rod seals. The first model is presently being fabricated and quotes have been received for the second model. A review of engineering drawings with selected vendors is planned prior to issuance of a purchase request for fabrication.

The principal area of investigation on the external cooling system will be the radiator. There are no plans to experimentally develop air-side fin geometries within this sub-task. However, experimental advances in fin design within the Ford Motor Company are currently planned for evaluation in radiators. Information on the results of these studies will be available in the spring of 1978. No evaluations on the effects of improved extended fin surfaces on metro-highway fuel economy have been conducted to date.

During the next reporting period work will continue on selecting a vendor to fabricate the second plastic cooling system model. It is anticipated that external cooling system opportunities will be ranked.

### Fuel Economy Assessment

The assessed fuel economy improvement contribution of Cooling System Analysis, sub-task 15, remained unchanged at 0.06 MPG (gasoline).



This Sub-task requires the complete Fuel Economy Assessment Chart (pages 1 through 5) which is attached.

## FUEL ECONOMY ANALYSIS, SUB-TASK 06

The purpose of this sub-task is to predict engine and vehicle fuel economy characteristics at higher confidence levels, using information acquired from other program sub-tasks and from established Stirling engine computer modeling programs. In addition, Ford will conduct required analyses to help select other powertrain parameters such as torque converter, transmission gear ratios, and axle ratios to maximize the fuel economy and performance characteristics of the Stirling engine. At periodic intervals Ford will publish reports which review updated fuel economy characteristics. At the end of this sub-task effort Ford will publish a final report which predicts the fuel economy capability of the Stirling engine based upon test results obtained during performance of Task I and its associated sub-tasks.

Computations of dynamometer engine constant volume sampling hot (CVS-H) and Environmental Protection Agency - highway (EPA-HWY) time weighting factors at selected speed/load (mapping) points were completed using the chassis dynamometer road load equations with and without allowances for air conditioning. (A time weighting factor is achieved by running an engine on a dynamometer at a fixed load and speed. This exercise simulates actual engine operating conditions which would be experienced by an engine in a vehicle.) This information will permit fuel economy projections of vehicle chassis roll tests using engine dynamometer test data.

Calculations have been made to ensure that the projected 0-60 MPH WOT performance of the fourth generation Stirling engine (4-247) is similar to the measured performance of the 1977 baseline Ford LTD II vehicle equipped with a 351 CID engine. The projected 0-60 MPH time of 13.55 sec. was found to be within 0.25 sec. (1.8%) of the measured 0-60 time for the baseline vehicle. This difference in time between test and projection is considered negligibly small and indicates that the WOT torque curve for the fourth generation engine has been properly defined.

The Fuel Economy Assessment chart has been updated to reflect an overall incremental fuel economy improvement of 6.41 MPG using fourth generation engine technology developments (refer to Attachment 3-1). This projected improvement is 31% greater than the 4.90 MPG incremental improvement reported in the ERDA proposal of May, 1977.

At this time, all improvements in fuel economy are based on estimates and theoretical analysis. During the course of Task I studies, fuel economy improvements obtained through component and engine dynamometer tests will be reported at higher confidence levels. The overall confidence level of present projections is reported to be 29% to meet 22.11 MPG (gasoline) and 32% to meet 20.6 MPG. The expected confidence level is reported to be 54% to meet 22.11 MPG and 59% to meet 20.6 MPG (gasoline).

TASK IFUEL ECONOMY ASSESSMENT CHARTMONTHLY SUMMARY

<u>Date of Issue</u>	<u>4th Generation<sup>a/</sup> Engine Projections (MPG)</u>	<u>Confidence Level (%)</u>	
		<u>Present</u>	<u>Expected</u>
July 1977	22.00	27%	-
Aug. 1977	22.00	27%	52%
Sept. 1977 <sup>b/</sup>	21.16	29%	54%
Oct. 1977	21.16	29%	54%
Nov. 1977	21.23	29%	54%
Dec. 1977	22.11	29%	54%

<sup>a/</sup> Phase I objective - 15.7 MPG  
DOE Proposal Estimate - 20.6 MPG

<sup>b/</sup> Start of contract

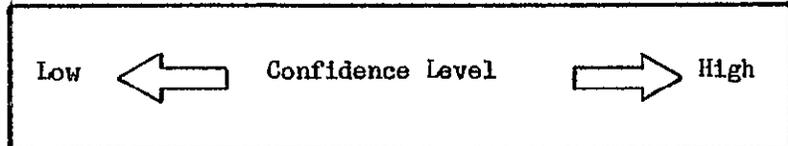
AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

VM-6301

TASK I - FUEL ECONOMY ASSESSMENT

SUB-TASKS 01-15

INCREMENTAL IMPROVEMENT  
IN METRO-HIGHWAY FUEL ECONOMY

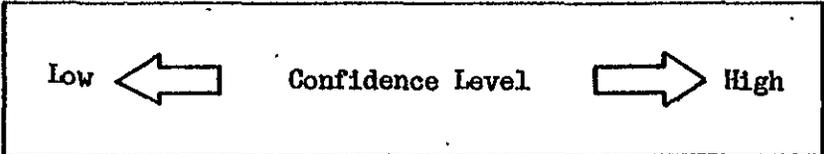


Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	Estimate	Theoretical Analysis	Component Test	Dynamometer Engine Test	Vehicle Projection
01	MAPPING & OPTIMIZATION (ERVIN)	.4					.38
	• Reduced EGR reqmts.	.04	.04				
	• Reduced exh. back pressure	.03	.03				
	• Minimum air flow reqmts.	.04	.04				
	• Temperature Scheduling	.27	.27				
02	BURNER SYSTEM (REAMS)	.2					.15
	• Low pressure drop burner	.02	.02				
	• Improved heater head temperature distribution	.13	.13				
03	PREHEATER (REAMS)	.3					.16
	• Engine driven preheater	.14	.14				
	• Thin wall material preheater core	.14	-(2)				
	• Seal friction reduction	.01	.00				
	• Reduced preheater leakage	.02	.02				

3-65

Low ← Confidence Level → High

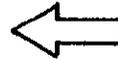
Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	Estimate	Theoretical Analysis	Component Test	Dynamometer Engine Test	Vehicle Projection
04	ENGINE DRIVE SYSTEM (KANTZ)	.2					.66
	• Crankshaft vs. Swashplate drive system	.10	.10				
	• Reduction of losses in accessory drive system	.05	.05				
	• Piston ring friction	-		.24			
	• Engine drive for fuel and air atomizing pump	-		+.27			
05	EXTERNAL HEAT AND BLOWER SYSTEM (KANTZ)	.1					.19
	• Improved blower design	.04	.04				
	• Improved blower drive	.05	.05				
	• Reduced air flow reqmts. (ref. subtask 10)	-	.10				
08	POWER CONTROL SYSTEM (KOSACHEFF)	.9					1.20
	• Hydrogen compressor plunger friction	.85	.85				
	• Hydrogen distributor friction	.05	.05				
	• Sealed piston dome	.05 (2)	.05				
	• Reduce power losses of power control actuator needed for fast transient response	-	.02				
	• Eliminate "short circuiting" power losses during decelerations	-	.03				
	• Alternate power control	-	.20				



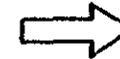
Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	Estimate	Theoretical Analysis	Component Test	Dynamometer Engine Test	Vehicle Projection
09	AIR/FUEL CONTROL SYSTEM (FENTON)	.2					.23
	• Low pressure drop A/F control	.04		.06			
	• Improve A/F control	.10	.10				
	• Reduce power loss of electronic power and control systems	-		.07			
10	CYCLE ANALYSIS (REAMS)	2.1					2.38
	• Part load reoptimization	.63	-	2.20			
	• Reduced thermal losses	.16	-				
	• Modified appendix gap	.27	-				
	• H <sub>2</sub> cooler tube material	.12	-				
	• Reduced power reoptimization	.63	-				
	• Increased heater head heat flux	.16	.16				
	• Reduce fuel loss used for engine warm-up	-	.02				

3-67

Low



Confidence Level

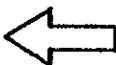


High

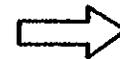
Sub-Task No.	Sub-Task Description	ERDA Proposal Estimate (1)	Estimate	Theoretical Analysis	Component Test	Dynamometer Engine Test	Vehicle Projection
14	OTHER FUEL ECONOMY-IMPROVEMENTS	-					1.00
	• Seal pumping rings & scrappers (cap seal)	-	.20				
	• Decreased air cleaner pressure drop	-	.02				
	• Accessory drive starting energy reqmts.	-	.02				
	• Reduction of engine & accessory inertia	-	.05				
	• Reduce oil pump reqmts.	-	.10				
	• Methods to reduce conduction losses (thin walls)	-	-				
	• Deceleration fuel shut-off	-	+.61				
15	COOLING SYSTEM (JONES)	.50					.06
	• Radiator fin improvement for lower pressure drop	-	.02				
	• W/P power reduction	-	.04				

3-68

Low



Confidence Level

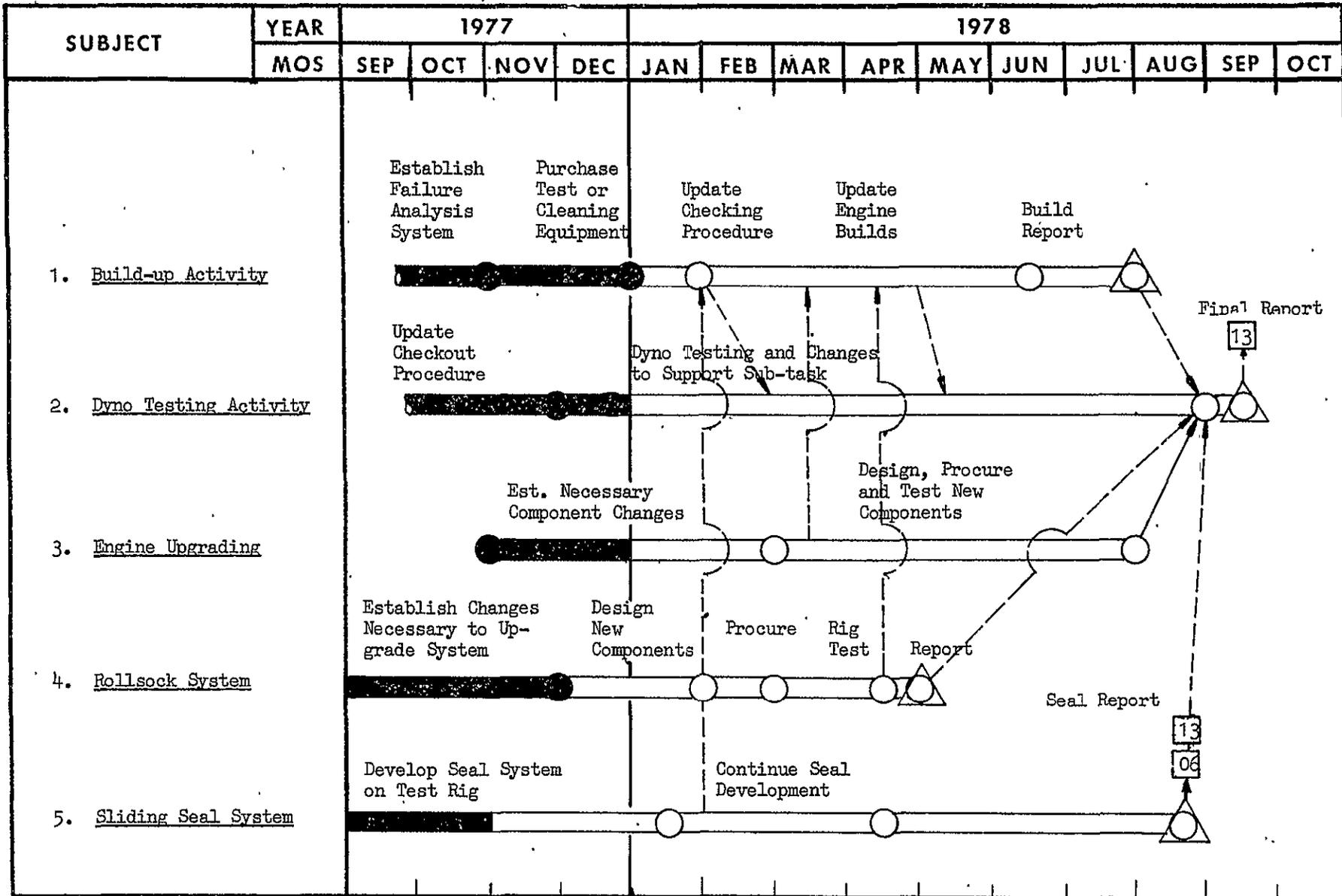


High

		Estimate	Theoretical Analysis	Component Test	Dynamometer Engine Test	Vehicle Projection
PHASE I OBJECTIVES (3)	-	-	-	-	-	15.7
ERDA PROPOSAL ESTIMATE (1)	4.90	-	-	-	-	20.6
FOURTH GENERATION ENGINE TECHNOLOGY (4)	-	3.57	2.84	0.00	0.00	22.11
Confidence Level Weighting Factor		.20	.40	.60	.80	
Confidence Level of Present Projections		20% to meet 22.1 mpg 32% to meet 20.6 mpg				
Expected Confidence Level		54% to meet 22.1 mpg 59% to meet 20.6 mpg				

ISSUE NO. 6 - DECEMBER, 1977

- (1) ERDA Proposal May 12, 1977 Volume II, Exhibit VII, page 5
- (2) Estimate included in the Total of CYCLE ANALYSIS, No. 10
- (3) Phase I objective; 4500 lb. (IWC), 2.75 rear axle ratio, 12.7 sec. (0-60 time)
- (4) 1977 baseline vehicle; 4500 lb. (IWC), 2.50 rear axle ratio, 13.3 sec. (0-60 time)



This Sub-task does not lend itself to Fuel Economy Assessment

## ENGINE DURABILITY UPGRADING, SUB-TASK 07

The purpose of this sub-task is to significantly upgrade the durability of the Stirling engine to be used in this program. This upgrading will improve the capability for running the Stirling engine for longer periods of time without the necessity of removing the engine from the dynamometer for repair.

At the time of contract start, engine 1X17 was installed in the dynamometer. At that time a continuous reading smoke detector was added to the engine to increase engine durability.

The smoke detector will be used to monitor exhaust gases and detect poor combustion. Poor combustion can cause a carbon build-up on the preheater resulting in a higher than normal restriction for incoming and outgoing air. The smoke detector will also make it possible to receive early exhaust indications as EGR levels and air/fuel ratios change. Engine 1X17 ran for a total of 23.5 hours before the #3 crosshead broke at the rear retaining groove.

Engine 3X16 was then installed in the test cell and has been run 24.2 hours since its installation at the end of November, 1977. However, the CO emissions measuring equipment created several problems which prevented the accumulation of a significant number of data points.

On December 22, 1977, a significant hydrogen leak developed which allowed hydrogen to escape into the water cooling system. Preliminary investigation indicated that the leak was in the vicinity of the regenerator coolers. The heater head will be removed for inspection. When the heater head has been replaced, two data points will be re-run to establish data repeatability.

At the present time the durability of the Stirling engine is limited. A major problem with durability has been the sealing system. Looking at engine failures which occurred prior to the Ford/DOE program, it becomes evident that a major portion of the engine failures have resulted from sealing problems (see figure 3-16). Presently there are two types of sealing systems; rollsock seals and sliding seals (see figure 3-17).

It should be noted that many sealing failures are a secondary result of some other failure. For example, if a hydrogen line were to rupture, a pressure differential in excess of the controlled 3 to 5 atmosphere differential is possible. This could result in a rollsock inversion and/or failure. In light of this, the rollsock protection device (which was designed, built, and installed prior to contract start) was improved by the addition of a device to protect against pressure surges (see figure 3-18).

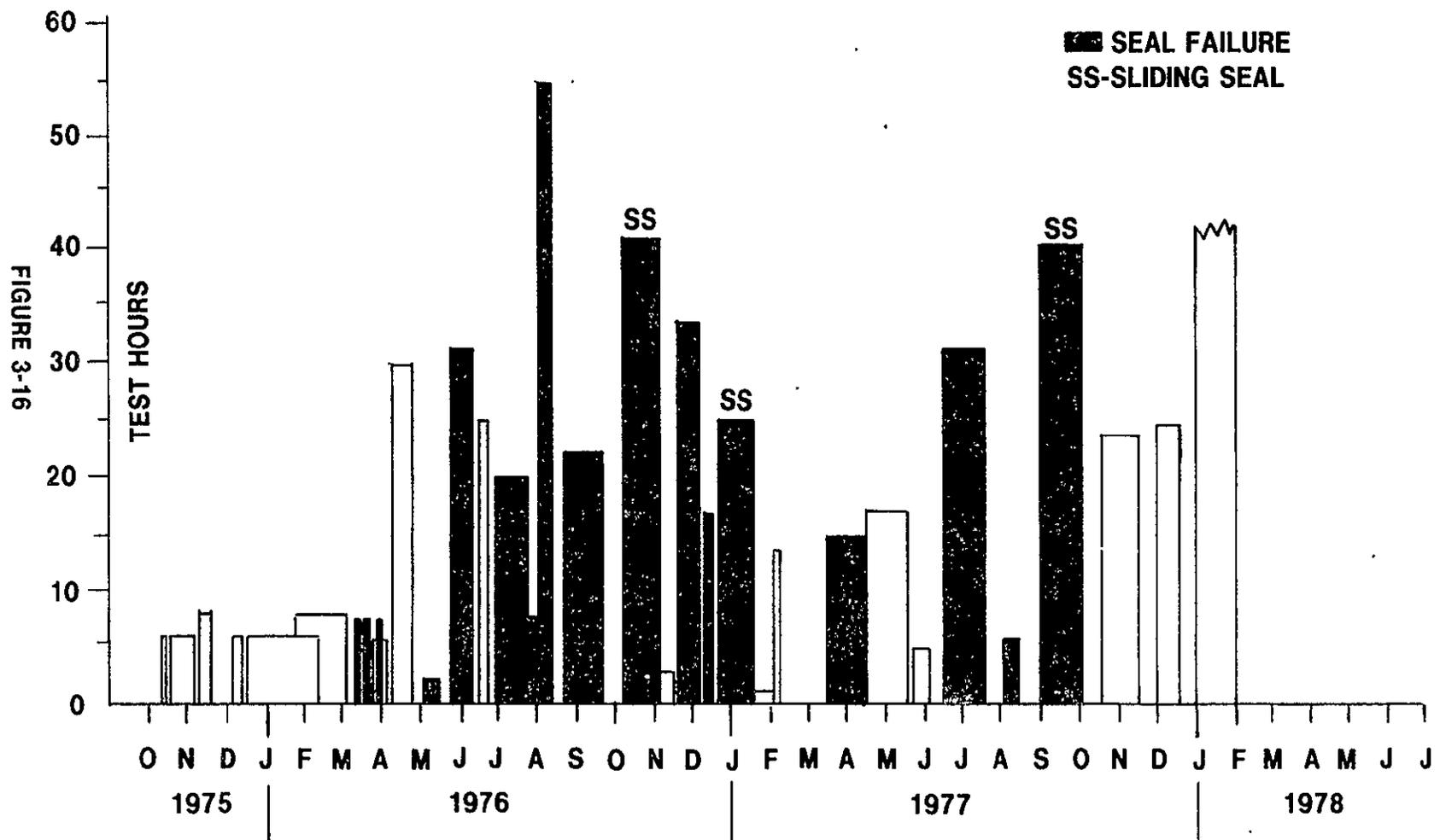
Engine Durability Upgrading, Sub-task 07 (Continued)

When a sealing system failure occurs, oil is passed to the gas side of the engine. This type of failure can sometimes lead to the oil contamination of the regenerators. When this occurs, the regenerators must be cleaned. To check the effectiveness of the cleaning method, a pressure drop test apparatus has been built which compares a cleaned regenerator with a new regenerator via a pressure check (see figure 3-19). Two test rigs for the piston rod rollsock sealing system, one crank drive and one swashplate drive, have been designed. Parts for both rigs have been ordered and some of the rollsock test rig parts have been received. Parts for the crank drive test rig are expected to be completed by February 1, 1978.

Meetings with NASA personnel were held on November 8 and 22, 1977 to discuss the piston rod sealing problems. The agenda for these meetings included the history and description of seal development programs at Philips and Ford, present testing and development plans, and new seal concepts from Ford and NASA.

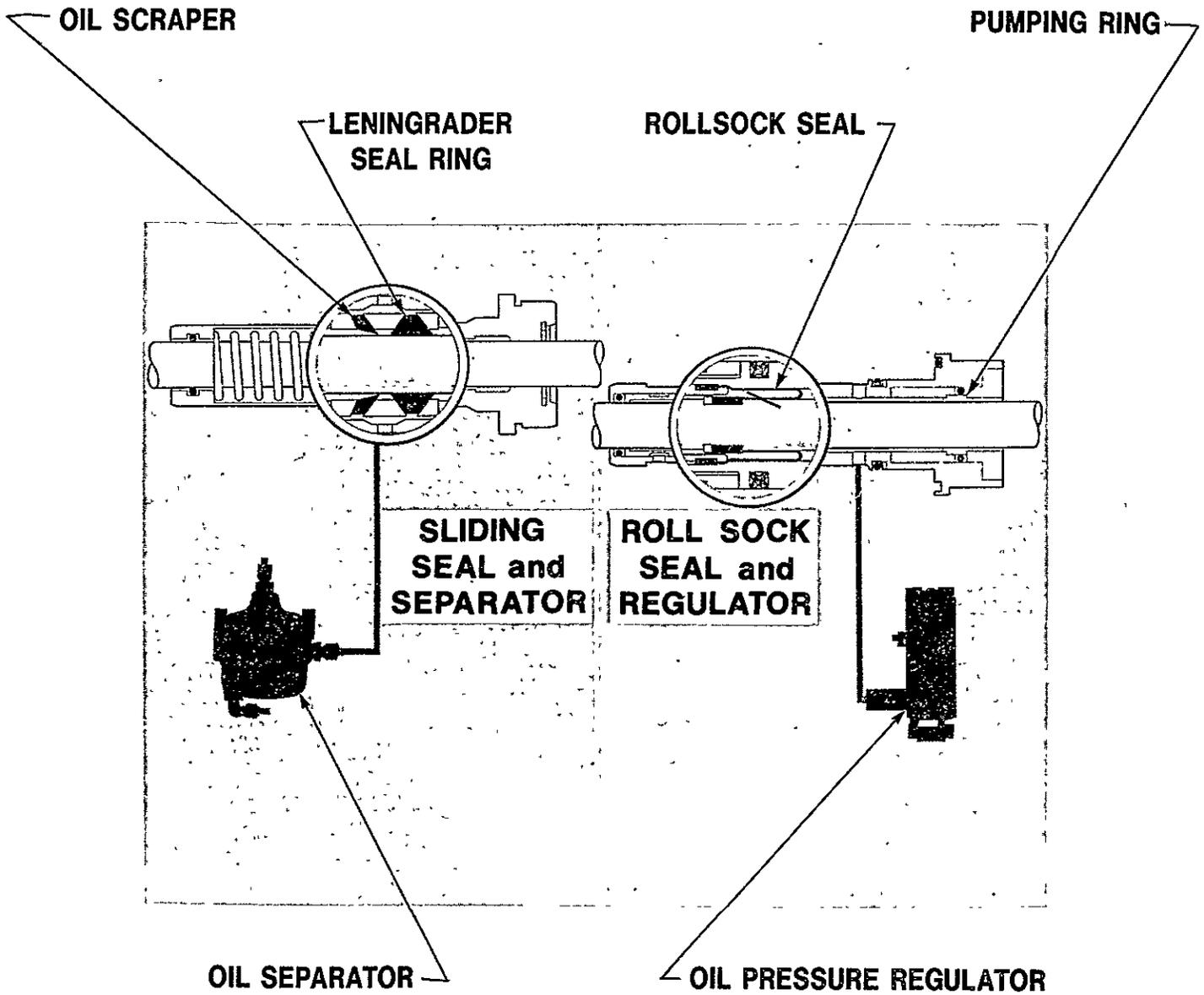
Installation of the crank drive sliding seal test rig is 80% complete. Additional personnel have been assigned to the piston rod seal problem in an effort to reach an early solution.

# STIRLING ENGINE 4-215 TEST HOURS PER ENGINE BUILD



**SLIDING SEAL**

**ROLLSOCK SEAL**



**COMPARISON OF ROLL SOCK AND SLIDING SEAL**

**FIGURE 3-17**

# ROLL SOCK GAS & OIL CIRCUITRY WITH PROTECTION DEVICES

## ORIGINAL SYSTEM — BOLD LINES

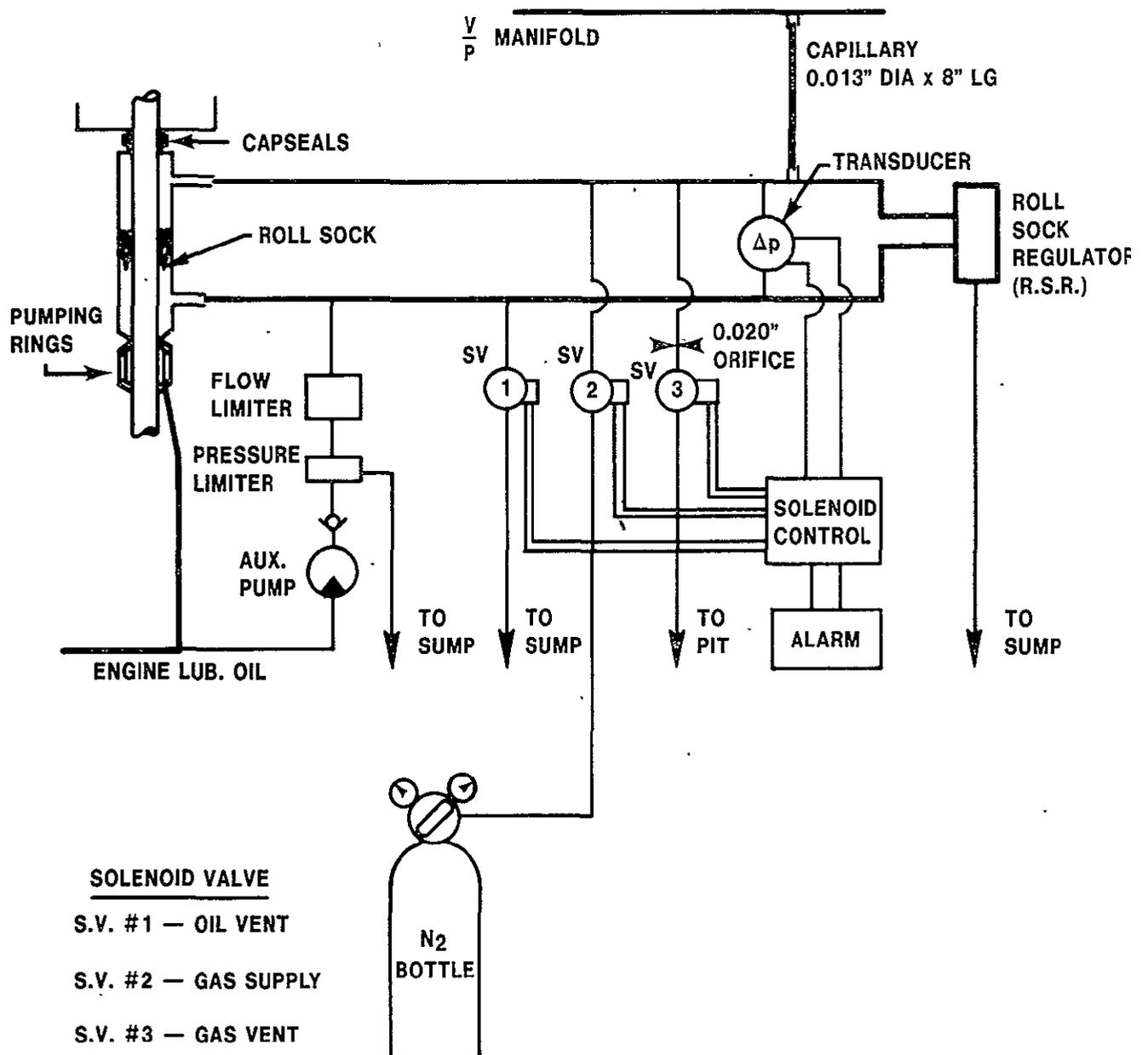
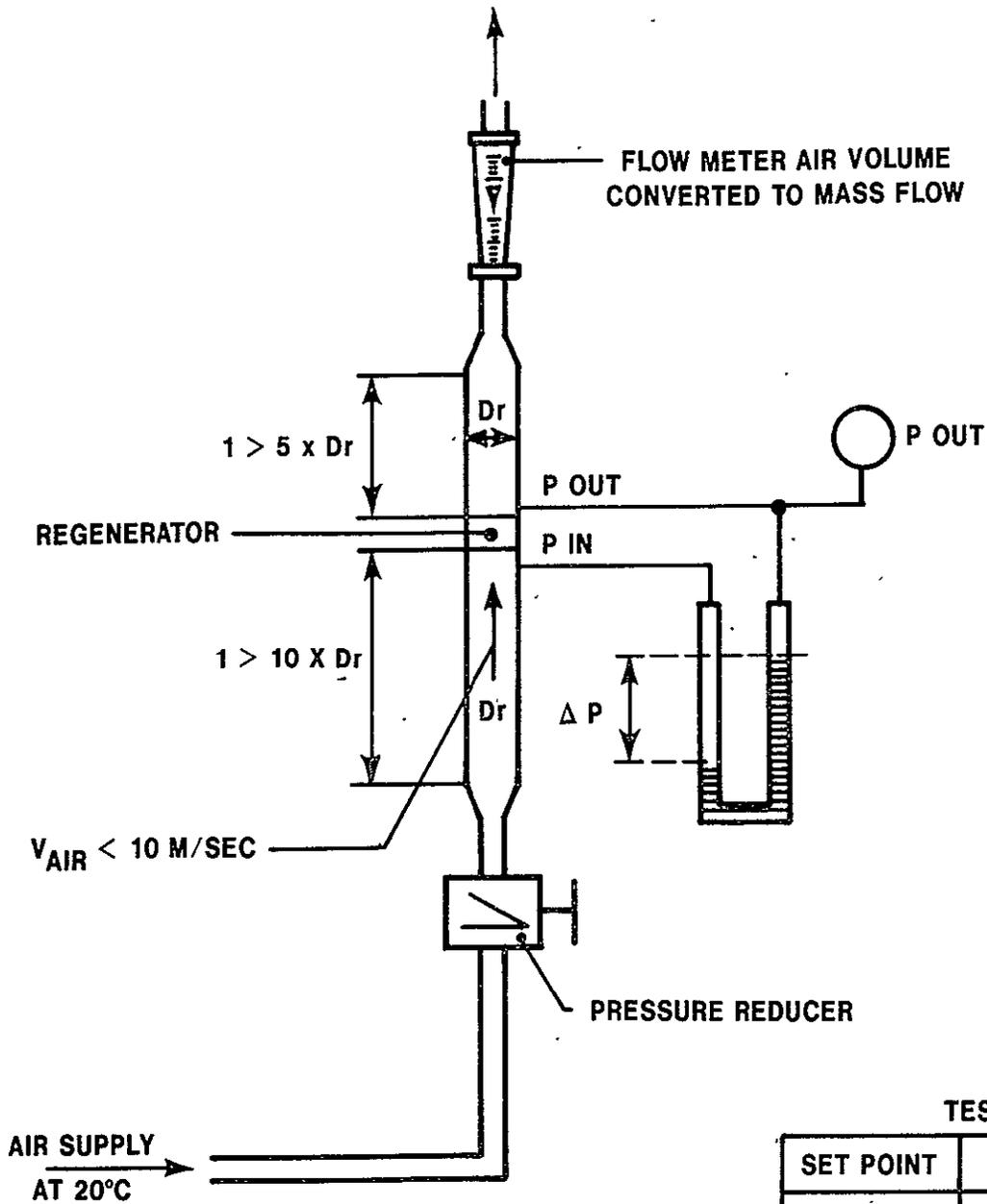


FIGURE 3-18

## SET-UP FOR MEASUREMENTS OF FLOW RESISTANCE ACROSS A REGENERATOR



TEST CONDITIONS

SET POINT	MEASURED	
P OUT CM OF H <sub>2</sub> O	$\Delta P$ CM OF H <sub>2</sub> O	MASS AIR g/s
5		
10		

FIGURE 3-19

RESPONSIVE SUPPORT, SUB-TASK 11

This sub-task provides manpower and funding for models, photographs, charts or other program information requested by DOE or NASA for use at Contractors' meetings or other reviews. Responsive support will be limited to a 1/2 person effort.

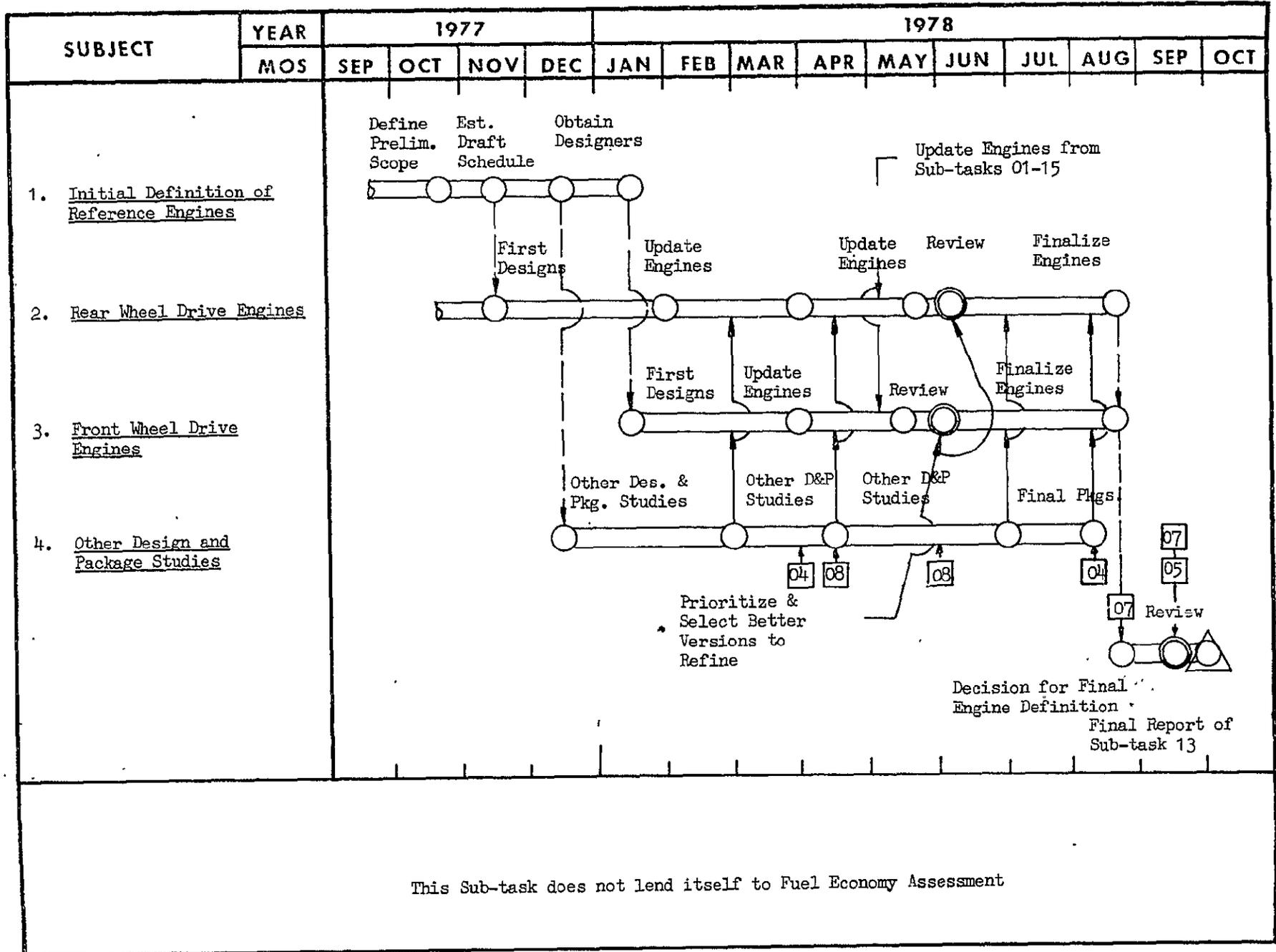
A publication was prepared for the Highway Vehicle Systems Contractors' Coordination Meeting which was held at the Hyatt Regency Dearborn Hotel in Dearborn, Michigan on October 4, 5, and 6, 1977.

At this meeting a progress report of the Stirling engine program was given by Norman D. Postma, Program Manager.

CONTRACT SUPPORT, SUB-TASK 12

This sub-task provides manpower and funding to prepare and submit to DOE and NASA a comprehensive Monthly Technical Progress Narrative Report and a Quarterly Technical Progress Report describing the progress of the Task I effort. Ford holds monthly review meetings so that DOE and NASA are informed of progress and have an opportunity to discuss specific items of Task I. At the end of Task I, a final report which summarizes all the efforts conducted under Task I will be submitted to DOE and NASA. This final report will describe all test results, summarize all analyses made, show final projections of Stirling engine capability, and make recommendations regarding follow-on programs.

Three Monthly Technical Progress Narrative Reports have been prepared and distributed to-date.



This Sub-task does not lend itself to Fuel Economy Assessment

REFERENCE ENGINES, SUB-TASK 13 .

This sub-task will supply manpower and funding to provide designs of complete Stirling engine and vehicle packages which incorporate information from the other sub-tasks and new concepts which might significantly improve the function of the Stirling engine. At the end of this sub-task effort, an interim preferred Stirling engine design will be prepared. This engine will serve as the basis for predicting the fuel economy capability of the Stirling engine.