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SCREENING ANALYSIS AND SELECTION OF EMISSION REDUCTION CONCEPTS FOR INTERMITTENT COMBUSTION AIRCRAFT ENGINES

by: B. J. Rezy, J. E. Meyers, J. R. Tucker, K. J. Stuckas

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TELEDYNE CONTINENTAL MOTORS
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16. Abstract

An analysis was conducted to screen, evaluate, and select three engine exhaust emission reduction concepts from a group of 14 candidate alternatives. A comprehensive literature search was conducted to survey the emission reduction technology state-of-the-art and establish contact with firms working on intermittent combustion engine development and pollution reduction problems. Concept development, advantages, disadvantages, and expected emission reduction responses are stated herein. A set of cost-effectiveness criteria was developed, appraised for relative importance, and traded off against each concept so that its merit could be determined. A decision model was used to aid the evaluators in managing the criteria, make consistent judgements, calculate merit scores, and rank the concepts.

An Improved Fuel Injection System, Improved Cooling Combustion Chamber, and a Variable Timing Ignition System were recommended to NASA for approval and further concept development. An alternate concept, Air Injection, was also recommended.

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1. INTRODUCTION

Teledyne Continental Motors (TCM), under contract to the National Aeronautics and Space Administration (NASA), is conducting a program to establish and demonstrate the technology necessary to safely reduce general aviation piston engine exhaust emissions with minimum adverse effects on cost, weight, fuel economy, and performance. The emissions must be reduced sufficiently to meet the Environmental Protection Agency (EPA) 1980 Emission Standards as published in the Federal Register of July 17, 1973. Current aircraft piston engines are generally operated at "Full Rich" mixture setting for other than cruise conditions and, as such, discharge exhaust emissions that are high in unburned hydrocarbons (HC) and carbon monoxide (CO). Oxides of nitrogen (NOx) are within the EPA limits.

Although emphasizing emission reduction, the NASA program has a secondary objective of reducing the fuel consumption of these engines. This contract is intended to provide a screening and assessment of promising emission reduction concepts that afford good fuel economy. It is also intended to provide for the preliminary design and development of those promising concepts mutually agreed upon. These concepts will then go through final design, fabrication, and integration with a prototype engine(s). Verification testing will then be performed at the TCM facility.

This report discusses the results of completing Task II, "Screening Analysis and Selection of Three Emission Reduction Concepts", that was conducted from February to June of 1976.

A systems analysis study and a decision-making procedure were used by TCM to evaluate, trade off, and rank the candidate concepts from a list of 14 alternatives. Cost, emissions, and 13 other design criteria considerations were defined and traded off against each candidate co cept to establish its merit and emission reduction usefulness. A computer program (1) was used to assist the evaluators in making the final choice of three concepts.

Many automotive concepts were investigated in this study, and it is important to note that the aircraft piston engine emission test cycle is considerably different from the automotive test cycles. For this reason any conclusions made in this study can only be applied to aircraft piston engines.

2. SUMMARY

The objectives of Task II were to conduct a screening analysis on a minimum of 10 promising concepts and select three concepts for further development. The approach used to fulfill the objectives was fivefold:

- Select a preliminary list of concepts
- Conduct a detailed literature search
- Contact firms for additional data
- Define criteria and method of evaluation
- Rank concepts based on a consistent set of weighted cost-effectiveness criteria.

Steps 1 through 3 of the approach produced a list of fourteen concepts which were investigated during the remainder of Task II. The promising concepts are listed in order of general category:

- Stratified Charge Combustion Chambers:
  - Honda Compound Vortex Controlled Combustion
  - Texaco Controlled Combustion System
  - Ford Programmed Combustion
- Improved Cooling Combustion Chamber
- Diesel Combustion Chambers:
  - Four-Stroke, Open Chamber
  - Two-Stroke, McCulloch
- Variable Camshaft Timing
- Improved Fuel Injection Systems
- Ultrasonic Fuel Atomization - Autotronics System
- Thermal Fuel Vaporization - Ethyl TFS
- Ignition Systems:
  - Multiple Spark Discharge
  - Variable Timing
- Hydrogen Enrichment
- Air Injection.

Step 4 was accomplished by selecting and defining the decision factors (criteria). The criteria chosen in the evaluation of the concepts were:

- Cost
- Reliability
- Safety
- Technology
- Performance
- Cooling
- Adaptability
- Materials
- Integration
- Producibility
- Fuel Economy
- Weight and Size
- Maintainability and Maintenance
- Emissions
- Operational Characteristics.

Each decision factor was further defined by listing specific questions which were used in evaluating each concept.

The ranking of the concepts, Step 5, was accomplished with a computer program that aids a decision maker in arriving at consistent decisions under conditions of both certainty and uncertainty. The model assists in obtaining consistent rankings of the decision criteria and of the concepts relative to each of the criteria. The emphasis coefficients assigned to each criterion, the merit scores assigned to each concept relative to each criterion, and the associated uncertainties determined the overall merit coefficient for each concept. These merit coefficients defined the concept ranking which was used as a guide in the final selection of the three concepts. The overall concept preference analysis is summarized below:

CONCEPT	RANK
Improved Cooling Combustion Chamber	1
Improved Fuel Injection System	2
Air Injection	3
Multiple Spark Discharge Ignition System	4
Ultrasonic Fuel Atomization, Autotronics	5
Variable Timing Ignition System	6
Thermal Fuel Vaporization, Ethyl	7
Hydrogen Enrichment, JPL	8
Texaco CCS	9
Two-Stroke Diesel, McCulloch	10
Ford PROCO	11
Variable Camshaft Timing	12
Honda CVCC	13
Four-Stroke Diesel, Open Chamber	14

The ranking of each concept relative to the most important criterion, emissions, reveals the dramatic effect the remaining criteria had on the overall preference analysis:

CONCEPT	RANK
Hydrogen Enrichment, JPL	1
Honda CVCC	2
Improved Fuel Injection System	3
Air Injection	4
Texaco CCS	5
Ford PROCO	6
Two-Stroke Diesel, McCulloch	7
Four-Stroke Diesel, Open Chamber	8
Improved Cooling Combustion Chamber	9
Variable Camshaft Timing	10
Thermal Fuel Vaporization, Ethyl	11
Ultrasonic Fuel Atomization, Autotronic	12
Variable Timing Ignition System	13
Multiple Spark Discharge Ignition System	14

Only two of the top five emission concepts ranked in the top five overall preference analysis: Improved Fuel Injection System and Air Injection. An Improved Cooling Combustion Chamber, ranking ninth on the emission scale, was the top overall preference.

3. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the concept-criteria tradeoff analysis, the following three concepts are recommended to NASA for approval and further development:

- Improved Fuel Injection System
- Improved Cooling Combustion Chamber
- Variable Timing Ignition System.

Air Injection, the third ranked overall preference concept, is recommended as an alternate concept for NASA consideration.

The fourth ranked concept, Multiple Spark Discharge Ignition System, and the fifth ranked concept, Ultrasonic Fuel Atomization, were bypassed as recommendations partly because of NASA contracts presently investigating these concepts. Ultrasonic Fuel Atomization was considered more applicable to carburetted engines than individual cylinder fuel-injected engines. A Multiple Spark Discharge Ignition System was considered less important than a system that provides an ignition spark regulated as a function of engine speed and load.

An Improved Fuel Injection System will consist of a timed, airflow sensitive system capable of supplying fuel at moderate pressure to the injectors. A timed, moderate fuel pressure system is required to ensure a fuel mist with adequate cylinder distribution as opposed to the present continuous flow, low pressure system. An airflow-sensitive system is required to maintain the desired fuel-air ratio, which will control the emission levels, and together with proper cylinder distribution, provide better engine transient response.

Throughout this study exhaust emissions were compared to the TCM IO-520-D engine operating at the lean fuel flow limit of the model specification. This fuel schedule was chosen as representative of a high volume production engine operating at the leanest fuel-air ratios recommended. Exhaust emission values quoted herein reflect minimum projected levels and no tolerance band is inferred. An Improved Fuel Injection System has the potential for reducing HC by 43%, CO by 29%, and increasing NOx by 93%. These emission potentials result in absolute emission levels of 55%, 90%, and 58% of the EPA standard for HC, CO, and NOx, respectively.

An Improved Fuel Injection System capable of maintaining lean fuel-air ratios cannot operate effectively for all engine applications because of possible cylinder head overheating. Operating at leaner than present fuel-air ratios requires a combustion chamber design capable of withstanding greater heat loads. Methods of obtaining an Improved Cooling Combustion Chamber are:

- Cooling fin redesign
- Exhaust port liners
- Exhaust port coatings.

An Improved Cooling Combustion Chamber will not significantly affect HC emissions; however, a 16% decrease in CO and a 47% increase in NOx were projected for the concept which resulted in emission levels of 106%, 95%, and 44% of the EPA standard for CO, HC, and NOx, respectively. The changes resulted through improved cooling during climb and takeoff, which allows leaner fuel-air ratios while maintaining engine power.

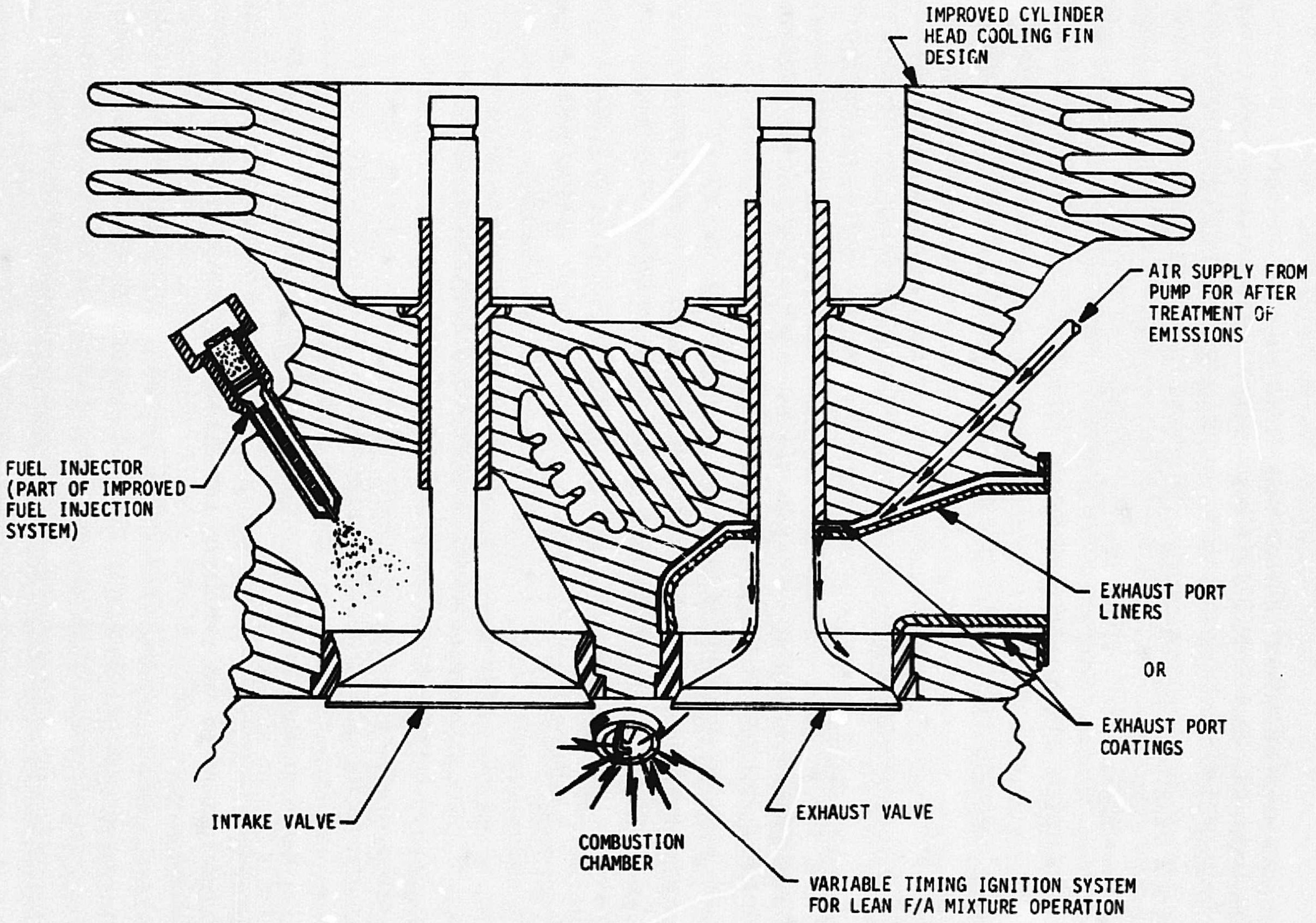
A Variable Timing Ignition System can provide improved engine acceleration characteristics while operating at leaner than present fuel-air ratios in idle, taxi, and approach modes. Light load operation in the idle and taxi modes will become smoother by retarding the spark, while vacuum advancing the spark in the cruise range will enhance lean mixture burning. A centrifugal advance would be required to compensate for changes in engine speed under constant manifold pressure.

Use of a Variable Timing Ignition System will not significantly reduce exhaust emissions relative to the aircraft emission cycle; however, the ability to provide variable ignition in idle, taxi, and approach modes will decrease the acceleration problem associated with leaning these modes. Potential leaning benefits would result in emission reductions of 11% for HC and 8% for CO, and an increase of 17% for NOx.

Air Injection was chosen as an alternate concept since after-treatment of the exhaust products does not attack the fundamental source of the problem, i.e., excessively rich fuel-air ratios. The potential of Air Injection, however, cannot be denied. Reductions of 33% for HC and 23% for CO, and an increase of 13% for NOx are projected for this concept.

The adaptability of all four concepts provides a means for many possible integrated emission reduction packages, as shown in the sketch on the following page. An Improved Fuel Injection System, an Improved Cooling Combustion Chamber, and a Variable Timing Ignition System complement each other in reducing emissions by overcoming the associated problems of operating at leaner than present fuel-air ratios. An exhuast port liner coupled with Air Injection provides a means of after-treatment of the exhaust products, ensures a cooler cylinder head, and suggests leaner fuel-air ratio operation.

The primary and alternate proposed concepts offer extremely promising combinations for a safe and versatile emission reduction package.


IMPROVED CYLINDER HEAD COOLING FIN DESIGN
AIR SUPPLY FROM PUMP FOR AFTER TREATMENT OF EMISSIONS
FUEL INJECTOR (PART OF IMPROVED FUEL INJECTION SYSTEM)
EXHAUST PORT LINERS
OR
EXHAUST PORT COATINGS
INTAKE VALVE
EXHAUST VALVE
COMBUSTION CHAMBER
VARIABLE TIMING IGNITION SYSTEM FOR LEAN F/A MIXTURE OPERATION

4. LITERATURE SEARCH

As partial fulfillment of Task II (Screening Analysis) as defined in the Technical Work Plan (2), TCM conducted a literature search through five main sources:

- SAE - Technical paper search
- NASA/Lewis - RECON key word search
- NTIS - Published searches
- NASA/Marshall Space Flight Center - RECON key word search
- References - Published references from technical papers were searched for additional reports.

Although the literature search, per se, is complete, new technical publications will be searched through the remainder of the contract for information and data pertaining to the chosen concepts. Conclusions from the completed literature search can be summarized as follows:

- No new concepts for reducing exhaust emissions were found, compared to the candidate concepts in the RFP or the 10 selected concepts in the original work plan.
- Minimal data were available for detailed modal analysis (most of the published data were in the form of grams/mile, dilute data, and/or low power conditions).
- Minimal data were available for supporting evaluation of the concepts on the basis of the criteria presented in Section 6.
- Additional data were required to evaluate certain concepts on the basis of emissions.

Based on the results of the above search, TCM contacted firms considered to be experts in their respective fields to obtain raw emissions data for analysis on the aircraft cycle as well as any other pertinent information on the promising concepts. The firms contacted were:

FIRM	CONCEPT
Autotronic Controls Corporation	Ultrasonic Fuel Atomization Multiple Spark Discharge System
Bendix Corporation	Electronic Fuel Injection
Borg-Warner Corporation	Electronic Fuel Injection
Chrysler Corporation	Variable Timing Ignition System
Environmental Protection Agency	General Emissions Data
Ethyl Corporation	Thermal Fuel Vaporization
Ford Motor Company	Stratified Charge - (Ford PROCO)
Honda American Motor Company	Stratified Charge - (Honda CVCC)
Jet Propulsion Laboratory	Hydrogen Enrichment Ultrasonic Fuel Atomization
McCulloch Corporation	Diesel, Two-Stroke
NASA - Lewis Research Center	General Emissions Data
Ricardo & Company Engineers	General Emissions Data
Southwest Research Institute (SWRI)	Diesel, Four-Stroke; Stratified Charge - (Honda CVCC, Ford PROCO, and Texaco CCS)
Texaco, Incorporated	Stratified Charge - (Texaco CCS)
Toyota Motor Company	Lean-Burn with Turbulence Generating Pot
White Engines, Incorporated	Diesel, Four-Stroke

A typical data request form is presented in Figure 1.

Emissions data in the required form were received for the following concepts:

CONCEPT	SOURCE
Diesel, Two-Stroke	McCulloch Corporation
Diesel, Four-Stroke Open Chamber	SWRI
Ford PROCO	SWRI
Honda CVCC	SWRI
Texaco CCS:	
Operation on Gasoline	Texaco, Inc., and SWRI
Operation on Diesel Fuel	SWRI
Thermal Fuel Vaporization	Ethyl Corporation

These analyses were based on the assumption that emissions from a particular combustion chamber are functions of operating conditions (speed, load, and mixture strength) and not application. That is, emissions from an automotive engine are valid for the aircraft emission cycle provided the emissions data were obtained at operational conditions specified for the respective aircraft cycle modes. The Jet Propulsion Laboratory (3) employed a similar approach for hydrogen enrichment studies in which specific emissions data from a Chevrolet 350 CID V-8 automotive engine operating at ultra-lean equivalence ratios were used to predict aircraft engine emissions at the same mixture strength. The automotive engine specific emissions data correlated well with similar data from a TCM IO-520-D engine at mutual equivalence ratios.

These raw emissions data were input to the TCM Aircraft Cycle Emissions Deck to determine mode and total cycle specific emissions. The input data and computer program results of those analyses are presented in Appendix A along with the assumptions that were required for analysis on the seven-mode cycle. The calculation procedure for these analyses and the definition of the seven-mode cycle are presented in Appendix B.

Where raw emissions data were not available, concepts were evaluated by analyzing their impact on emissions as applied to the IO-520-D engine. The IO-520-D engine operating at the lean fuel flow limit of the model specification was chosen as representative of a high-volume production engine.

5. CONCEPT DEFINITIONS AND EMISSION RESULTS

In accordance with the contract, a preliminary screening of promising concepts for reducing exhaust emissions and improving engine specific fuel consumption was submitted to NASA for approval.

Approval was granted to study the following concepts in further detail:

- Stratified Charge Combustion Chambers
- Improved Cooling Combustion Chambers
- Diesel Combustion Chambers
- Variable Camshaft Timing
- Improved Fuel Injection Systems
- Ultrasonic Fuel Atomization
- Thermal Fuel Vaporization
- Improved Ignition Systems
- Hydrogen Enrichment
- Air Injection.

The first step in the analysis was to define in greater detail each concept as it applies to this study and to establish emission levels. The basic concepts analyzed in this task are detailed in Sections 5.2 through 5.11 by general category. Emission values quoted for the concepts reflect minimum projected levels and no attempt has been made to establish tolerance bands. Since exhaust emissions levels for some concepts were based on their predicted impact on the emissions from the TCM IO-520-D engine, definitions of that engine and its emission characteristics are provided in Section 5.1.

5.1 TCM IO-520-D ENGINE

The IO-520-D is an air-cooled, 520 CID, horizontally opposed, naturally aspirated, six-cylinder aircraft engine featuring fuel-injection and rated at 300 horsepower. The engine is representative of current high-volume production engines.

Under FAA-NAFEC Contract No. DOT FA74NA-1091, TCM has conducted extensive IO-520-D testing to establish the effects of lean operation on exhaust emissions and safety limits. The testing resulted in categorization of emission data by three separate fuel system schedules: Baseline, Case 1, and Case 2. Figure 2 presents the fuel-air equivalence ratio for each fuel schedule as a function of power. Modal power points are also shown for reference. Baseline is defined as the average fuel flow rate established by the fuel system production tolerance band when operated with the mixture control at the full rich position. Case 1 is defined as the minimum allowable fuel flow rate established by the engine type certificate. Case 2 is defined as the fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety limit occurred with the engine operating on a test stand. The engine test stand installation incorporated the same constant speed propeller as would normally be used on the airframe configuration. Safety limits which developed during testing were cylinder head overheating or inadequate acceleration from a given mode of operation and were defined as "uninstalled" safety limits.

The general trend in mixture strength (i.e., richer at low power, leaner at the mid-power range, and richer at maximum power) is typical of all TCM fuel-injected engines that have been evaluated. This trend may be rationalized by considering the present fuel injection system design. Rich mixtures are required at the low power idle-taxi regime to provide adequate fuel distribution to all cylinders and to ensure adequate engine transient response (acceleration). Since the IO-520-D fuel system is not temperature compensating, the fuel flow required for the idle-taxi modes is dependent on the fuel-air ratio required for cold day operation. As the induction air temperature increases, the resultant fuel-air ratio enriches. Leaner mixtures are acceptable and desirable in the mid-power range where fuel distribution is good and cylinder head temperatures are well within the limits. Richer mixtures are required at high power points for cylinder head cooling and detonation suppression. The Federal Aviation Administration requires that the minimum certified fuel-flow rate be at least 10% above the fuel flow rate at which detonation occurs. Note the mixture strength schedule trend with respect to Baseline, Case 1, and Case 2 fuel schedules. A wider equivalence ratio band exists between each fuel schedule at low power and this band decreases to a minimum at maximum power. This is due to the larger tolerance band associated with controlling low fuel flow rates. This trend is typical of all TCM engines that have been evaluated.

Figure 3 presents the IO-520-D emission levels in percent of the EPA standard as a function of time-weighted fuel-air equivalence ratio, ϕ_{tw}. Time-weighted fuel-air equivalence ratio is defined as the summation of the product of modal time and the modal equivalence ratio divided by the total cycle time. In equation form:

$$\phi_{tw} = \frac{\sum_{i=1}^{7} T_i \cdot \phi_i}{27.3}$$

where

T_i - time in mode i, minutes

ϕ_i - equivalence ratio in mode i.

Time-weighted equivalence ratio provides a means of establishing Baseline, Case 1, and Case 2 emission levels as a function of a common reference for each pollutant. The results of leaning can therefore be quickly recognized. As expected, leaning the engine resulted in a decrease for carbon monoxide (CO) and hydrocarbons (HC), while the oxides of nitrogen (NOx) increase. The Baseline mixture schedule resulted in a ϕ_{tw} of 1.43 with CO and HC above the standard and NOx well below the limit. Decreases of 34% for CO and 19% for HC were observed when the engine was leaned to a ϕ_{tw} of 1.23 (Case 1), and NOx increased 118% but remained considerably below the limit. Case 2, ϕ_{tw} of 1.12, resulted in levels for all three pollutants below the EPA standards with decreases from Case 1 of 34% for CO and 37% for HC. NOx increased by 83%. From Figure 3, an estimated band of time-weighted fuel-air equivalence ratios which meet all of the EPA standards can be determined. This total band ranges from a ϕ_{tw} of 1.02 to 1.16; however, when Case 2 is considered (uninstalled safety limits), this band is reduced to a ϕ_{tw} range of 1.12 to 1.16, which results in a ±1.75% tolerance band on fuel-air ratio for the complete seven-mode cycle.

Figure 4 represents the effect of modal equivalence ratio on CO, HC, and NOx for the IO-520-D engine. The figure illustrates the pollutant percent of EPA standard as a function of modal equivalence ratio decrease from Case 1. The curve clearly shows the effects of each mode on the total cycle emission level as the modes are leaned beyond the lean limit of the engine model specification. Case 1 was chosen as the starting point from which the leaning was referenced since leaning beyond Case 1 is mandatory to reduce CO and HC to values below the EPA standard, Figure 3.

Each modal curve has been identified with symbols which locate two important points of reference, Case 2, and the stoichiometric fuel-air ratio. The closed symbols represent the reduction in modal equivalence ratio required to provide a stoichiometric mixture and the corresponding emission level for the cycle. The flagged symbols represent the reduction in modal equivalence ratio required to lean to the uninstalled modal safety limit. Dashed lines represent extrapolations of available data.

Significant information can be derived from these curves, such as the effect of modal leaning on CO. For example, if only the climb mode was leaned to Case 2 ($\phi = 0.07$ decrease from Case 1) the CO percent of EPA standard would drop from 124 to 107%, or a delta reduction of 17%. Any combination of modal leaning can be predicted by summing the individual modal delta reductions. To obtain the absolute emission level the sum is subtracted from the Case 1 value.

The above test results established emissions levels for the IO-520-D engine as a function of fuel mixture strength and are the basis for determining the minimum projected emission levels for various concepts described in this report.

5.2 STRATIFIED CHARGE COMBUSTION CHAMBERS

Charge stratification is the generation of a significant spatial variation of fuel-air ratio in the combustion chamber at time of ignition and during at least a portion of the progressive burning process.

The object of the strata is to provide a fuel-rich environment near the point(s) of ignition and progressively leaner zones as the flame front traverses the combustion region. This formation promotes the establishment of the flame kernel and a strong flame front that can easily traverse the leaner fuel-air zones. The result is more nearly complete combustion of an overall lean mixture (generally stoichiometric or leaner) with attendant low pollutant emission levels and improved fuel economy.

The two main classifications for stratified charge engines are prechamber engines and open-chamber engines. The former is characterized by a mechanically divided combustion chamber with the individual chamber sections connected by an orifice. The latter engines obtain the spatial fuel-air ratio variation through coordination of direct fuel injection and dynamic air motion. The three stratified charge concepts investigated were:

5.2.1 Honda Compound Vortex Controlled Combustion (CVCC)

The CVCC, Figure 5, is a prechamber stratified charge engine with a "compound" carburetor and third valve in the prechamber. During the intake stroke the "compound" carburetor supplies a fuel-rich mixture to the prechamber via the auxiliary valve and a leaner-than-stoichiometric mixture to the main chamber through the main intake valve. A prechamber spark plug initiates ignition in the fuel-rich prechamber mixture. The resulting prechamber pressure forces burning gases through the connecting orifice into the main chamber where a mixture of intermediate richness has formed as a result of proper geometry and proportioning of air and fuel. This "mixture cloud" (4) is ignited by the flame initiated in the auxiliary chamber and ensures positive combustion of the lean mixture in the main chamber. Raw emission data (5) received for the Honda CVCC were based on operation with the standard exhaust system. This system did not include a catalytic converter or a thermal reactor, per se. The exhaust manifold was designed with an inner liner, Figure 5, to increase exhaust gas residence time and provide an intake manifold "hot spot". Therefore some benefits of HC and CO oxidation and thermal fuel vaporization are inherent in the data. The data were evaluated on the aircraft seven-mode emission cycle, and emissions were well below EPA limits despite a time-weighted equivalence ratio slightly rich of stoichiometric (1.01). These favorable emission levels resulted in an emission ranking of second for the Honda CVCC, Table I.

The literature search produced the following Pros and Cons which further characterized the Honda CVCC:

PROS

- Good Specific Fuel Consumption
- Stable Combustion Assured
- Good Operational Characteristics
- Low Octane Fuel Requirements
- Low Emissions for Aircraft Emission Cycle

CONS

- Possible Cooling Problems
- Hardware Complexity
- High Surface Area-to-Volume Ratio
- High Rate of Pressure Rise at Rich Mixtures
- Implementation Problems
- Increased Weight
- Expensive
- Increased Maintenance.

5.2.2 Ford Programmed Combustion System (PROCO)

The PROCO, Figure 6, is an open-chamber stratified charge engine which relies on the coordination of directly injected fuel into circumferentially swirling air to stratify the fuel-air mixture.

The intake port is shaped to impart a high-rate (three to five times crankshaft speed) circumferential swirl to the incoming air. The swirling air charge is compressed at a high compression ratio (≈11:1) into the cup-shaped combustion chamber. The chamber is located concentrically in the piston with about 65% squish area. Fuel is directly injected into the cylinder during the compression stroke in a soft, low-penetrating, wide-angle, conical spray which results in a rich mixture at the center, surrounded by a leaner mixture and excess air (6). Combustion progresses rapidly in the rich mixture around the spark plug which is located either near the bore centerline or just above the spray. The toroidal mixture resulting from the squish action plus the intake swirl promotes flame travel as combustion spreads out of the rich region into the leaner regions. Air motion tends to homogenize the mixture and promote nearly complete combustion as the swirling charge expands from the piston cup into the cylinder space during the expansion stroke. Air throttling is utilized for part-load fuel-air control.

The Ford PROCO emission data (5) evaluated on the aircraft emission seven-mode cycle indicated high nitric oxide emissions (32% over EPA limit) at a relatively lean 0.5 time-weighted equivalence ratio. Hydrocarbons and carbon monoxide at less than 10% EPA standard were typical of lean operation. The high nitric oxide emissions resulted in the PROCO being ranked sixth in the emission ranking.

The literature search produced the following Pros and Cons which further characterized the Ford PROCO:

PROS

- Low HC and CO Emissions for Aircraft Emission Cycle
- Good Specific Fuel Consumption

CONS

- Octane Sensitive
- Not Easily Turbocharged
- Implementation Problems
- Air Throttling Required for Low Emissions
- High NOx Emissions for Aircraft Emission Cycle
- Expensive.

5.2.3 Texaco Controlled Combustion System (TCCS)

The TCCS (7, 8), Figure 7, is an open-chamber stratified charge engine which encompasses direct fuel injection, air swirl, and positive ignition.

Suitably shaped intake passages and combustion chamber impart a high rate (up to ten times crankshaft speed) circumferential swirl to the normally unthrottled air charge. Fuel is injected directly into the cylinder late in the compression stroke to establish a flame front immediately downstream from the nozzle. A combustible mixture is supplied to the stabilized flame through continued injection and is burned as rapidly as it is formed. Part load fuel-air ratio is maintained by fuel injection duration and quantity.

Three sets of raw emission data (5) from two TCCS equipped engines were evaluated on TCM's version of the aircraft emissions seven-mode cycle. The resulting time-weighted equivalence ratios were essentially the same in all three instances. In two cases the engines were operated on gasoline while the third case was for diesel fuel operation. Nitric oxide emissions were comparable for all three cases and exceeded EPA limits by up to 38%.

Carbon monoxide emissions were also similar for all three cases and were well below EPA standard. Hydrocarbons were well below EPA standards but not as consistent as NOx or CO, varying from 12% to 58% of the EPA limit. The high NOx level forced the TCCS concept into fifth position for the emission ranking, one position above the Ford PROCO.

The literature search produced the following Pros and Cons which further characterized the Texaco CCS:

PROS

- Limited Air Throttling Requirements
- Low Octane Fuel Requirements
- Multi-Fuel Capability with Comparable Performance and Emissions
- Easily Turbocharged
- Good Specific Fuel Consumption
- Good Starting Characteristics
- Low Wall Quenching Potential
- Low HC and CO Emissions for Aircraft Emission Cycle

CONS

- Incomplete Air Utilization
- Limited Speed Range
- Implementation Problems
- Poor Performance
- Expensive
- High NOx Emissions for Aircraft Emission Cycle.

5.3 IMPROVED COOLING COMBUSTION CHAMBERS

Improved Cooling Combustion Chambers entail modifications or redesign of the cylinder head/combustion chamber to improve cooling characteristics and thereby allowing leaner fuel-air operation and, in some cases, increased HC/CO oxidation.

TCM has evaluated the effect of lean operation on exhaust emissions for the IO-520-D, Figures 3 and 4. That information was used to predict exhaust emissions by realizing that improved cooling during climb and takeoff will permit leaner fuel-air ratios while maintaining engine power. For idle, taxi, and approach modes, Case 1 was used because of inadequate acceleration at Case 2 which improved cooling techniques would not affect. For takeoff and climb modes, Case 2 was used because excessive cylinder head temperature is the limiting factor with current cooling characteristics. Figure 4 indicates that this modal leaning results in a CO decrease of 20% of the EPA standard and an NOx increase of 14% of the EPA standard. The resulting absolute levels of CO and NOx were 106% and and 44% of the EPA standard, respectively. Hydrocarbon emissions were not significantly affected, Table I. Candidate improvements for improving combustion chamber cooling are described in Sections 5.3.1 through 5.3.3.

5.3.1 Redesigned Cylinder Head Cooling Fins

This concept will encompass a detailed thermal analysis to ascertain the required fin geometry (size, shape, separation, etc.) for increased heat dissipation in the cylinder head. The basic redesign problem involves only heat transfer characteristics of the extended surface and hardware considerations (cost, weight, available space, pressure drop, etc.), and, as such, no information was expected or obtained through the emission-type literature that was researched. Detailed NACA reports are available, however, for establishing the effects of fin geometry.

The following Pros and Cons for redesigned cylinder head cooling fins were utilized in assessing Improved Cooling Combustion Chambers:

PROS

- Allows Leaner Operation in Certain Modes
- Versatile - One Basic Configuration for All Applications
- Minimal Weight Penalty
- No Increased Maintenance Requirements
- No Performance Penalty
- No Effect on Operational Characteristics
- Relatively Inexpensive

CONS

- Implementation Problems
- No Fuel Economy Benefits
- Complex Heat Transfer Analysis Required.

5.3.2 Exhaust Port Coatings

This cooling technique requires evaluation of various ceramics to determine their benefit as low thermal conductors. The emission reduction potential would be gained through leaner operation, which is possible only if the exhaust heat can be retained in the exhaust gases rather than transferred to the cylinder head. The literature provided minimal information on the subject since most research is being directed toward exhaust port liners rather than coatings.

The following Pros and Cons for exhaust port coatings were considered in evaluating Improved Cooling Combustion Chambers:

PROS

- Allows Leaner Operation in Certain Modes
- Minimal Hardware Change
- Relatively Inexpensive
- No Effect on Operational Characteristics
- Relative Ease of Implementation
- Simple
- Minimal Weight Penalty
- No Performance Penalty

CONS

- Subject to Damage from Expansion and Contraction of Cylinder Head
- Brittle - Subject to Mechanical Shock Damage
- No Fuel Economy Benefits.

5.3.3 Exhaust Port Liners

This concept requires the assessment of materials and geometry that offer low thermal conductance, durability, ease of installation, and good gas flow characteristics with reasonable cost and weight.

The basic concept, Figure 8, has been tested in automotive engines (9) with significant cooling effects, Figure 9. A liner with low thermal conductivity in conjunction with the enclosed (small free-convection currents) air space provides excellent insulation against the flow of exhaust heat to the cylinder head. An additional merit of the liner is its versatility, i.e., the potential for adding an air injection feature that will maintain good cooling potential while increasing HC and CO oxidation in the exhaust. A typical scheme is presented in Figure 10. Cooling air is pumped through the nozzle into the space behind the liner which is film cooled as the air flows to the openings at the valve and into the exhaust gas stream.

TCM has proved the cooling potential of the proposed method during testing of a similar concept for air cooling exhaust valves, Figure 11. In this case cooling air was pumped to the plenum at the valve guide sleeve and through the four passages between the outer surface of the valve guide and the inner surface of the valve guide sleeve for dispersion over the valve neck. The extent of valve cooling is indicated by the substantial decrease in neck temperature presented as a function of cooling air flow in Figure 12. Cylinder head temperatures were monitored during the testing, and decreases on the order of 5° to 10°F were observed at the normal thermocouple head location.

The following Pros and Cons for the exhaust port liners were employed in evaluating Improved Cooling Combustion Chambers:

PROS

- Allows Leaner Operation in Certain Modes
- Proven Concept
- Provides Air Injection and Valve Cooling Potential
- Minimal Weight Penalty
- No Increased Maintenance Requirements
- No Performance Penalty
- No Effect on Operational Characteristics
- Relatively Inexpensive
- Simple

CONS

- Implementation Problems
- No Fuel Economy Benefits.

5.4 DIESEL COMBUSTION CHAMBERS

Since the principles of compression ignition (diesel) are well established and understood, a detailed explanation is omitted. The diesel combustion chamber concepts investigated are described in Sections 5.4.1 and 5.4.2.

5.4.1 Four-Stroke Open Chamber Diesel

This concept, Figure 13, is characterized by high pressure fuel injection through a multiple orifice directly into the clearance space or chamber between the piston and cylinder head. Intake valve shrouding or intake port design is utilized to impart swirl to the unthrottled air charge. This air swirl moves the unsprayed air into the fuel spray. Small clearance volume induces high turbulence as the gases are forced out of the small clearances and agitates the mixture. The combustion is compression initiated and results in high temperatures and high pressures which necessitate more stringent structural considerations than the spark ignition counterpart with attendant cost, weight, and size implications.

Only the open chamber concept was considered due to marginal cooling potential for a prechamber configuration in which the combustion process has relatively high fluid friction and heat transfer losses.

Data from three four-stroke open chamber diesels (5, 10) were evaluated on the aircraft emission seven-mode cycle. Data from one engine, a Datsun, is suspect due to the extremely low NOx emissions. Nitric oxides for the other two cases exceed EPA limits by up to 90%. This high level resulted from the high peak temperatures incurred in diesels, even though equilibrium considerations suggest very low production for such lean operation, i.e., 0.3 time weighted equivalence ratio. Carbon monoxide and HC were well below EPA standards for all three cases.

The literature search produced the following Pros and Cons which further characterize the Four-Stroke Open Chamber Diesel:

PROS

- Low HC and CO Emissions for Aircraft Emission Cycle
- Low Fuel Costs
- Good Fuel Economy
- No Air Throttling Requirements
- Easily Turbocharged

CONS

- High NOx Emissions for Aircraft Emission Cycle
- Poor Performance
- Limited Speed Range

- Hard Starting
- Exhaust Smell and Smoke
- Expensive
- Implementation Problems
- Noisy
- Heavy.

5.4.2 Two-Stroke Diesel, McCulloch

This concept is a turbocharged engine combining the two-stroke cycle with the diesel principle of operation. The existing prototype for which emission data were obtained is a radial configuration; however, the basic concept could be applied to horizontally opposed cylinder arrangements. A unique combustion chamber design (11, 12), Figure 14, is utilized to produce low peak pressures (1,100 psi) relative to the four-stroke diesel (1,600 to 2,000 psi). A portion of the chamber called the "poker" is attached to the piston. The upper face of the poker is part of a toroid and has five or more equally spaced vertical slots about its cylindrical periphery. The cylinder head recess has a cylindrical lower section and an upper end which is one-half a toroid. The combustion process occurs in two stages. The first stage occurs during compression when the compressed air in the outer ring between the cylinder head and the outer top edge of the piston is forced through the vertical slots in the poker into the toroidal part of the chamber. Violent circular motion is imparted to the air in the toroid which tears the fringe from the injected fuel spray (8 deg BTDC), mixes it with the heated air, and ignites it. As the piston reaches TDC the gas flow reverses direction because of high toroid pressure and because the fuel spray core has reached the poker slots. The second combustion stage begins as the heated air carries the fuel spray core down the slot and into the space above the piston, incurring high turbulence as it does so. Fuel atomization and thorough fuel-air mixing occur as regulated burning takes place until the fuel injection is terminated. The burning mixture emerges from the slots and into the quench area, the purpose of which is to slow the burning rate and hold the mixture temperature down to minimize NOx formation. This technique is reflected in the low NOx emission (54% EPA standard) compared to that of conventional four-stroke open chamber diesels (up to 190% of the EPA standard). This quenching may also account for the high HC emissions which exceed the EPA standard by 40%, whereas HC emissions for conventional four-stroke open chamber diesels was 53% below the EPA limit. The CO emission at 10% of the EPA limit was representative of lean operation, 0.32 time-weighted equivalence ratio. The high HC emission forced the McCulloch two-stroke diesel into seventh position in the emission ranking, which is just above the four-stroke diesel concept. It should be noted that the HC level is conservative since full power data were not available and the rated power was reduced accordingly. Hydrocarbons should decrease for the higher speed/load conditions.

The Pros and Cons inherent in such a design are summarized below:

PROS

- High Power/Weight Ratio
- Good SFC
- Multi-Fuel Capability
- Aircraft Configuration Prototype Built and Tested
- Low Peak Pressures
- Low CO and NOx Emissions for Aircraft Emission Cycle
- Good Starting Characteristics
- No Air Throttling Requirements
- Less Exhaust Smoke Than Conventional Diesels
- Quieter Than Conventional Diesels

CONS

- Unproven Durability
- High HC Emissions for Aircraft Emission Cycle
- Turbocharging Required
- Radial Configuration Not Readily Adaptable to Conventional Aircraft
- Expensive.

5.5 VARIABLE CAMSHAFT TIMING

Variable Camshaft Timing was conceptually envisioned as a multi-piece camshaft, Figure 15, capable of rotating the intake cams relative to the exhaust cams. The purpose of this variability is to provide optimum valve overlap (a measure of time the intake and exhaust valves are open simultaneously) for all speed ranges. At low engine speeds low valve overlap is desired for good idle quality and HC control, while greater valve overlap is required at higher engine speed for efficient breathing.

In evaluating variable camshaft timing, a general design concept (13) was assumed. The design has a central actuating member translatable along the camshaft axis of rotation. The angular position of the intake cams relative to the exhaust cams can be altered without affecting the exhaust cams by sliding the central member in and out as a function of engine speed. It was assumed that such a design would fit within standard engine camshaft spaces without major engine modifications. The literature search (14) revealed that rotating the intake cam rather than the exhaust cam was the more efficient means of reducing emissions by varying valve overlap.

The emission reduction feature of variable camshaft timing is twofold. First, hydrocarbons (and fuel consumption) may be decreased at low engine speeds by retarding the intake valve opening relative to the exhaust valve closure. This eliminates much incoming charge "short circuiting", i.e., being exhausted during the intake stroke. Second, NOx and HC reductions as well as good breathing can be provided at high engine speeds by increasing valve overlap, e.g., advancing the intake cams relative to the exhaust cams. In this case, the difference between exhaust backpressure and intake manifold pressure forces some of the exhaust gases to reverse direction and flow back into the combustion chamber and intake manifold. These residual exhaust gases dilute the incoming charge and curb NOx formation by limiting peak combustion temperature. This process is known as internal exhaust gas recirculation. The exhaust gases may be selectively recirculated because of exhaust gas stratification (14, 15) to effect a reduction in HC. Exhaust gas stratification means that the exhaust gases highest in HC are adjacent to the combustion chamber walls (quench gases). Since these gases are the last portion of the exhaust gases to leave the cylinder, they comprise a large portion of the exhaust gases retained for charge dilution. Carbon monoxide effects in either case are minimal.

Emission predictions for variable camshaft timing were based on Tiara 6-285-B data for idle, taxi, and approach modes and on IO-520-D Case 1 data for climb and takeoff. Tiara data were considered representative of HC emissions that could be expected on the IO-520-D for low valve overlap in low speed modes. This is due to higher engine speeds of a geared engine in these modes and because of the comparatively low Tiara valve overlap. The Tiara emission data were taken at IO-520-D fuel-air ratios for the respective modes and corrected for flow rate differences. No exhaust emission reduction benefits from exhaust gas recirculation were assumed for the IO-520-D because the design point for valve overlap is at high engine speed, i.e., large valve overlap already exists on the IO-520-D and no increase in internal exhaust gas recirculation would be expected from variable camshaft timing as defined here.

Consistent with the literature (13, 14), CO remained essentially unchanged from the standard engine value, exceeding the EPA limit by 27%, and was the determining factor in Variable Camshaft Timing being ranked tenth. Hydrocarbons were reduced by 49% of the EPA standard (from 97% to 48%) relative to the standard engine. Nitric oxide emissions remained essentially unchanged at 33% of the EPA standard.

The literature search produced the following Pros and Cons which further characterized Variable Camshaft Timing:

PROS

- Minimal Hardware Change
- Minimal Weight Penalty
- Improved Performance
- Reduced HC Emissions for Aircraft Emission Cycle

CONS

- Complex Mechanism
- Little Effect on CO and NOx for Aircraft Emission Cycle
- Unproven Design.

5.6 IMPROVED FUEL INJECTION SYSTEMS

An Improved Fuel Injection System will mechanically provide moderate high pressure fuel flow (100 to 200 psi) metered as a function of engine air flow by monitoring and responding to intake manifold pressure, temperature, and engine speed. The system will be timed to supply a fuel mist to each intake valve as it opens. Cylinder mixture formation will be improved through the use of pintle nozzles, Figure 16, which will promote better fuel atomization than the current continuous flow nozzle used by TCM, Figure 17. Such a system will result in a more homogeneous fuel-air mixture within each cylinder and decrease cylinder-to-cylinder fuel-air ratio variation, provided an even air distribution is supplied by the intake manifold. This will allow leaner operation without the attendant operational problems with carburetted or conventional (low pressure) fuel injection systems while providing the fuel-air ratio necessary to maintain low exhaust emissions at all load conditions.

A system manufactured by Simmonds Precision Products, Inc. (16) which meets all the above requirements was utilized for evaluation of the concept based on the cost-effectiveness criteria. In this system, a multi-plunger, axial-driven pump rotates a wobble plate, Figure 18. An oil-operated servo system responding to manifold pressure and temperature varies the stroke of the pump. Fuel distribution from the individual plungers to the designated injection nozzle is coordinated by a valving mechanism which permits each plunger to deliver fuel to two different cylinders on alternate crankshaft revolutions. This is necessary on this particular unit because the pump is driven at engine crankshaft speeds in order to inject over a 180-degree period. On a six-cylinder engine, for instance, each of three plungers supplies fuel to two different cylinders.

For the purpose of predicting exhaust emissions for operation with such a system, the fuel-air ratios that could be maintained for the seven-mode aircraft cycle were defined as a time-weighted equivalence ratio range of 1.03 to 1.13. Exhaust emission reductions were based on the IO-520-D engine, Figure 3, resulting in absolute emission levels of 55%, 90%, and 58% of the EPA standard for HC, CO, and NOx, respectively, and in an emission ranking of third for the Improved Fuel Injection System.

The literature search produced the following Pros and Cons which further characterized an Improved Fuel Injection System:

PROS

- Less Cylinder-To-Cylinder Fuel-Air Ratio Variation
- Versatile, i.e., One Design for All Applications
- Improved Engine Response
- Better Specific Fuel Consumption
- Minimal Weight Penalty
- Air Flow Sensitive Fuel Flow
- Timed Fuel Flow, i.e., No Fuel Accumulation Between Intake Strokes
- Increased Fuel Atomization
- Low Emissions for Aircraft Emission Cycle

CONS

- Expensive
- Close Manufacturing Tolerances Required
- Possible Cylinder Head Cooling Problems.

5.7 ULTRASONIC FUEL ATOMIZATION

This concept achieves good fuel atomization, i.e., breaking fuel down to small droplet diameter, over a wide range of operating conditions by separating the fuel-air metering requirements from the atomization requirement. Better atomization provides a more homogeneous fuel-air mixture for delivery to the cylinders and decreases cylinder-to-cylinder fuel-air ratio variations which extends lean-burn capability. Various means are available for providing segregated fuel atomization, some of which claim an order-of-magnitude reduction in fuel droplet diameter. Some systems employ mechanical agitation of an ultrasonic driver mounted in the carburetor throat. The principle of operation is similar to spraying a liquid on the diaphragm of an operating compression type hi-fi "tweeter" (17). The transducers used for this application may be a magnetostrictive type or a piezoelectric type driven at frequencies from 20 to 40 kHz into a half horn.

No raw emission data were obtained for ultrasonic fuel atomization. To rank the concept for emissions relative to the other thirteen concepts it was assumed to have the same emission reduction potential as Thermal

Fuel Vaporization (Section 5.8). This approach was taken because both concepts have essentially the same end result, i.e., homogeneous fuel-air mixture with decreased cylinder-to-cylinder fuel-air ratio variation. The predicted emission levels are presented in Table I and result in a rating of 12 for Ultrasonic Fuel Atomization, one position below Thermal Fuel Vaporization. The literature search produced the following Pros and Cons which further characterized Ultrasonic Fuel Atomization:

PROS

- Increased Fuel Atomization Over a Wide Range of Operating Conditions
- Reduced HC Emissions for Aircraft Cycle
- Function Independent of Ambient Temperature
- Fail-safe
- Better Starting Characteristics
- Relatively Inexpensive

CONS

- Possible Power Requirements
- Primarily for Carburetted Applications
- Implementation Problems
- Possible Increased Frontal Area
- No Effect on CO and NOx Emissions for Aircraft Emission Cycle

5.8 THERMAL FUEL VAPORIZATION

This concept promotes a more uniform fuel-air mixture through utilization of waste exhaust heat. The Ethyl Corporation version of the concept, termed the Turbulent Flow System (TFS) (9) was considered a typical Thermal Fuel Vaporization system for the purposes of Task II. The system, designed for carburetted applications, includes a specially designed intake manifold called the Turbulent Flow Manifold (TFM). The purpose of this manifold is to utilize exhaust heat, increased mixing length, and a turbulence generating geometry to provide better fuel-air mixture preparation. The result has been some direct extension of the lean limit, but, more important, it has helped to ensure that all cylinders consistently receive a fuel-air charge that is richer than the lean limit at time of ignition. This improves the poor operational characteristics generally associated with lean mixtures. An additional claim for the TFM is alleviation of cycle-to-cycle fuel-air ratio variation by delivering the above homogeneous mixture into a plenum at low velocity so that the tank will be filled uniformly and evenly withdrawn by the individual cylinders. This prevents the formation of large unstable vortices in the intake manifold which collapse in random fashion under certain conditions.

The TFM illustrated in Figure 19 is for water-cooled applications; however, exhaust gases could serve as the heating media for air-cooled engines. The mixing tube extends beneath the primary barrel(s) of the carburetor and terminates in the conditioning chamber. The conditioning chamber is located beneath the plane of the intake manifold with exit tubes leading from the top of the conditioning chamber to the floor of the intake manifold. Portions of the conditioning chamber exterior are heated by engine coolant (or exhaust gas for air-cooled applications). This inherent increase in mixing length provides much better fuel-air mixing of the two jets set up downstream of the throttle plate by increasing time for expansion and formation of one stream. Lips on the walls above the primary mixing tube aid in the single jet formation but also reentrain any liquid fuel which might collect on the walls. The TFM with its 180-degree change in direction in the conditioning chamber collects large fuel droplets in the conditioning chamber and vaporizes them with heat.

Raw emissions data from two engines, an American 350 CID V-8 and a European 121 CID I-4, were obtained from Ethyl Corporation and evaluated on the aircraft emissions seven-mode cycle. The results were inconsistent for the two engines. The results for the American V-8 seemed more reasonable because of the predictable insignificant effect on NOx, whereas for the European four-cylinder the NOx was reduced by almost 60%. For that reason, the results of the American V-8 data analysis were used for ranking the TFM emission reduction potential relative to the other concepts. As expected, only HC emissions were reduced (39%) with the addition of the TFM, which resulted in Thermal Fuel Vaporization being ranked eleventh for the emission ranking.

The Pros and Cons associated with Thermal Fuel Vaporization are:

PROS

- Less Cylinder-to-Cylinder Fuel-Air Ratio Variations
- Increased Intake System Fuel and Air Turbulence
- No Power Requirements
- Relatively Inexpensive
- Durable
- Reduced HC Emissions for Aircraft Emission Cycle
- Improved Lean Operation Characteristics
- Fail-safe
- Low HC Emissions for Aircraft Emission Cycle

CONS

- Primarily for Carburetted Applications
- Possible Increased Frontal Area
- Implementation Problems
- No Effect on CO and NOx Emissions for Aircraft Emission Cycle.

5.9 IMPROVED IGNITION SYSTEMS

Conventional aircraft piston engine ignition systems employ fixed timing and single-spark firing. Two potential improvements for existing systems, therefore, are multiple-spark firing and spark timing variability. Representative systems capable of providing these improvements are presented in Sections 5.9.1 and 5.9.2.

5.9.1 Multiple Spark Discharge Ignition

This concept was envisioned as a high-energy, capacitive-discharge ignition system capable of providing a series of ignition sparks with fast voltage rise time through 20 degrees of crankshaft rotation. The principle of operation is that ignition (particularly of a lean mixture) is more likely to occur if a series of high-energy, fast-rise sparks over some time interval is applied to the mixture rather than a single slow-rise spark of decreasing magnitude, for less time, Figure 20. A typical system is manufactured by Autotronic Controls Corporation for automobile applications but could be adapted to aircraft systems. This particular system was considered for the purpose of evaluating the Multiple Spark Discharge Ignition concept.

The literature search (18) indicated that lean misfire limit extension over conventional ignition systems is the primary benefit of the concept. The improvement was found to decrease for increasing load. No emission reduction capability was demonstrated over a sizeable range of fuel-air ratios except for HC emissions which differed beyond the point of incipient misfire. For the purpose of ranking Multiple Spark Discharge Ignition based on emission reduction potential this theory was adhered to, i.e., emissions would not be affected for a given fuel-air ratio above the lean limit of a conventional system. IO-520-D Case 1 emission levels were assumed to be the standard. As a result, the Multiple Spark Discharge Ignition System was ranked last, Table I.

The literature search produced the following Pros and Cons which further characterized the Multiple Spark Discharge Ignition System:

PROS

- Improved Ignition Under All Operating Conditions
- Better Starting Characteristics
- Relatively Easily Implemented
- Minimal Weight Penalty
- Relatively Inexpensive

CONS

- Possible Radio Frequency Interference
- No Emission Reduction Potential Has Been Demonstrated.

5.9.2 Variable Timing Ignition

A Variable Timing Ignition System would employ methods of advancing and retarding spark timing as a function of speed/load conditions such as the conventional automotive centrifugal/vacuum system. Spark timing variability would improve transient operation and reduce incipient lean fuel-air limits imposed by acceleration problems. The effect of ignition timing on the Tiara 6-285-B lean misfire limit is presented in Figure 21.

Estimated leaning potential on the IO-520-D resulted in CO, HC, and NOx emissions of 116%, 85%, and 35% of EPA standards, respectively. These levels were predicated on Variable Timing Ignition improving transient operation at idle, taxi, and approach modes since IO-520-D "safety butt-lines" at these modes were established as inadequate acceleration. The quantity of improvement was defined as that required to alleviate acceleration problems at the richest fuel-air ratio at which transient problems were encountered during lean-out testing of the uninstalled engine. This method resulted in fuel-air ratios richer than existing "safety butt-lines" but leaner than best power fuel-air ratios (Case 1) for the above modes. Best power (Case 1) fuel-air ratios were used for climb and takeoff modes. The resultant exhaust emissions are considered conservative because at the fuel-air ratios chosen only transient hesitation was noted rather than complete response failure. Variable Timing Ignition should easily provide at least the minimum improvement required for satisfactory transient operation at the above conditions.

Additional benefits from a vacuum advance would be smoother operation at light loads while maintaining or improving the lean mixture combustion in the cruise range. The former effect could be realized through spark retardation relative to the latter case, which requires early spark timing to compensate for the slow burning characteristics of lean fuel-air mixtures. A centrifugal (speed) advance would be required to compensate the initial flame speed for changes in engine speed.

The literature search produced the following Pros and Cons which further characterized the Variable Timing Ignition concept:

PROS

- Extended Lean Misfire Limit
- Improved Acceleration
- Improved Fuel Economy
- Improved Light Load Operation
- Reduced HC and CO Emissions
- Relatively Inexpensive
- Relatively Easily Implemented

CONS

- Increased NOx Emissions
- Ignition System Size Increase.

5.10 HYDROGEN ENRICHMENT

Hydrogen Enrichment is the process of mixing hydrogen with normal gasoline (or other hydrocarbon fuel) to form a fuel mixture with the lean flammability limit extended to ultralean fuel-air ratios. Ultralean operation results in higher thermal efficiencies, hence lower fuel consumption, and low exhaust emissions that accompany lean operation in the fuel-air range possible. For the purposes of evaluating the concept in Task II, the system proposed by Jet Propulsion Laboratory (3) was considered typical. The proposed system reportedly requires relatively small modifications to aircraft engines (3) but high turbulence valves, combustion chamber shape, spark plug location, high energy ignition, and camshaft timing might require consideration to obtain maximum benefit from ultralean operation (17).

Safety and logistics problems which could be associated with such a concept are reduced substantially by catalytically generating the hydrogen from the gasoline on the aircraft as the engine requires it rather than storing gaseous or liquid hydrogen on board. Integration of a hydrogen generator with a turbocharged fuel injected aircraft piston engine is illustrated schematically in the simplified flow diagram of Figure 22. Conventional operation without hydrogen enrichment is denoted by solid lines, whereas the dashed lines indicate the additional requirements (plus the generator and heat exchanger) for Hydrogen Enrichment. For the latter mode of operation, some of the fuel and compressed air are diverted to the generator where they are heated, mixed, and passed into a hot catalyst bed where partial oxidation decomposes the mixture to form a hydrogen-rich product gas. (At input fuel flow rates of less than 18 lbm/hr, the variation of hydrogen produced is reported to be very nearly linear with fuel input with approximately 8.5 lbm of fuel consumed to generate 1.0 lbm of hydrogen.) To avoid thermal distress in the air induction system and maintain high volumetric efficiency, the product gas is passed through an air/gas heat exchanger to reduce the temperature of the product gas prior to engine induction. No raw emissions data were available for determining the exhaust emission reduction potential for an aircraft piston engine utilizing Hydrogen Enrichment. The Jet Propulsion Laboratory (3) predicted emission characteristics for a standard aircraft engine utilizing Hydrogen Enrichment. The predictions were based on the assumption that the correlations of indicated specific emission production with equivalence ratio are valid. The data base utilized in generating these representations at richer equivalence ratios (>1.1) was for a TCM IO-520-D engine. Data for ultralean operation were obtained by JPL for a 350 CID V-8 engine operating with both straight gasoline and mixtures of gasoline and hydrogen-rich gases from a hydrogen generator. Reasonable coalescence occurred where the data sets joined. Hydrogen Enrichment emission levels for Task II were determined through the use of the above ultralean data and IO-520-D data.

Idle, taxi, and approach modes emission rates (lbm pollutant/indicated horsepower·hr) were defined by JPL data at 0.6 equivalence ratio. The corresponding values of indicated horsepower were calculated from known brake horsepower and friction horsepower characteristics for the IO-520-D engine. Hydrogen Enrichment was assumed nonoperational at climb and takeoff in order to maintain engine power. Emission levels for climb and takeoff were taken directly from IO-520-D data for Case 1 (best power). The method is outlined in Tables II and III. Applying Hydrogen Enrichment to the IO-520-D engine produced CO, HC, and NOx levels of 68%, 43%, and 30% of the EPA standards, respectively, and resulted in Hydrogen Enrichment being ranked first for emission reduction potential, Table I. The literature search produced the following Pros and Cons which further characterized Hydrogen Enrichment.

PROS

- Ultralean Operation
- Improved Fuel Economy
- Low Emissions for Aircraft Emission Cycle

CONS

- Increased Weight
- Added Complexity
- Increased Engine Nacelle
- Costly
- Performance Penalty.

5.11 AIR INJECTION

Air Injection is an exhaust after-treatment concept that promotes secondary oxidation of incompletely oxidized carbonaceous species, CO and HC. The process is accomplished by adding supplementary air to the exhaust gases to provide an oxidizing environment. The conceptual design considered for the purposes of Task II evaluation included an engine-driven pump and associated hardware, including tubing necessary to inject secondary air through injection nozzles located in the exhaust port of each cylinder. The feasibility of the concept is well-proven and has had widespread use in controlling automotive emissions. TCM demonstrated the exhaust gas thermal effects of air injection during Tiara 6-320 testing of an air-cooled exhaust valve concept, Figure 11. Thermocouples measuring exhaust gas temperatures at the port exits and at the turbocharger inlet indicated that the oxidation reaction occurred between those locations. The typical data for a particular engine fuel-air ratio (fuel flow) are presented in Figure 23 over the range of cooling air flows considered. The air flow actually reduces the exhaust gas temperature at the port exit, indicating that little or no oxidation has occurred up to that point. The turbocharger inlet gas temperature increases, however, indicating that the reaction has occurred or is occurring at that point. At leaner engine fuel-air ratios where lower levels of HC and CO emissions would be predicted, the turbocharger inlet temperature leveled off at the higher cooling air flows and showed indications of decreasing. This indicated that essentially complete oxidation had occurred and further Air Injection would only reduce the exhaust gas temperature.

Bendix Corporation (19) evaluated the emission reduction potential of Air Injection on a TCM O-200 engine. The results of that analysis were converted to terms that express the change in each pollutant per quantity of air injected as a function of equivalence ratio by the following:

$$\left[\frac{\%\Delta(\text{Pollutant})_i}{\%\ \text{Air Injected}}\right]_\phi = \frac{\dfrac{\left\{\left[(\text{Pollutant})_i\right]_{\text{Air}} - \left[(\text{Pollutant})_i\right]_{\text{No Air}}\right\}}{\left[(\text{Pollutant})_i\right]_{\text{No Air}}}}{\text{Air Injection Flow Rate/Engine Air Flow}}$$

where ϕ is equivalence ratio and subscript i designates pollutant HC, CO, or NOx. These effects were applied to IO-520-D Case 1 (best power) emission data at the appropriate time-weighted equivalence ratio, assuming an Air Injection flow rate equal to 20% of the engine inlet air flow rate. A rate of 20% was selected on the basis of minimum Air Injection flow rate necessary to meet EPA standards for all three pollutants at reasonable pump size and power requirements. The results, Table I, placed Air Injection fourth in the emission ranking.

The literature search produced the following Pros and Cons which further characterized Air Injection:

PROS

- Simple
- Fail-safe
- Easily Implemented
- Low Maintenance
- Inexpensive
- Minimal Weight Penalty
- Proven Concept
- Reduced HC and CO For Aircraft Emission Cycle

CONS

- Power Requirements
- High Temperatures
- Possible Increased NOx Emissions

5.12 EMISSION RESULTS

Figure 24 represents the emission levels for the concepts evaluated using raw emissions data. Shown for reference are the emission levels for the IO-520-D Case 1 and two automotive engines, a conventional high-production Chevrolet 350 CID V-8 engine and a high-performance BMW 121 CID I-4 engine. The Chevrolet engine was a 1975 model without a catalytic converter, exhaust gas recirculation, or secondary air injection. The BMW engine was a 1973 model lacking the same pollution control devices. Neither engine met the EPA aircraft emission standard. While CO and HC were within the limits, the oxides of nitrogen were well over the allowable emissions, as compared to 30% of the allowable emissions for the IO-520-D engine.

Graphical representation of engine emissions as a function of time-weighted fuel-air equivalence ratio from Figure 24 and four current production TCM engines resulted in the generalized curves presented in Figure 25. Data from four TCM engines (IO-520-D, GTSIO-520-K, O-200-A, and Tiara 6-285-B) operating at three mixture strength schedules, were utilized in developing the rich end of the curves. Emissions from all open-chamber four-stroke Otto cycle engines evaluated adhered very closely to these trends. Note that only a narrow band of seven-mode, time-weighted equivalence ratios, 1.03 to 1.13, exists where all three regulated pollutants are at or below the EPA limits.

Conclusions which have been made from these analyses are:

- Conventional automotive engines exceeded aircraft NOx limits (50% to 120%); HC and CO were below limits

- The four-stroke open chamber diesel engine exceeded aircraft NOx limits (up to 90%); HC and CO were below limits

- Thermal Fuel Vaporization (Ethyl TFS) reduced HC 39%, with insignificant effects on CO and NOx.

- The two-stroke diesel (McCulloch) produced less NOx than any other concept evaluated and was well below aircraft NOx and CO limits. Hydrocarbons exceeded the limit.

- Texaco CCS, operating on gasoline or diesel fuel, produced CO and HC emissions well below the EPA Aircraft Standard; NOx limit was exceeded (20% and 30%, respectively).

- Honda CVCC met all EPA emission standards and was the best Stratified Charge Concept evaluated on overall emission reduction.

- Ford PROCO exceeded NOx limits but was well below CO and HC standards.

- The NOx emissions for all concepts evaluated, except the two-stroke diesel, exceeded those for the IO-520-D operating at fuel-air ratios from baseline to safety butt-line.

- Generalized plots of open chamber four-stroke Otto cycle engine emissions as a function of time-weighted equivalence ratio are possible, Figure 25.

- Only a narrow band of seven-mode time-weighted equivalence ratios exist where all three major pollutants are below EPA limits, Figure 25.

Table I presents the percent of EPA exhaust emission standards assigned to each of the fourteen concepts and the resultant concept ranking for emissions. Values in the table were based on the previously discussed raw emission data analyses, assumptions, and considerations and reflect minimum projected levels without tolerance band considerations.

6. DECISION MODEL

6.1 DECISION SITUATION

It is desired that the necessary technology be develcped to effectively and safely reduce general aviation piston engine exhaust emissions to meet the EPA 1980 emission standards. Major engine exhaust emissions being discharged are unburned HC, CO, and NOx. Further, it is desired to reduce these pollutants in such a way that they have minimum adverse effects on aircraft and engine cost, weight, fuel economy, and performance. Secondary emission reduction design considerations must be defined and analyzed to ensure that they do not penalize aircraft performance or significantly affect equipment configuration. The decision situation is:

- Develop a set of cost-effectiveness criteria for evaluating and screening 14 emission reduction concepts so that three candidates may be chosen for further development.

6.2 OBJECTIVES AND THE DECISION CRITERIA

The primary objective is to reduce intermittent combustion aircraft engine exhaust emissions consistent with the EPA exhaust emission standards as indicated in Section 87.31 of Reference 20. The secondary objective is to reduce engine specific fuel consumption (SFC) without incurring a loss of engine rated horsepower. The decision criterion is:

- Select the alternative concepts that effect the maximum opportunity to reduce engine emissions and SFC while minimizing adverse consequences to critical aircraft system design and performance characteristics.

6.3 DEVELOPMENT OF CRITERIA AND ATTRIBUTES

Cost and design emission reduction criteria were selected after extensive documentation review (21 through 50) and internal discussion. Further, the criteria (defined as "decision factors") are traceable to the NASA Request for Proposal (LeRC RFP No. 3-499786Q). A list of solution attributes (indicating a further breakdown of policy, monetary, and technical issues pertinent to the criteria) were generated and used for evaluating the merit and usefulness of emission reduction concepts. A solution attribute is defined as a subset of knowledge, considerations, and thoughts (sometimes intangible or ill defined) that identifies, particularizes, or supplements the meaning of the criteria. Solution attributes actually drive the definition of criteria elements. Table IV depicts a listing of the criteria used in this study. Sample listings of the attributes for each of the criteria elements are shown in Table V. These tables present a summary of attributes that played an important role in buttressing our understanding of the criteria and how they are related to emission reduction requirements. The assignment portion, to be used during the evaluation of the concepts, is also shown. Table VI presents a correlation of the number of attributes that were actually generated and used for a given criteria element as opposed to the partial listing shown in Table V.

6.4 EVALUATION AND RANKING OF DESIGN CRITERIA

Four evaluators were asked to make critical value judgments concerning the relative importance of the criteria as they would be used to assign merit to the emission reduction alternative concepts. A total of 42 years of industrial experience in combustion analysis, equipment design, reciprocating and turbine engine development, and systems engineering is noted for the evaluation team. The criteria were ranked according to their importance as perceived by each evaluator. The method for accomplishing this task is explained in Reference 1. A model of the procedure, as used in the NASA Apollo-Skylab Space Program, is presented in Figure 26. Some liberty was taken to relate the emission reduction problem situation to the original decision model. These changes are depicted in Figure 27. Each evaluator reviewed the criteria and the associated attributes. The evaluators were then asked to choose between sets of criteria as to their relative importance. For example, given any pairwise combination of criteria elements, which ones are preferred? Are cost criteria more important than emissions criteria? What criteria should be ranked first and those last? Figure 28 shows a sample worksheet provided to each evaluator. The criteria choices were denoted by rows and columns. Criteria comparison choices were numerically recorded in each cell for the attending row and column. By distributing a value whose interval lies between (0, 1) among criteria ith, criteria jth, and the associated uncertainty ijth, the evaluator logically orders the criteria to emphasize its importance to him. Thus, the equation below illustrates a formal statement of the value assignment procedure between any pair of properties and the associated uncertainty:

$$\begin{matrix}\text{RELATIVE}\\ \text{IMPORTANCE}\\ \text{OF PROPERTY j}\end{matrix} = 1 - \begin{pmatrix}\text{RELATIVE}\\ \text{IMPORTANCE}\\ \text{OF PROPERTY i}\end{pmatrix} - \begin{pmatrix}\text{ASSOCIATED}\\ \text{UNCERTAINTY}\\ \text{OF PROPERTY ij}\end{pmatrix}.$$

Property ith value assignment is recorded in the upper left-hand portion of the matrix cell, property jth value assignment is calculated as the complement of the matrix cell, and the associated uncertainty between the properties is recorded in the lower right-hand portion of the cell as shown in Figure 29. Hence, by substituting arbitrary values for cost, reliability, and the associated uncertainty, it follows that

$$\begin{aligned} \text{RELIABILITY}\left(j\right) &= 1 - \text{COST}\left(i\right) - \text{UNCERTAINTY}\left(ij\right) \\ &= 1 - 0.6 - 0.1 \\ &= 1 - 0.7 \\ &= 0.3 \end{aligned}$$

were the specific values assigned according to Figure 30. A total of 105 pairwise choices were made. A simple logic check, based on the theory of transitivity, was made on the evaluator's choices to ensure consistent pairwise value judgments. Once the evaluator's value judgments were assigned and consistency established, a second computer program was used to rank his multidimensional complex criteria set. The criteria ranking emphasis coefficient is based on the theory of combinations as used to normalize the relative importance and uncertainty scores. An emphasis coefficient is associated with each criterion and it is defined as the sum of the importance scores for that criterion normalized by the total number of pairwise comparisons made. Table VII presents each evaluator's ranked criteria set.

6.5 SYNTHESIS OF THE SOLUTION ALTERNATIVES

The synthesis and description of the design concepts, designated as solution alternatives, actually began at contract initiation. Selection of the 14 alternatives occurred after the completion of a literature search, review of concept performance characteristics, and an implementation feasibility assessment. A comprehensive description of each design concept is presented in Section 5.

6.6 EVALUATION AND RANKING OF THE SOLUTION ALTERNATIVES

Each evaluator was asked to make a value judgment concerning the choice among selected pairs of design concepts when traded off against a criteria element. It is desired to order the solution alternatives according to one's preference based on a weighted merit score that accounts for his value judgment and gives an indication of his confidence level. Each evaluator answered the questions and followed the assignment instructions shown in Table V. The answers were scored on worksheets, Figure 31, to obtain a preliminary ordering of the solution alternatives with respect to the criteria elements. Seven worksheets were supplied to each evaluator so he could record his notions and make a preliminary assessment of the alternatives. Other columnar schemes were used by some of the evaluators, but they are actually a variation of Figure 31. Where clusters of solution alternatives occurred and appeared to be ranked at the same level, they were reassessed and reordered within the ranking. The preliminary ordering was used to logically organize facts, crystallize ill-defined notions, and recognize intangible ideas about the design concepts and the criteria elements. This procedure forced the evaluator to recognize his knowledge weakness and expertise strengths.

Actual ranking of the concepts began after the above task was completed. Its procedure is identical to that of ranking the criteria, except that the concern is now with selecting a concept with respect to a criteria element, as shown in Figure 32. That is, given the choice among alternative concepts, when traded off against the criteria, which ones are preferred? Is the Improved Cooling Combustion Chamber concept preferred over the Air Injection concept when considered from emission benefits, advantages, and disadvantages? These were the fundamental questions answered by each evaluator. The choices among pairwise solution alternatives were depicted numerically. By distributing a value among alternative ith, alternative jth, and the associated uncertainty ijth, the evaluator logically ordered the concepts to emphasize the importance to him. A total of 1,365 pairwise choices (91 decisions for each of the 15 criteria elements) were made by each evaluator. Again, a consistency check was made to ensure a logical ordering of the evaluator's preferences. A second program that calculates the evaluator's merit scores (associated with his comparison of solution alternatives and criteria elements) was used after consistency was established. The procedure for the ranking of alternative solution approaches is similar to that of the criteria, as explained above. The calculation of the merit coefficient is simply a summation of the product of criteria emphasis coefficients multiplied by the concept merit scores. The merit coefficient yields the statement of preference. An example of a concept comparison tradeoff evaluation for an evaluator is shown in Figure 33.

6.7 SELECTION OF AN OPTIMUM SOLUTION ALTERNATIVE PREFERENCE DATA SET

After each evaluator had established his individual criteria set and design concept preference ranking (and associated merit scores), he was directed to meet with his colleagues and select an optimized criteria and concept data set that reflects the consensus of the group. This was accomplished by arguing in favor of a generalized or explicit interpretation of the attributes/criteria elements, amalgamating ideas, compromising individual differences, and forming an opinion that was tolerated by the evaluation group. The optimized criteria data set was selected first and then the group assembled an optimized concept data set.

Consider the individual criteria emphasis ranking in Table VII. The criteria are listed in order of highest ranking (largest numerical emphasis coefficient). The uncertainty coefficient is a measure of the evaluator's level of confidence in his value judgments (the larger numerical value indicates less confidence). Summation of the emphasis and uncertainty coefficient equals unity. Each evaluator rated Emissions and Safety in the top 3 ranking. The remaining criteria are ranked considerably differently, however. Table VIII depicts the criteria ranking based on the consensus of the evaluators and is used as part of the input data to form an optimized solution approach. The formulation of the consensus involved three discrete tasks: 1) fine-tune the selected criteria data, i.e., make slight changes in value assignments, 2) input the selected criteria data into the computer program to determine the optimized emphasis coefficients, and 3) ensure that the criteria data really represent the group's attitude. Table IX shows an ordering of the criteria based on a simple arithmetic average of each evaluator's criteria ranking. However, after subsequent discussion, it became apparent that the group reordered its priorities and assigned a new criteria ranking as shown in the optimized case of Table VIII.

A set of solution alternatives were arrived at in the same manner as the criteria set. Table X presents a summary of individual design concept preferences with associated merit and uncertainty coefficients. It should be realized that the individual preferences are a summation of the comparisons of concepts as a function of criteria tradeoff merit scores. Where possible, a consensus was reached to select an individual's data set that best satisfied the decision criterion. The Emissions and Performance tradeoff merit scores were slightly modified to meet the group's considered value judgment. The merit scores, together with the criteria emphasis set, formed the optimized input data for the solution approach. The rank order of the solution approaches shown in Table XI represents the consensus of the evaluators. The optimized preference listing of emission reduction design concepts was generated by the decision algorithm. Table XII is submitted as supportive data showing the optimized ranking for each concept as a function of the criteria.

6.8 EXAMINATION OF THE DECISION CRITERION AND DESIGN CONCEPT CHOICES

The optimized emission reduction criteria ranking and concept preference selection was evaluated for a reasonable fit to the decision criterion. Inspection of Table VIII shows that Emissions, Performance, and Fuel Economy rank within the top 40 percentile of 15 criteria elements. Emissions is ranked first; Performance, third; and Fuel economy, sixth. The above criteria elements are considered congruent with respect to the decision criterion since they are explicitly stated in the primary and secondary objectives as the needs to be satisfied. Safety, ranked second; Cooling, fourth; and Weight and Size, fifth, are important criteria design considerations that are also included in the upper 40 percentile. The first seven criteria elements are considered the dominant requirements that have the greatest influence on the selection of solution alternatives.

The Reliability requirement was considered marginally important insofar as two evaluators thought it should be placed in the upper 40 percentile. However, Engineers 1 and 3 could not justify or substantiate a strong rationale that favored such high esteem for it. The consensus relegated Reliability to eighth position while the order of the first seven criteria elements prevailed.

In most cases, the evaluators considered Technology, Operational Characteristics, and Maintainability and Maintenance moderately important but lacking in authority. This can be attributed to either the evaluator's ignorance and unfamiliarity of how the criteria requirement relates to the emission reduction problem or the realization that they are coupled to a higher ordered criteria element that has already been satisfactorily answered. The same rationale is used for expressing the consensus for the last four ranked criteria. They do not significantly influence the selection of the solution alternatives at this time. This does not mean that Integration, Materials, Producibility, and Adaptability are to be totally ignored. Most evaluators considered the above criteria of minor importance when selecting a design concept. However, the evaluators may indeed be forced to reassess their initial criteria ranking as subsequent tasks are pursued.

Inspection of Figure 34 shows the optimized correlation matrix for each concept as a function of criteria rank ordering. The concepts are listed in order of their final ranking for the optimized preference analysis. The numbers shown at each intersection point represent the order of concept ranking based on the merit scores when compared with the criteria element. The Improved Cooling Combustion Chamber design concept is ranked first because it scores well among the dominant criteria elements, i.e., first for safety, cooling, and weight and size, and moderately well among the remaining four dominant criteria. The Improved Cooling Combustion Chamber ranked ninth with the emissions criteria, but the influence of the remaining dominant criteria elements forced this design concept to be the top ranked candidate. The Improved Cooling Combustion Chamber candidate was also ranked within the top three design concepts for each evaluator.

The Improved Fuel Injection Systems and Air Injection design concepts are ranked second and third, respectively. Inspection of the dominant criteria (Figure 34) shows a relative high rank scoring for these two candidates when compared against the remainder of design concepts. Again, the Improved Fuel Injection Systems candidate was ranked within the top three design concepts for each evaluator. It becomes apparent that the further one proceeds down the list of design concepts, the corresponding numerical ranking values increase in magnitude for the criteria elements, thus indicating lower utility.

Table XI shows that the first four concepts offer considerable promise at meeting the decision criterion. When considered from the perspective of what is now known about small aircraft reciprocating engine emission reduction methods; the state-of-the-art for emission reduction technology; current industry in-progress emission reduction efforts; and the likelihood of meeting present and future EPA air quality standards, it is envisaged that the first six concepts offer a good chance of successful exploitation. The evaluators believe that the rank ordering of the design concepts, merit coefficient scores, and uncertainty coefficients are realistic and represent a true and accurate estimate of their judgment.

ILLUSTRATIONS

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Engine Description:

Engine Displacement:

Engine Rated Brake Horsepower:

Fuel Hydrogen-Carbon Ratio:

	ENGINE CONDITIONS REQUIRED		DATA REQUIRED											ACTUAL ENGINE CONDITIONS		
					INDUCTION AIR UPSTREAM											
MODE NAME	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr) OR MASS FUEL-AIR RATIO	TEMPERATURE (°F)	PRESSURE (in. Hg abs)	SPECIFIC HUMIDITY (lb/lb)	HC	NOx	CO	CO_2	O_2	MANIFOLD PRESSURE (in. Hg abs)	ENGINE TORQUE (ft/lb)	ENGINE SPEED (rpm)	INDICATED H.P. OR FRICTIONAL H.P.
Idle	--	600 rpm														
Taxi	--	1200 rpm														
Take-Off	100	100% of Maximum Speed														
Climb	80	90% of Maximum Speed														
Approach	40	87% of Maximum Speed														

NOTES:

HC	-	Total hydrocarbons in ppm Cx Hy by volume	- Undiluted	(or) gm/hr of Cx Hy	(define x and y)
NOx	-	Total oxides of nitrogen in ppm by volume	- Undiluted	(or) gm/hr of NOx	(define x)
CO	-	Carbon monoxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO	
CO_2	-	Carbon dioxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO_2	
O_2	-	Oxygen in ppm or % by volume	- Undiluted	(or) gm/hr of O_2	

If volumetric data is provided, please designate whether concentrations are wet or dry (water vapor removed) values.

FIGURE 1. RAW EMISSIONS DATA REQUEST FORM

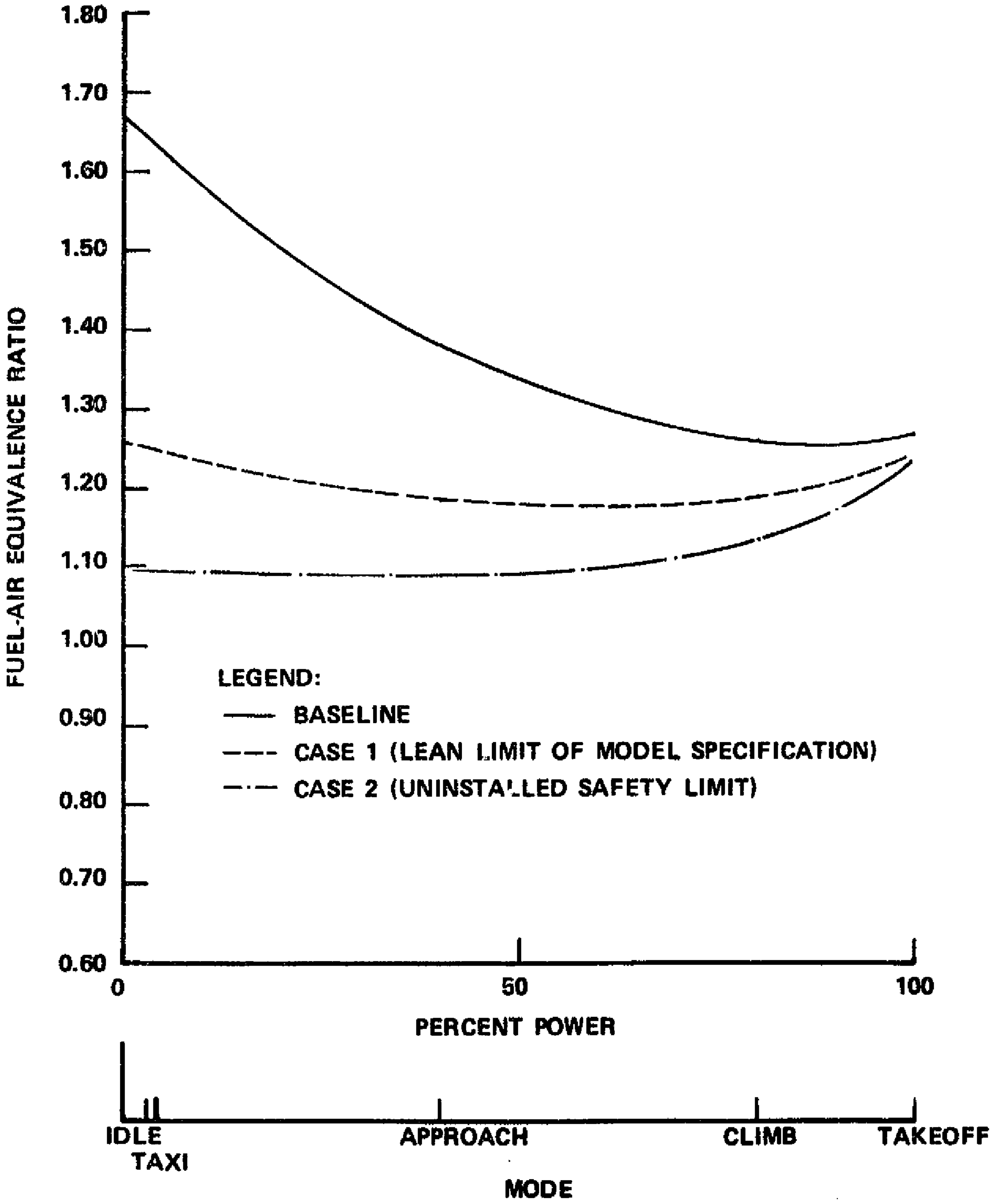


FIGURE 2. IO-520-D, EMISSION CYCLE MIXTURE STRENGTH SCHEDULE

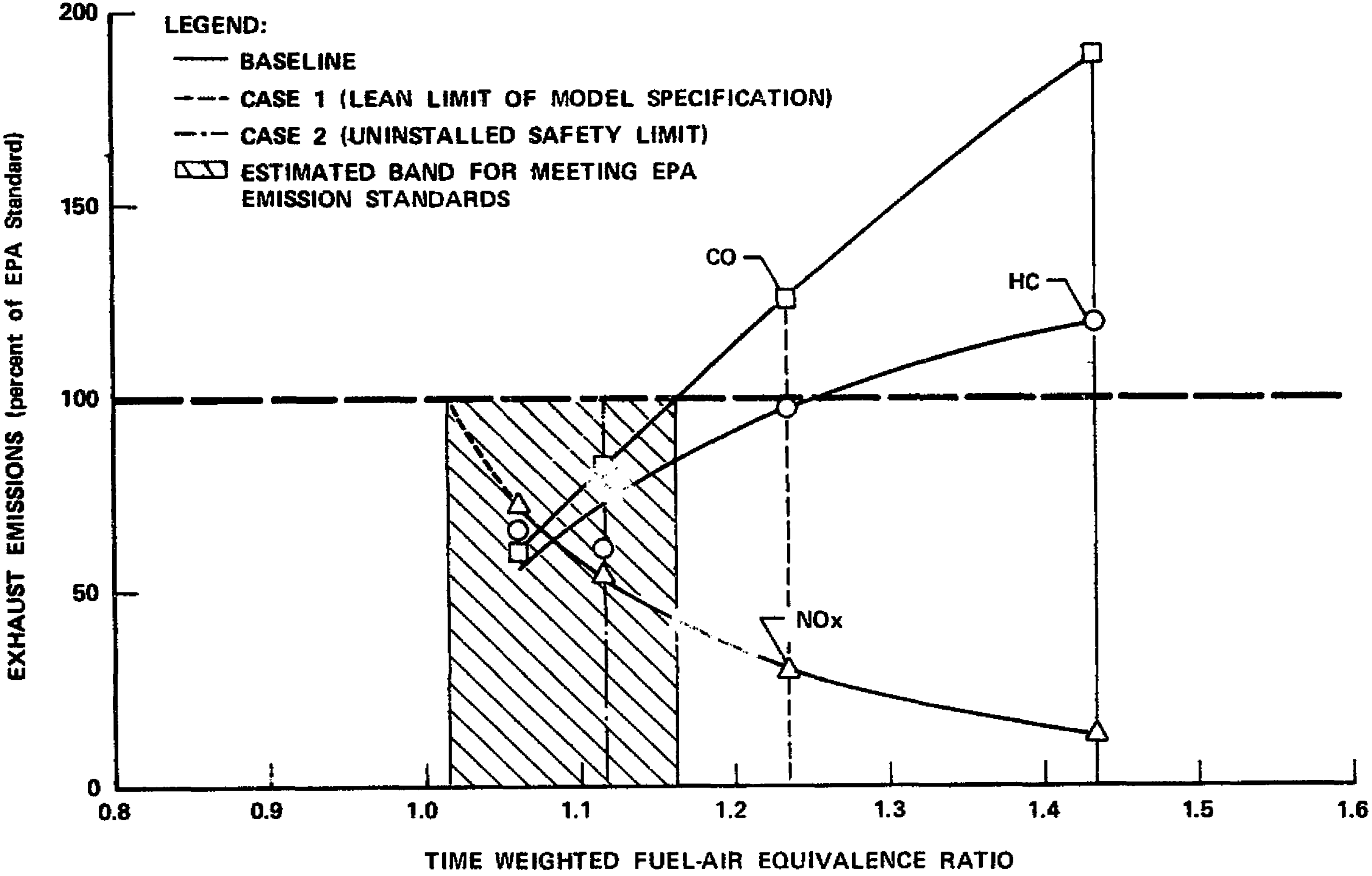


FIGURE 3. IO-520-D, EXHAUST EMISSION LEVELS FOR VARIOUS MIXTURE STRENGTH SCHEDULES

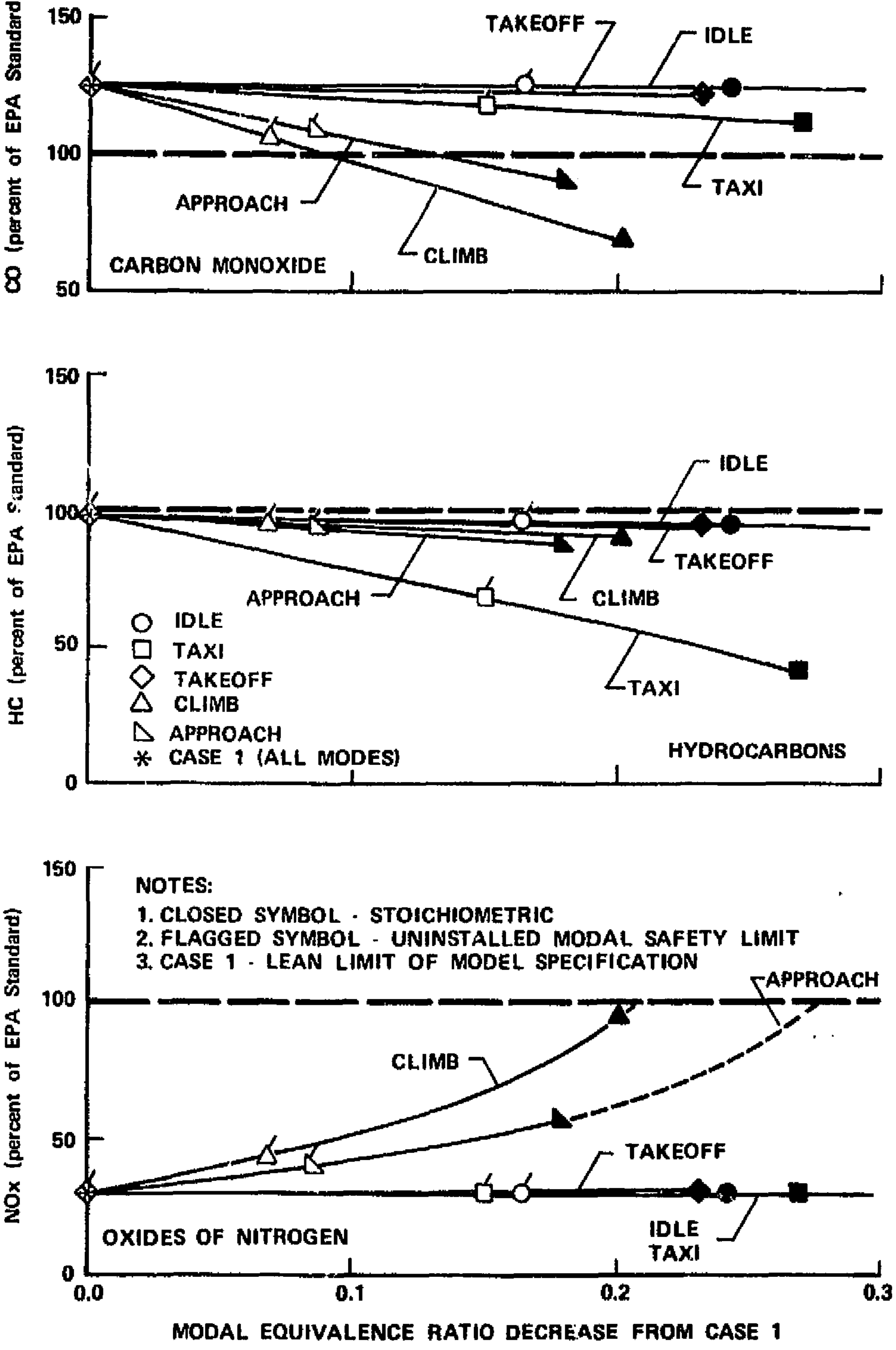


FIGURE 4. IO-520-D, EFFECT OF MODAL EQUIVALENCE RATIO ON CO, HC, AND NOx

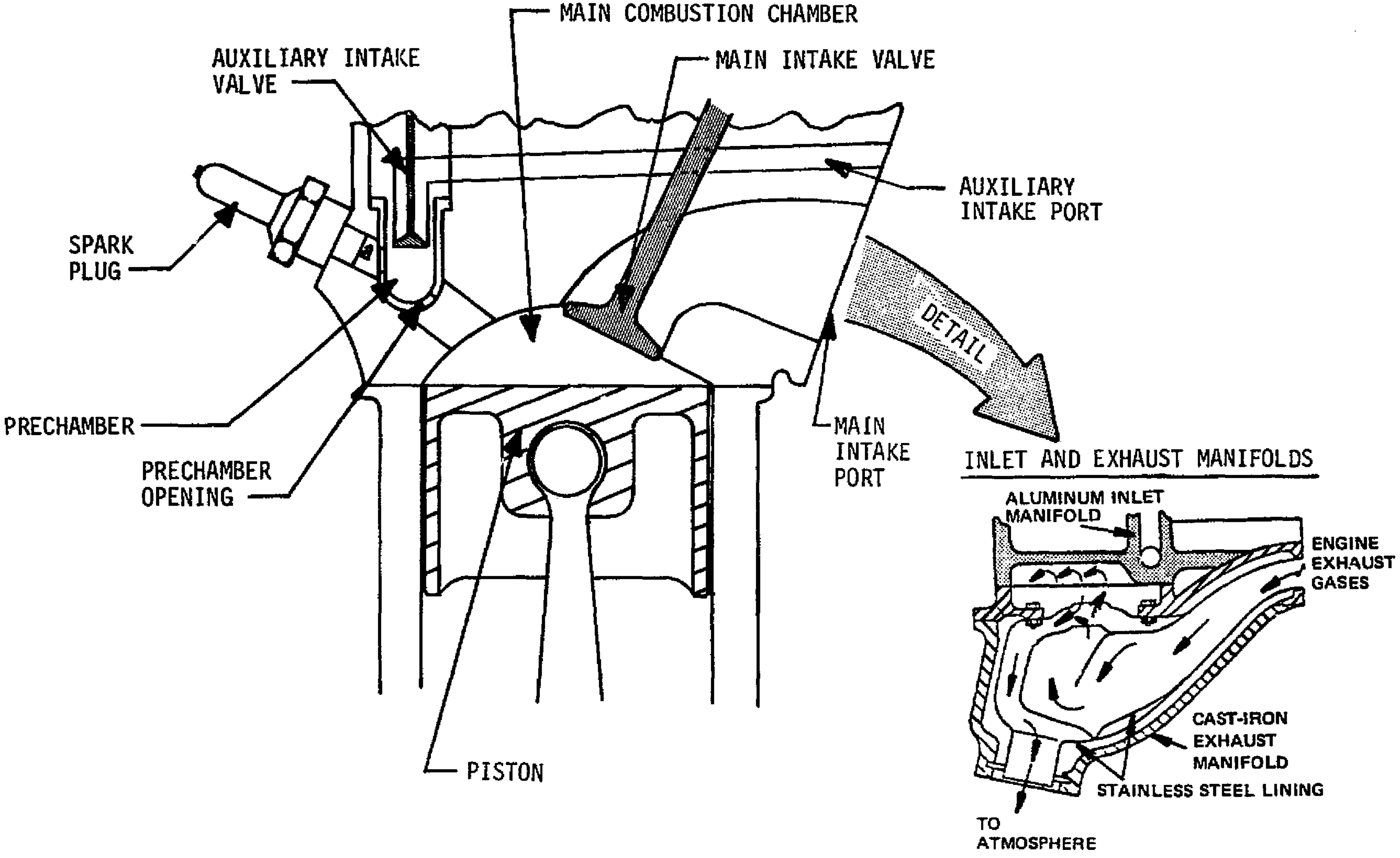


FIGURE 5. HONDA CVCC ENGINE CONCEPT

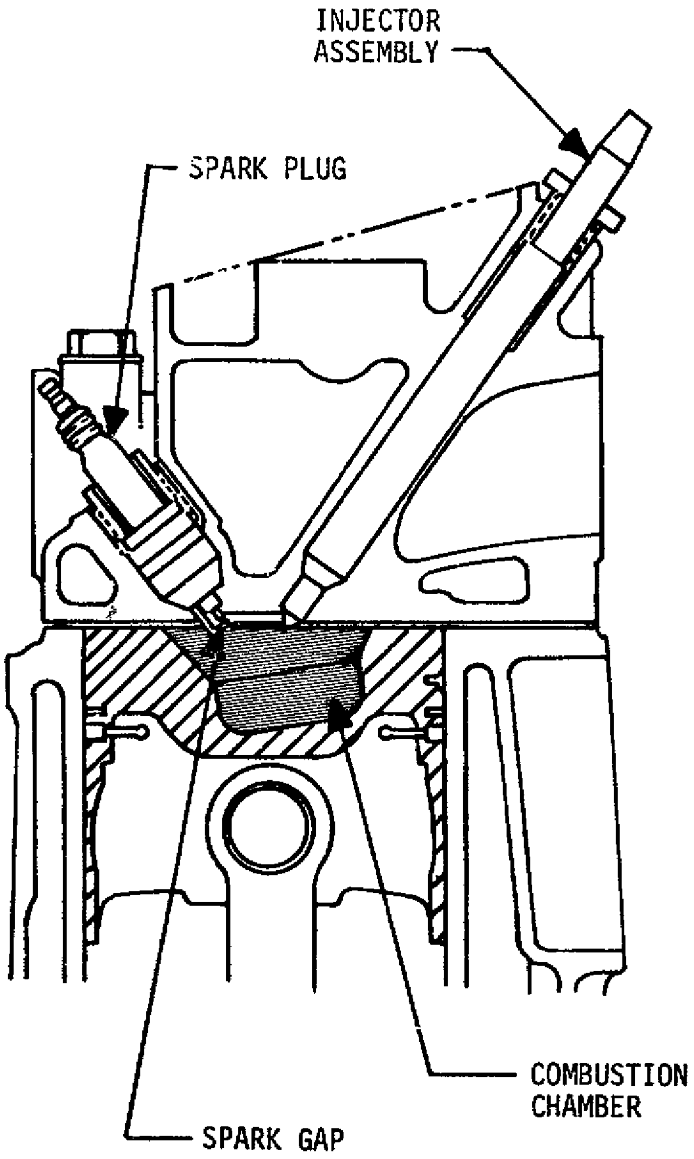


FIGURE 6. FORD PROCO STRATIFIED CHARGE CONCEPT

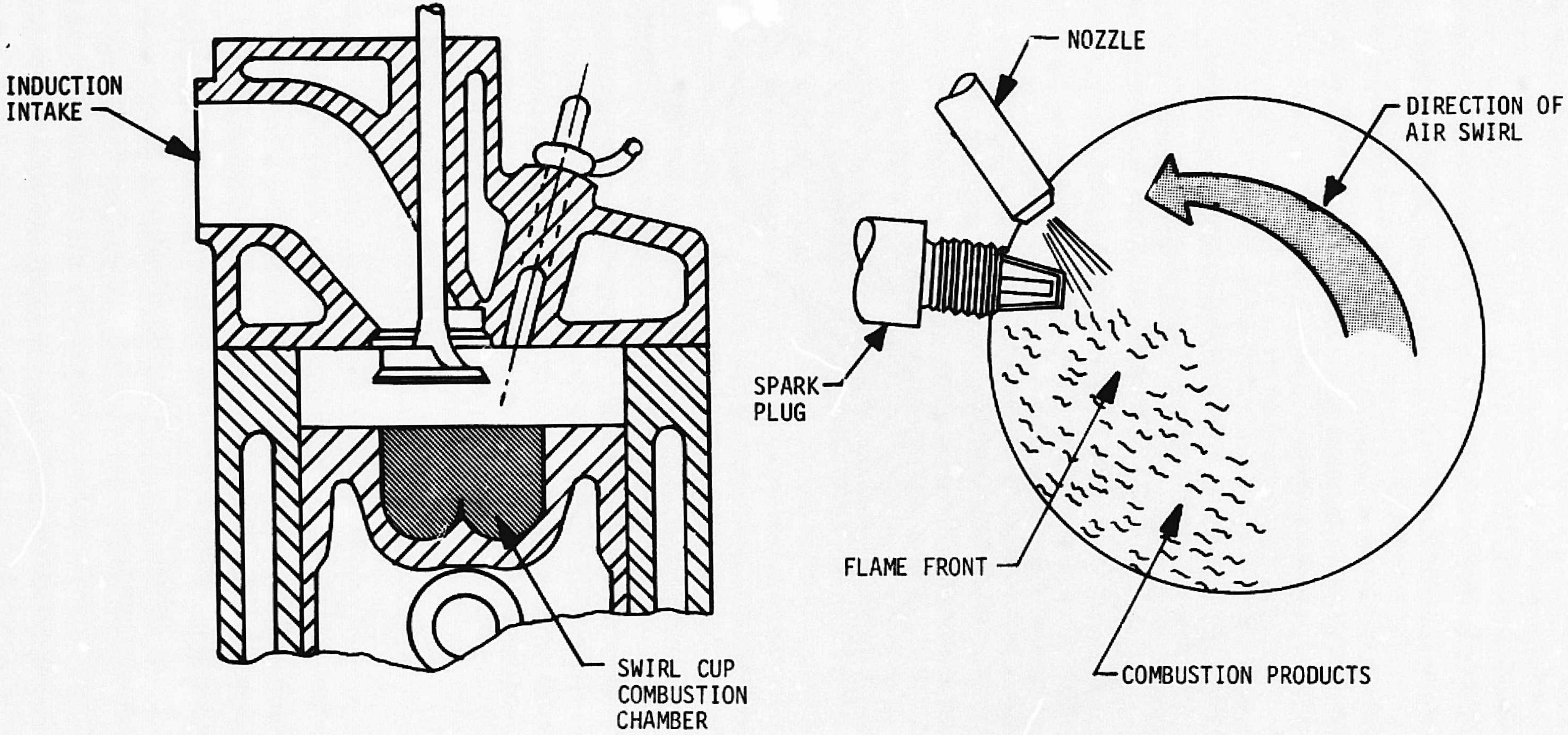


FIGURE 7. TEXACO CONTROLLED COMBUSTION SYSTEM CONCEPT

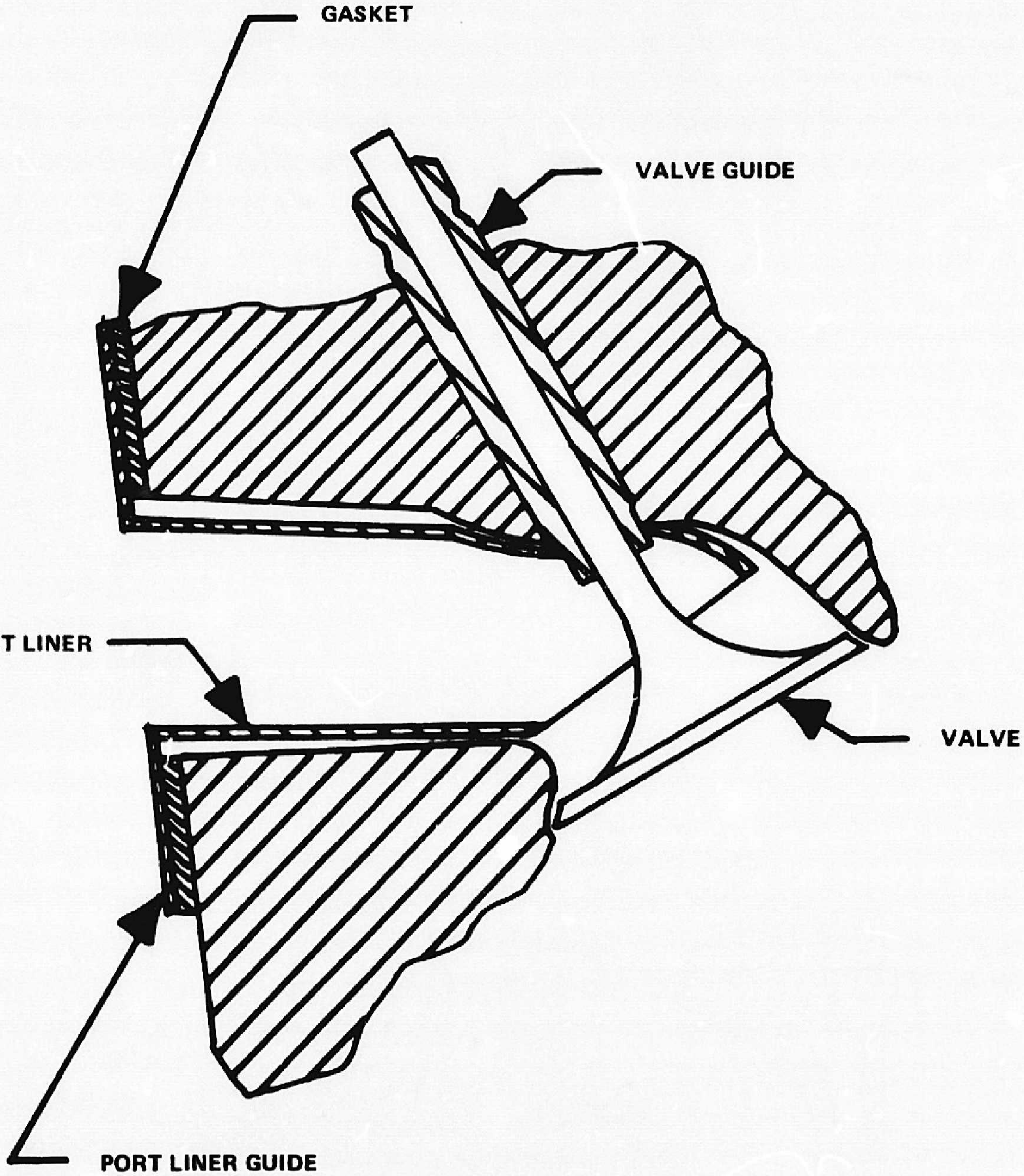


FIGURE 8. TYPICAL PORT LINER

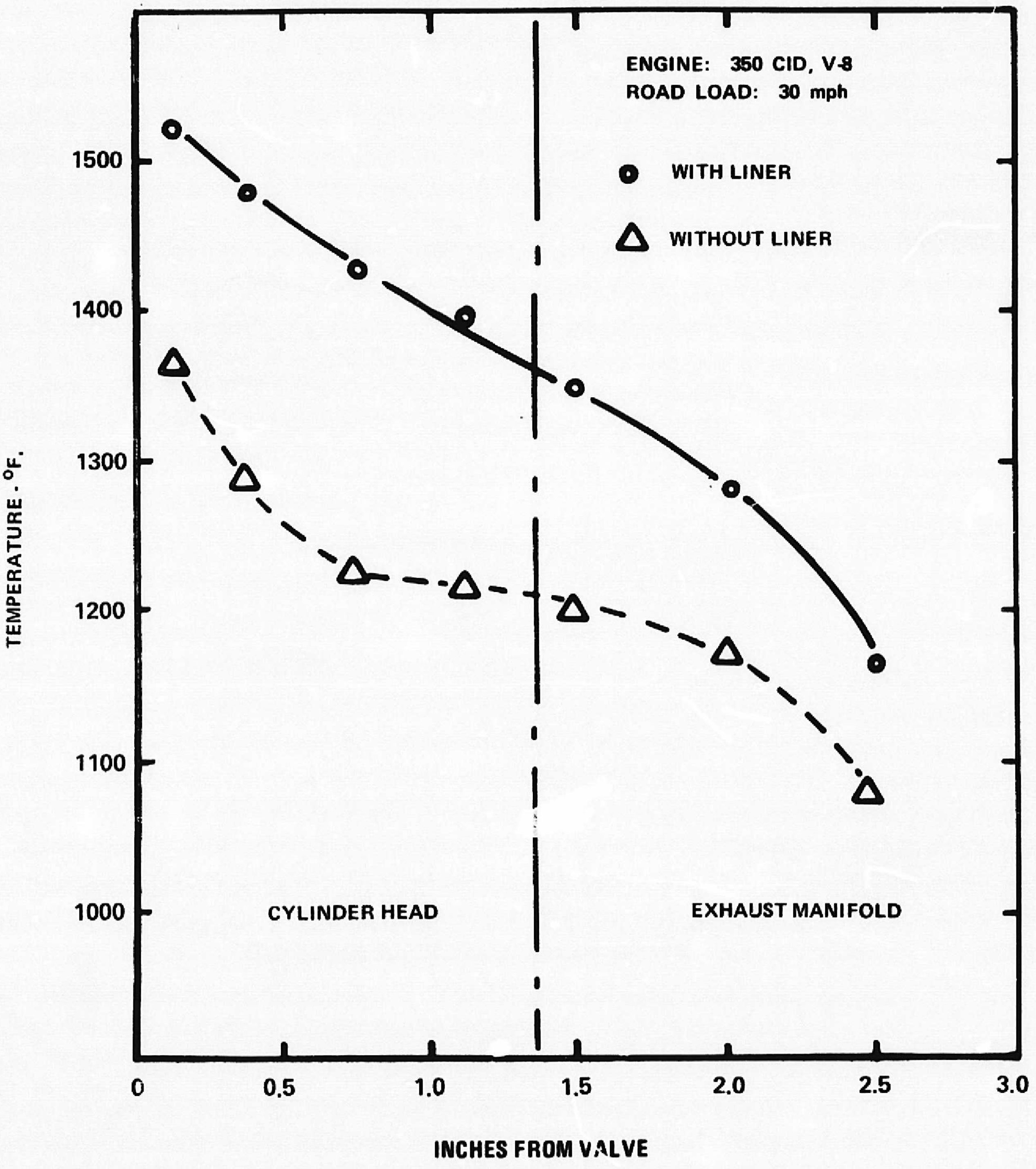


FIGURE 9. EFFECT OF PORT LINER ON EXHAUST GAS TEMPERATURE

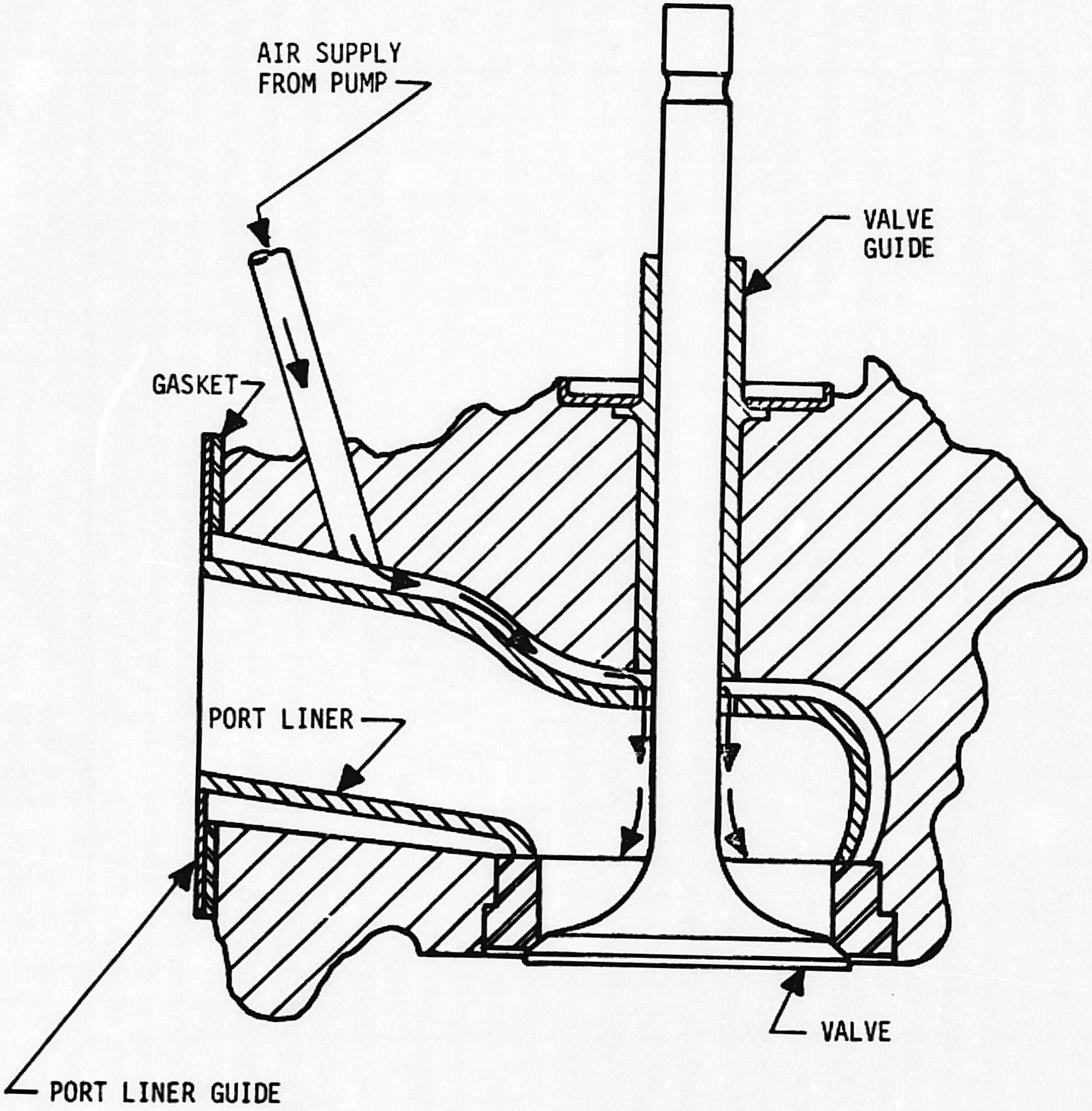


FIGURE 10. EXHAUST PORT LINER CONCEPT

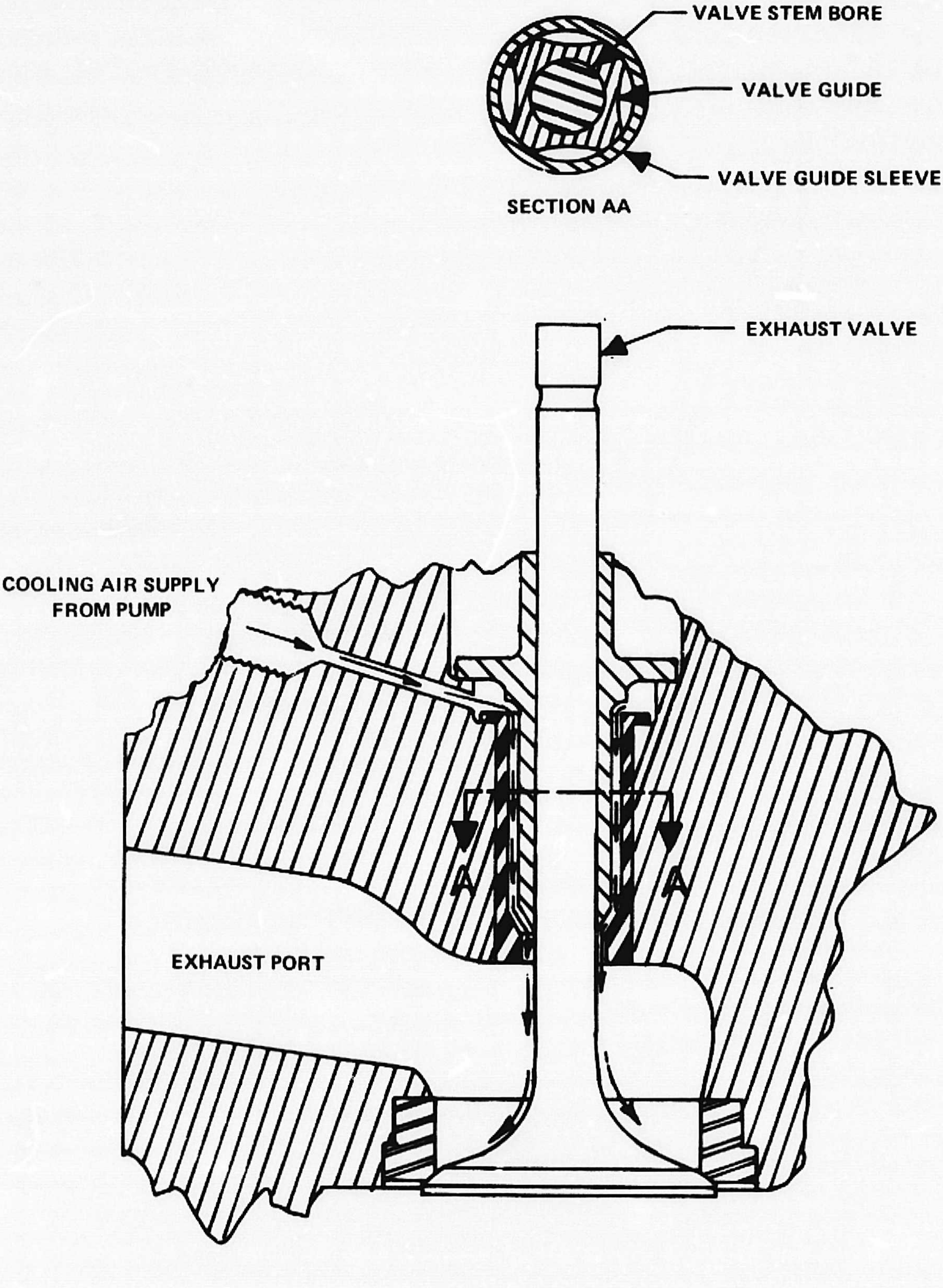


FIGURE 11. TCM AIR-COOLED EXHAUST VALVE CONCEPT

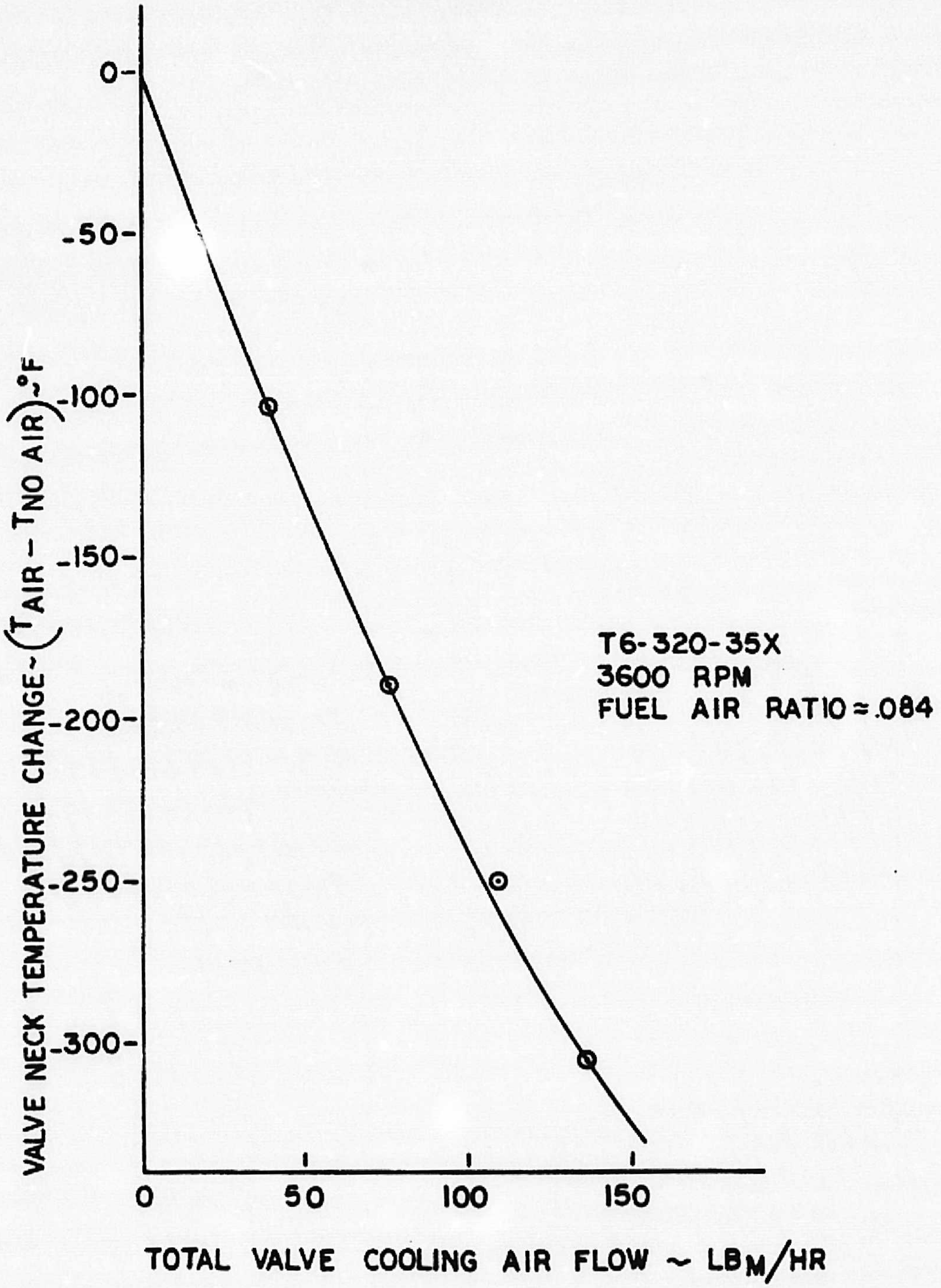


FIGURE 12. EFFECT OF VALVE COOLING AIR FLOW ON VALVE NECK TEMPERATURE

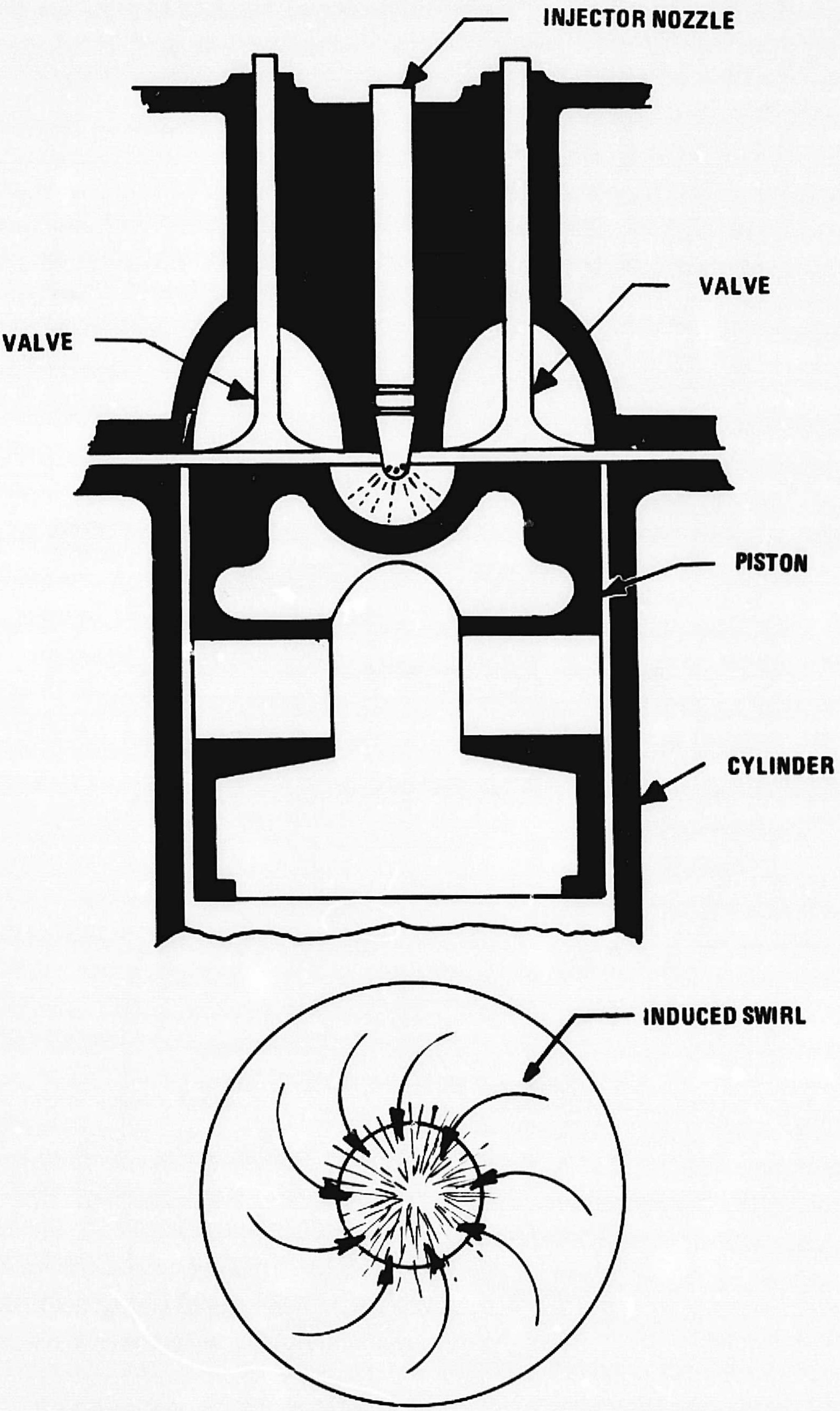


FIGURE 13. TYPICAL FOUR-STROKE DIESEL OPEN COMBUSTION CHAMBER

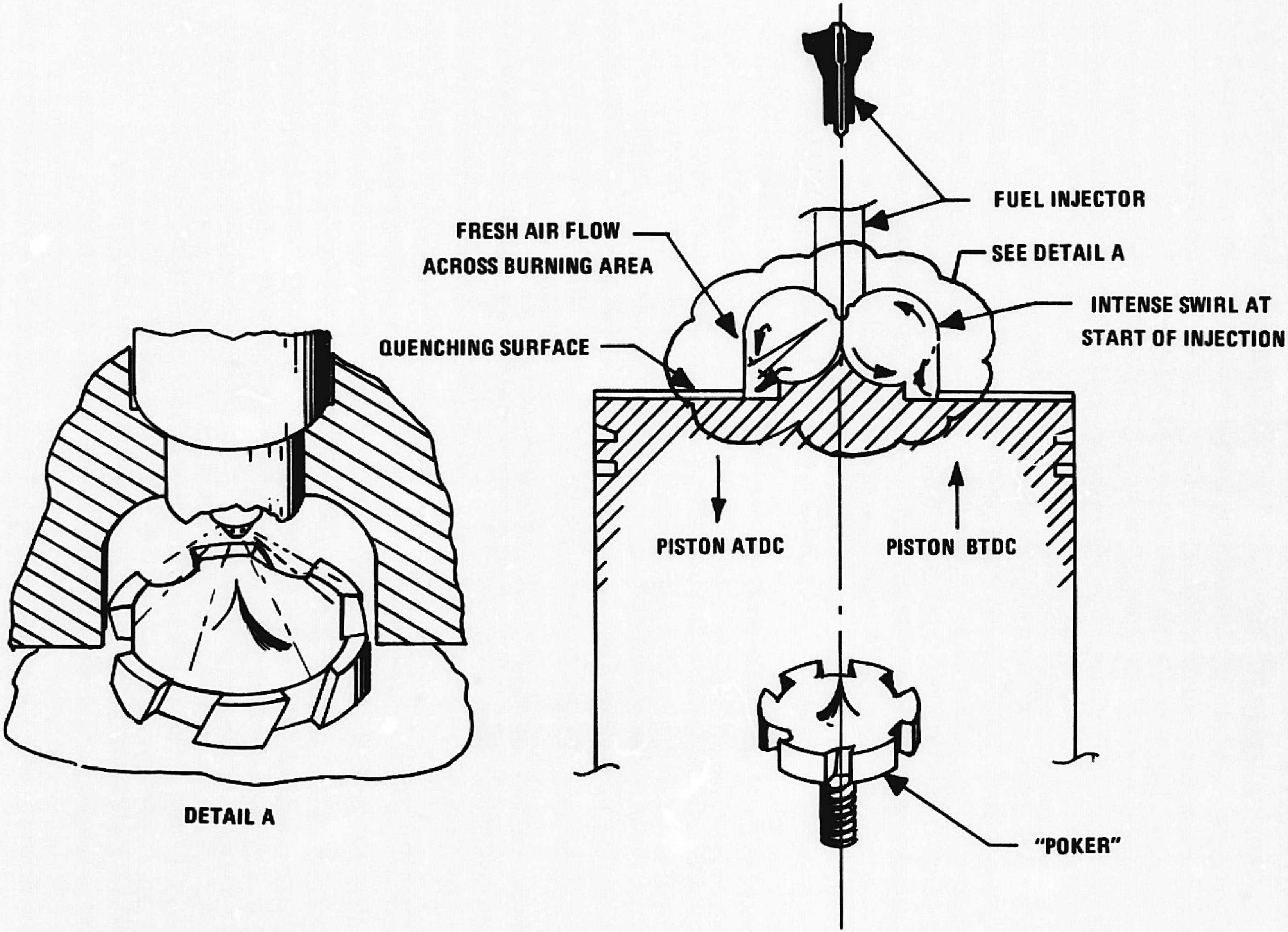
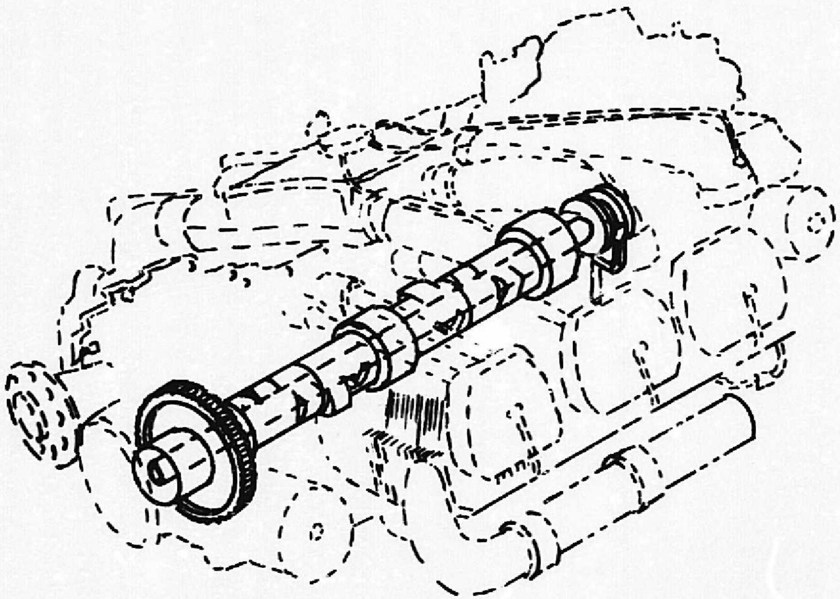


FIGURE 14. McCULLOCH TWO-STROKE DIESEL COMBUSTION CHAMBER



ENGINE INSTALLATION

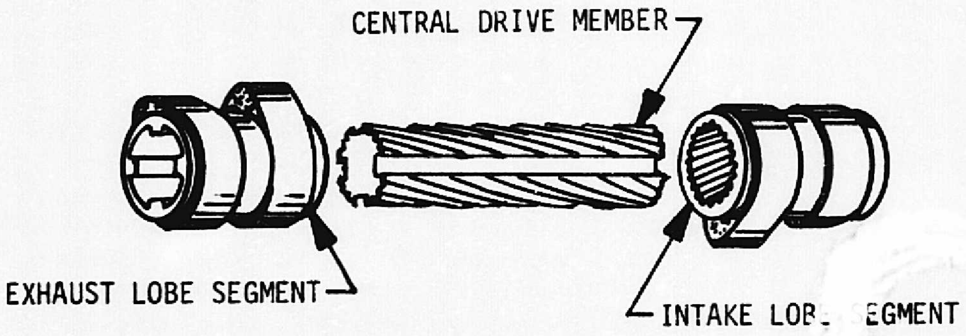


FIGURE 15. VARIABLE CAMSHAFT TIMING CONCEPT

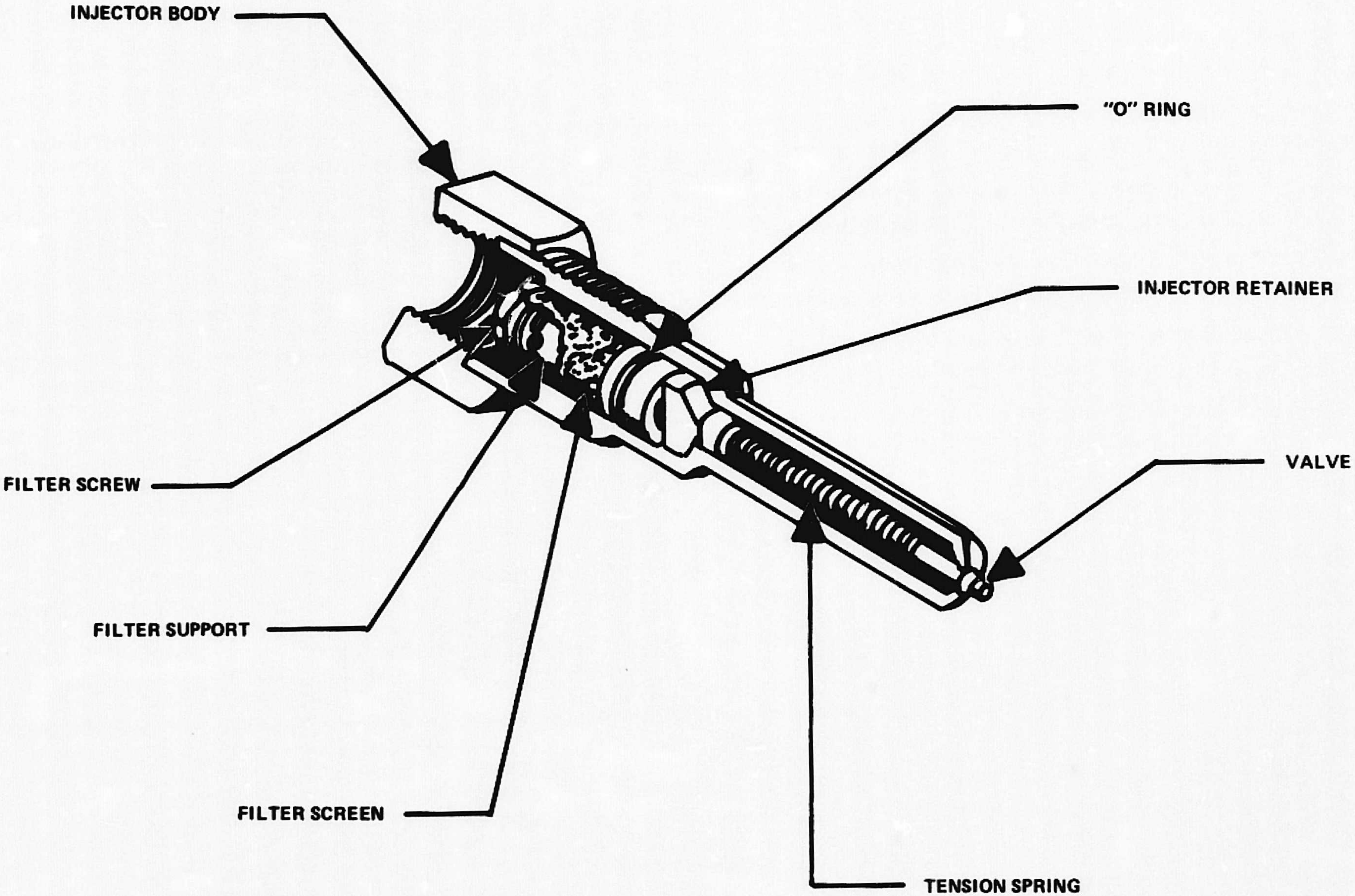


FIGURE 16. TYPICAL PROPOSED INJECTOR NOZZLE - CUTAWAY

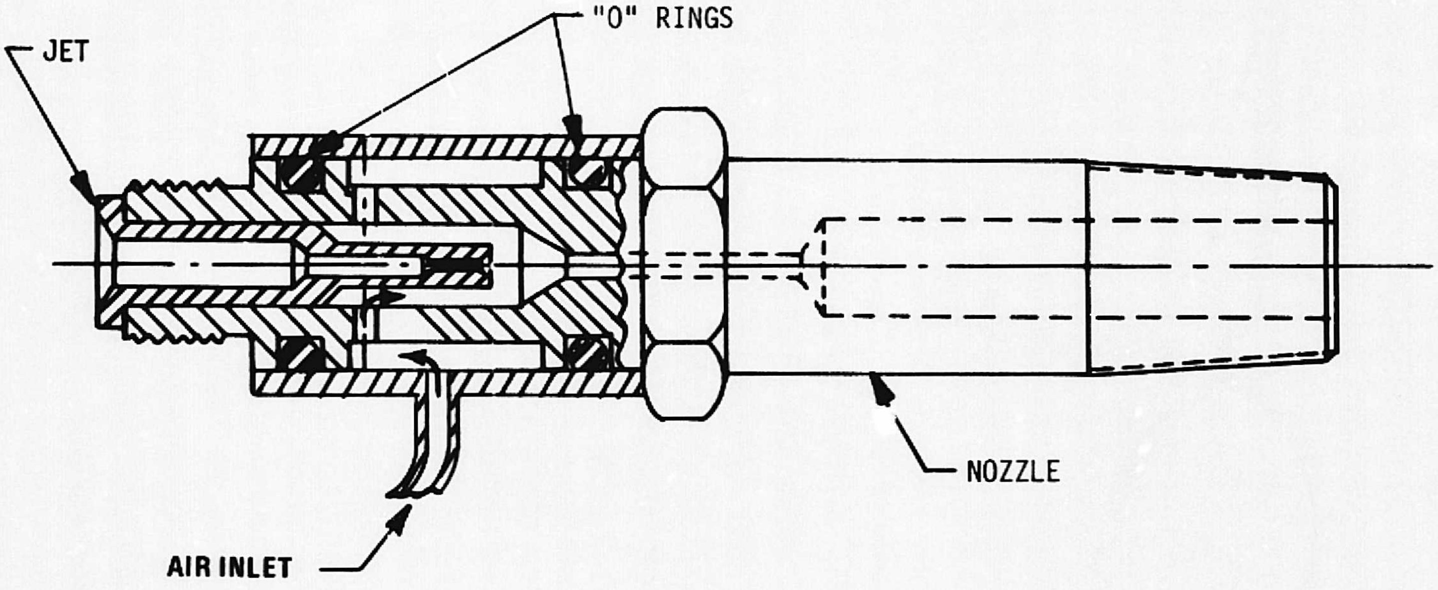


FIGURE 17. TELEDYNE CONTINENTAL MOTORS FUEL INJECTOR NOZZLE ASSEMBLY

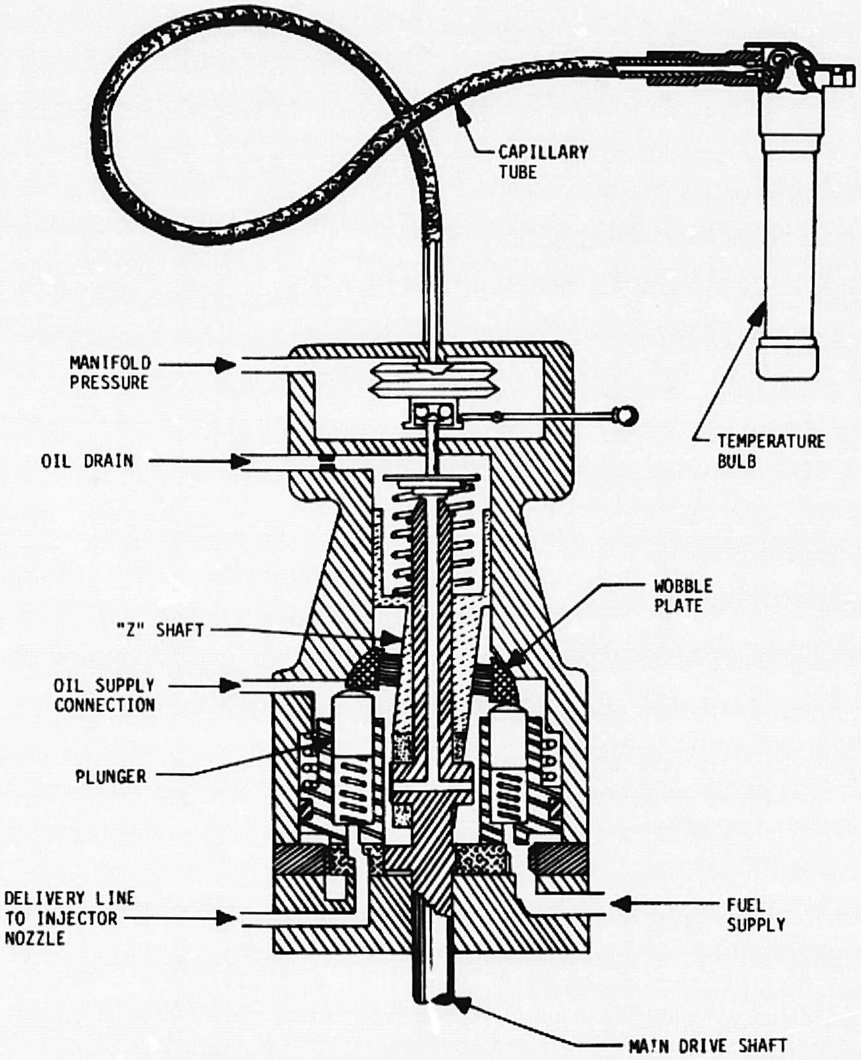


FIGURE 18. PRESSURE-TEMPERATURE COMPENSATED FUEL INJECTION PUMP CONCEPT

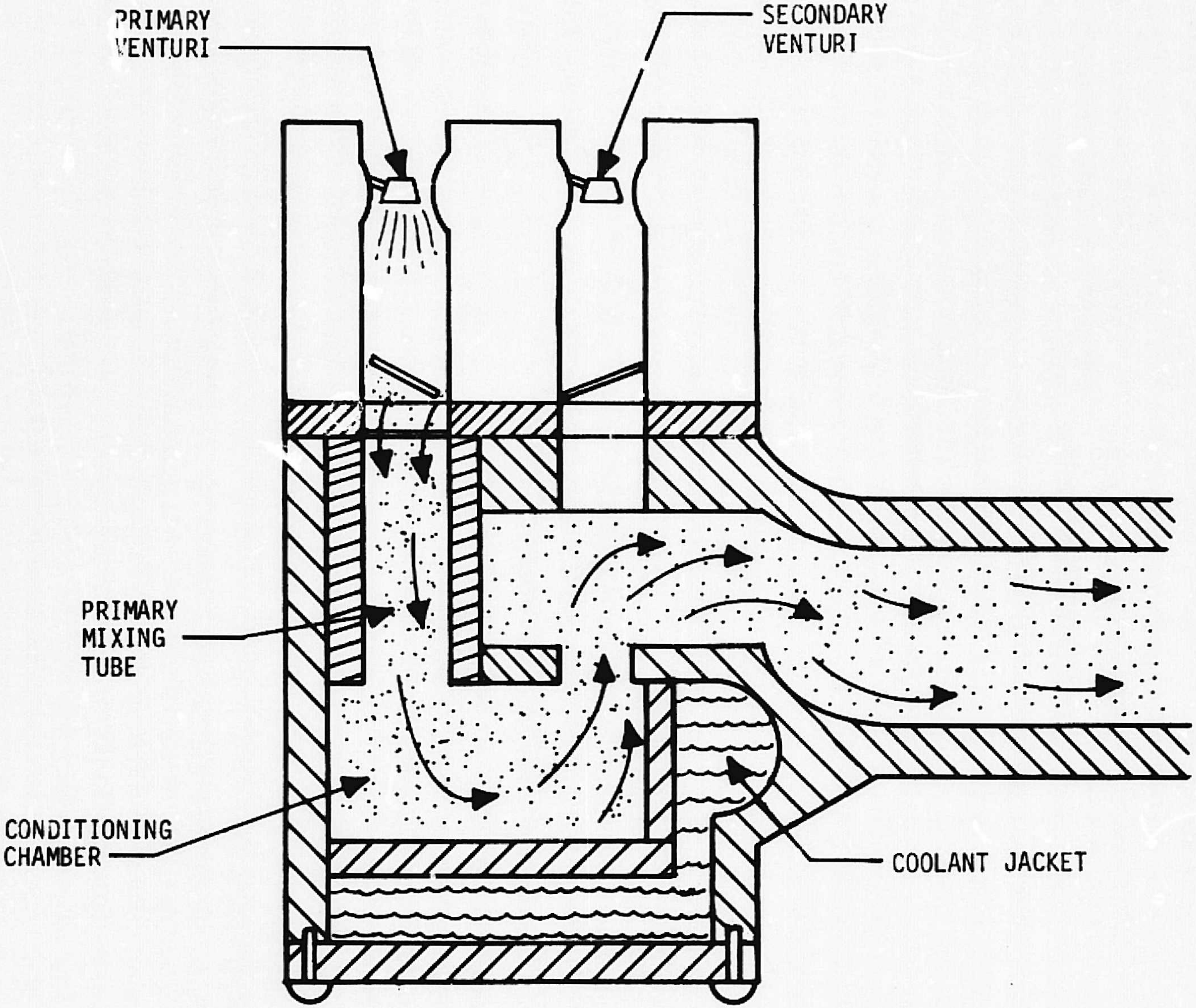


FIGURE 19. ETHYL TURBULENT FLOW MANIFOLD CONCEPT

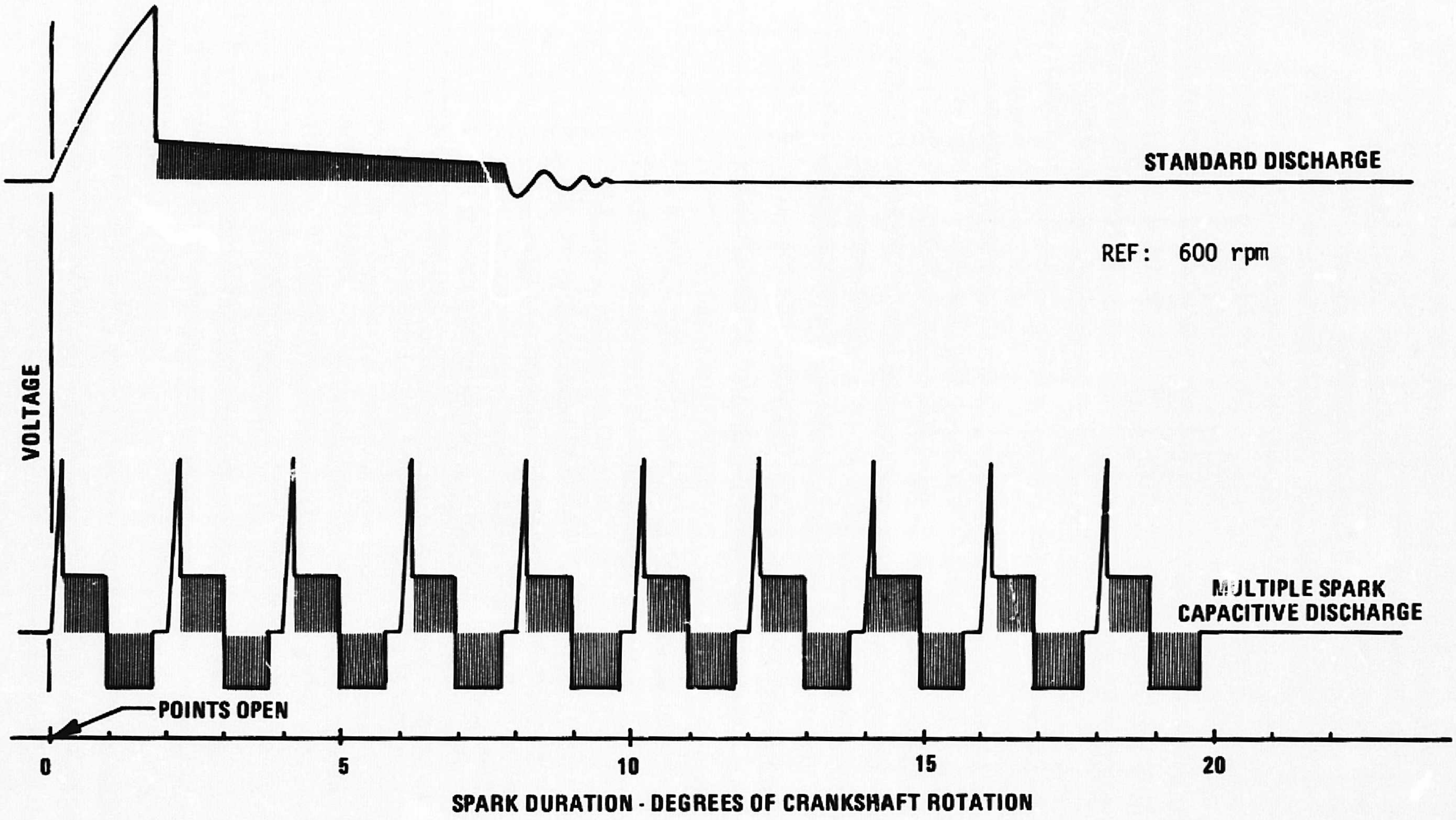


FIGURE 20. TYPICAL IGNITION SYSTEM WAVEFORMS

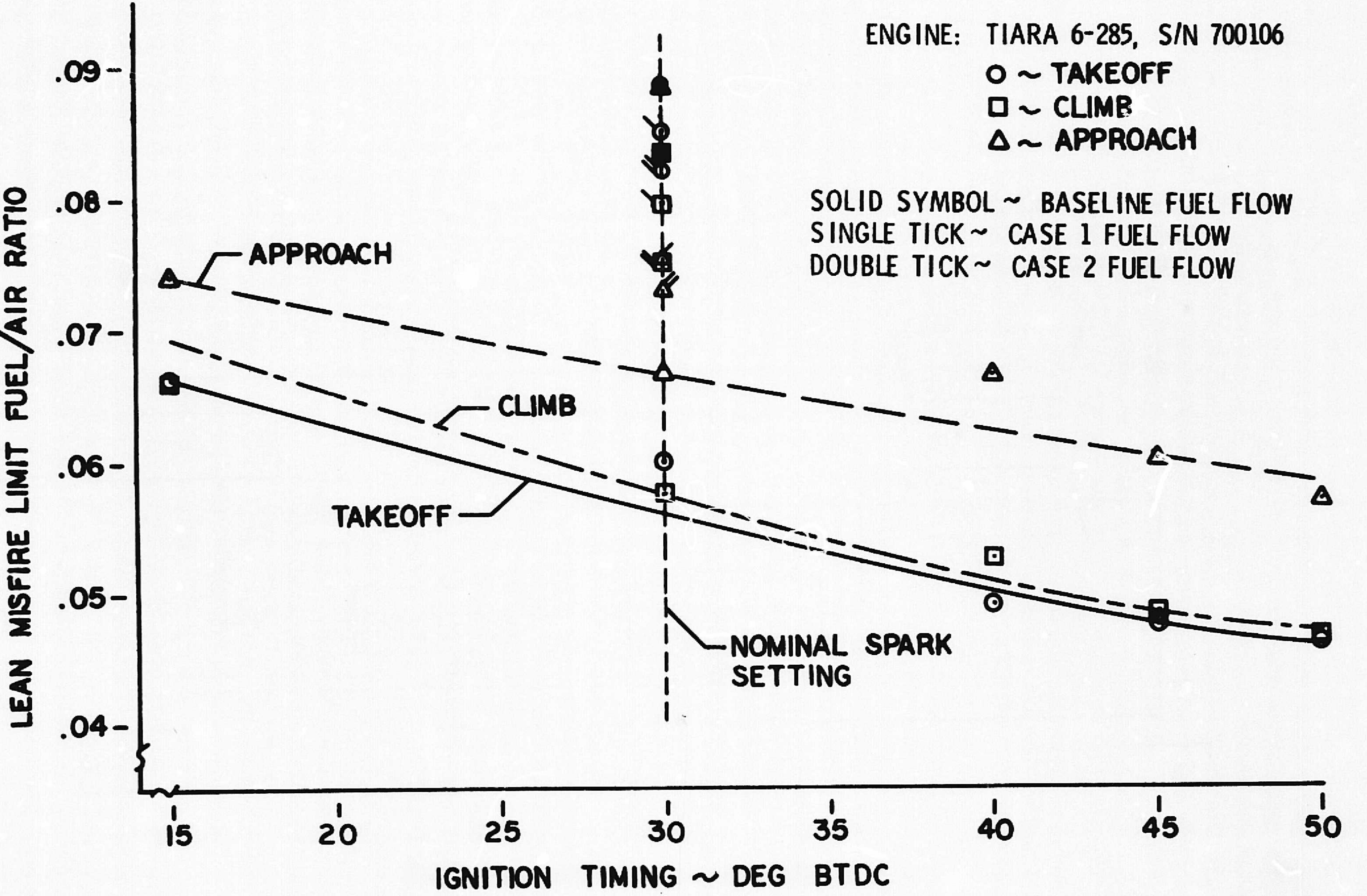
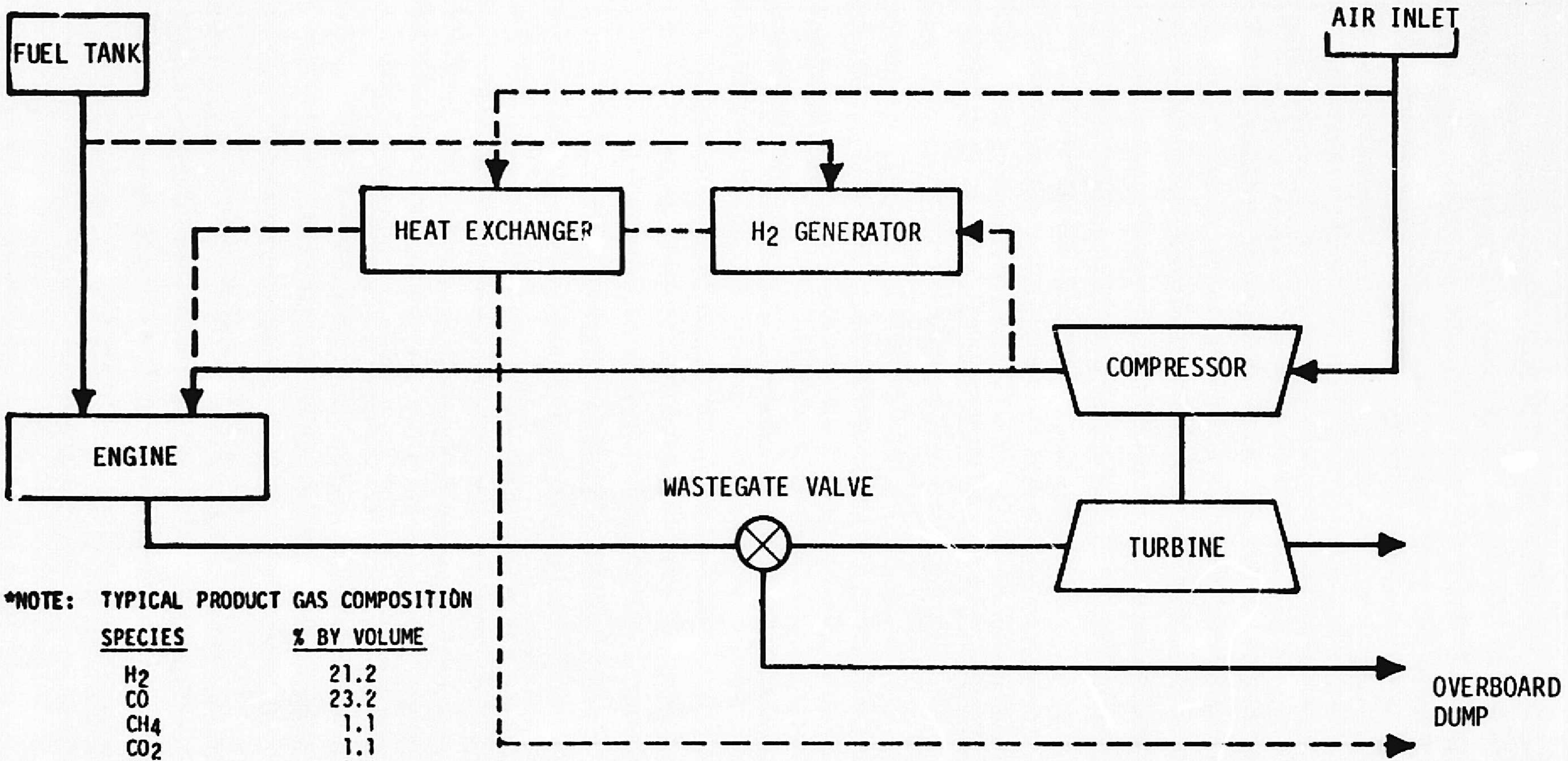


FIGURE 21. EFFECT OF SPARK TIMING ON LEAN MISFIRE LIMIT



*NOTE: TYPICAL PRODUCT GAS COMPOSITION

SPECIES	% BY VOLUME
H_2	21.2
CO	23.2
CH_4	1.1
CO_2	1.1
H_2O	1.3
N_2	52.1

FIGURE 22. ENGINE WITH HYDROGEN GENERATOR - SCHEMATIC

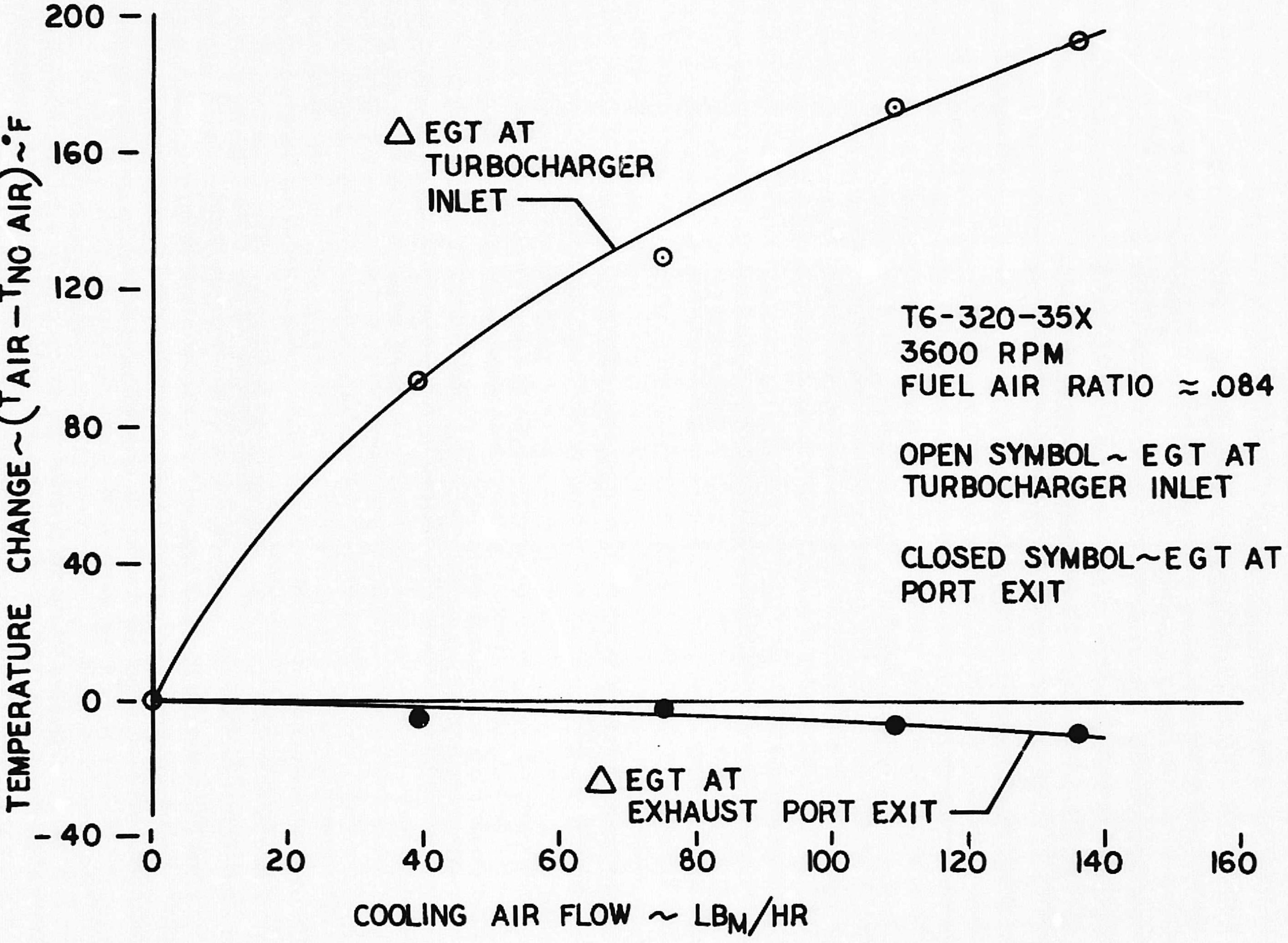


FIGURE 23. EFFECT OF AIR INJECTION ON EXHAUST GAS TEMPERATURE

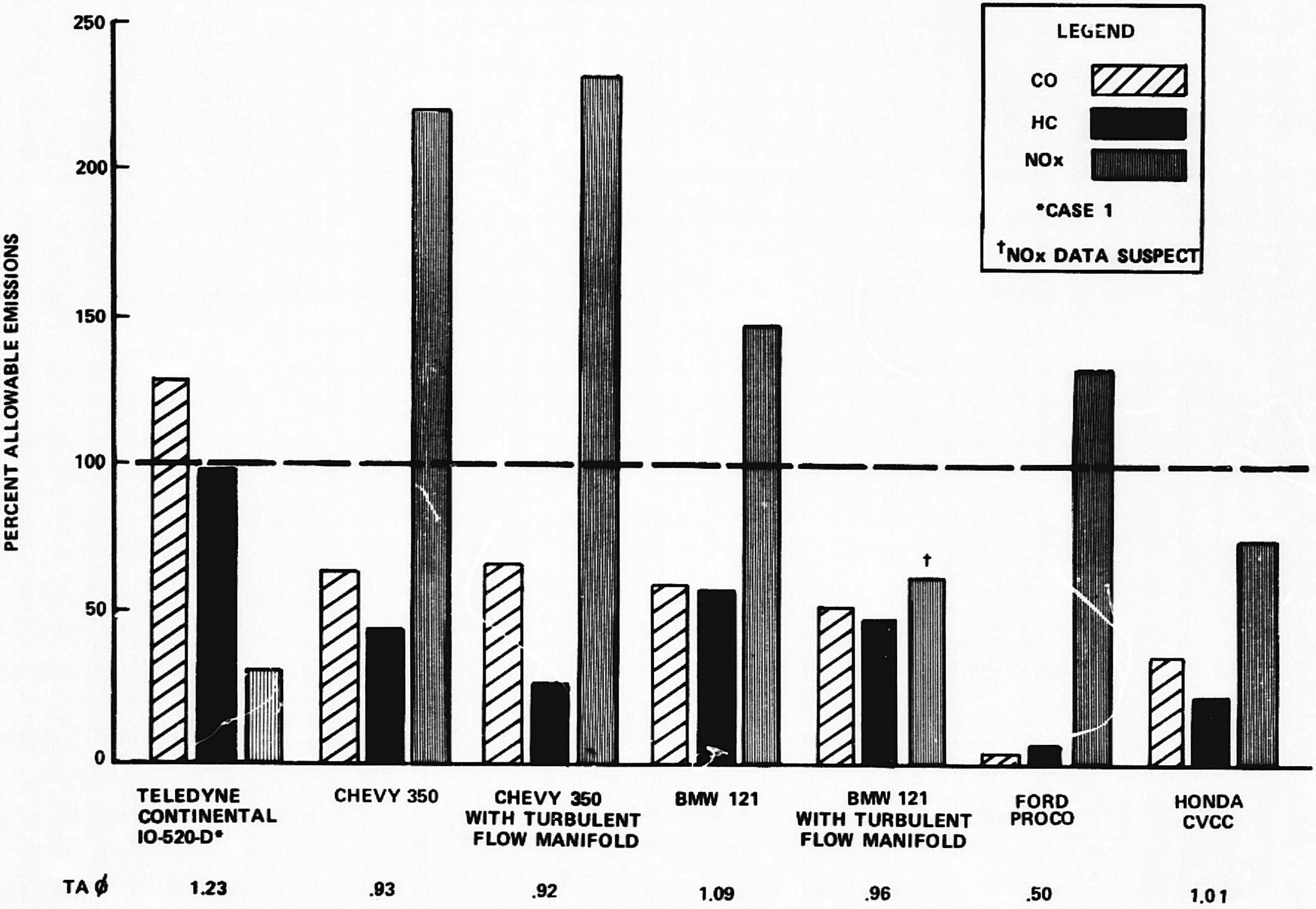


FIGURE 24. PERCENT ALLOWABLE EMISSIONS FOR CONCEPTS EVALUATED ON A 7-MODE AIRCRAFT EMISSION CYCLE

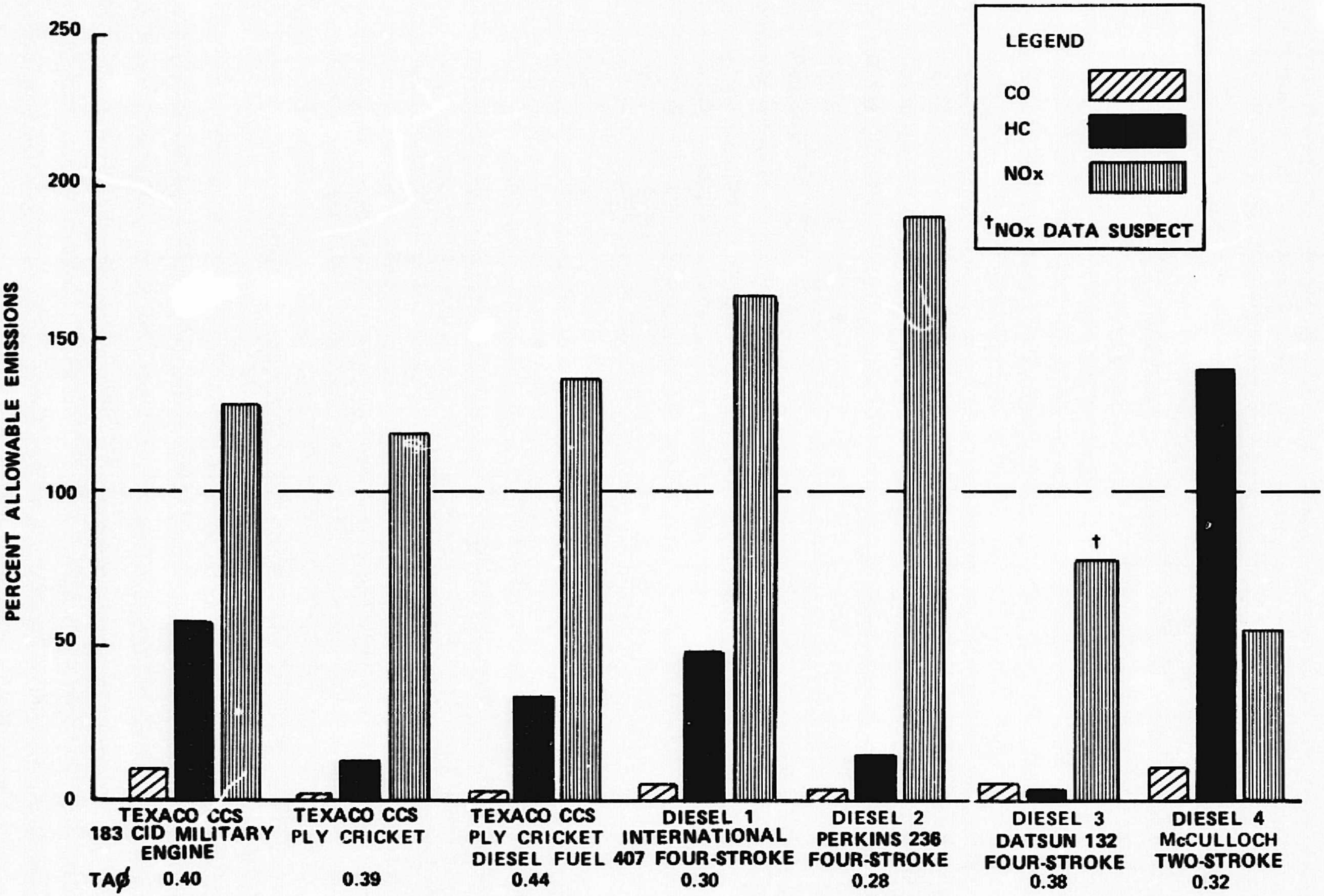


FIGURE 24 - Concluded

NOTE: $$\phi_{TW} = \frac{\sum_{i=1}^{7}\left[(TIM)_i \times \phi_i\right]}{27.3}$$

WHERE i = CYCLE MODE
TIM = TIME IN MODE
27.3 = TOTAL CYCLE TIME

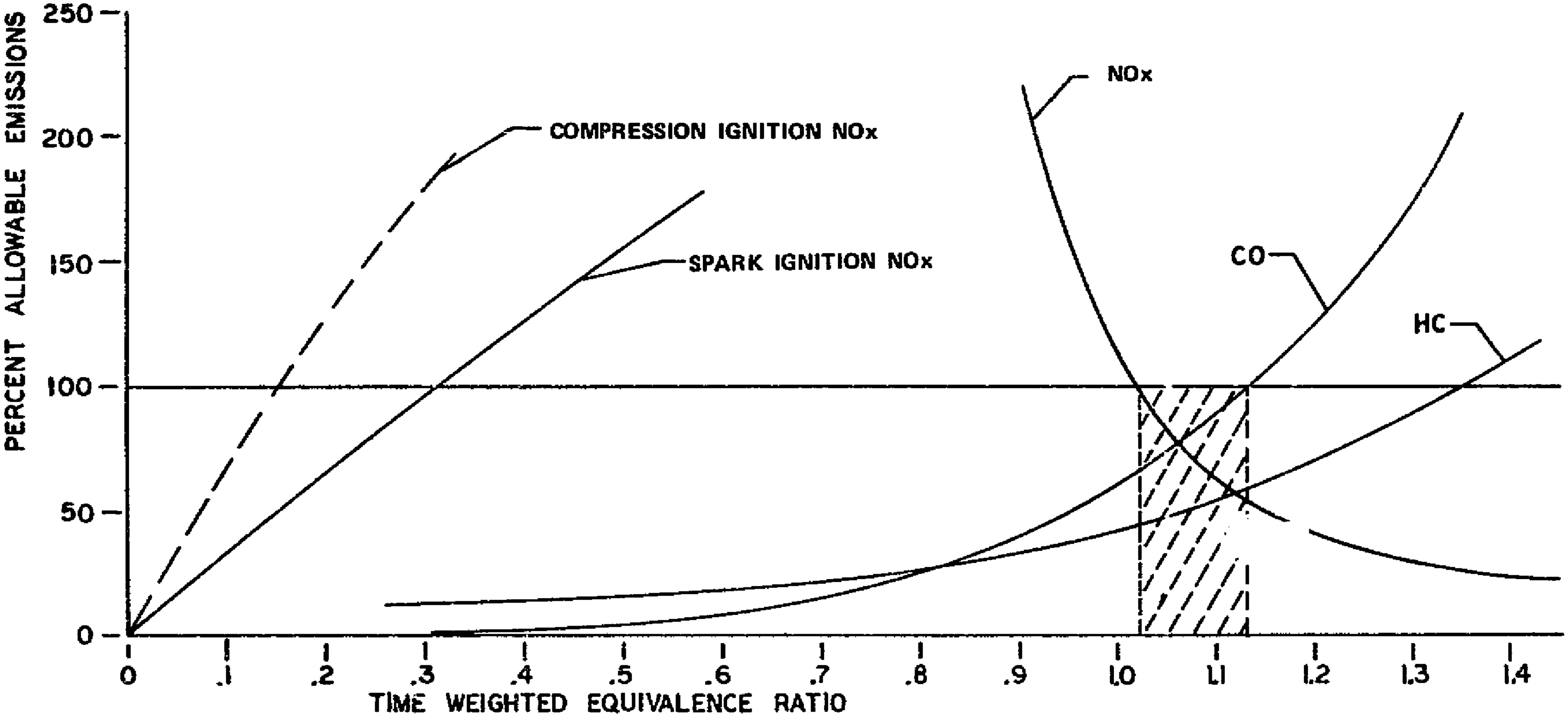


FIGURE 25. PERCENT ALLOWABLE EMISSIONS VERSUS TIME WEIGHTED EQUIVALENCE RATIO FOR ENGINES EVALUATED ON A 7-MODE AIRCRAFT EMISSION CYCLE

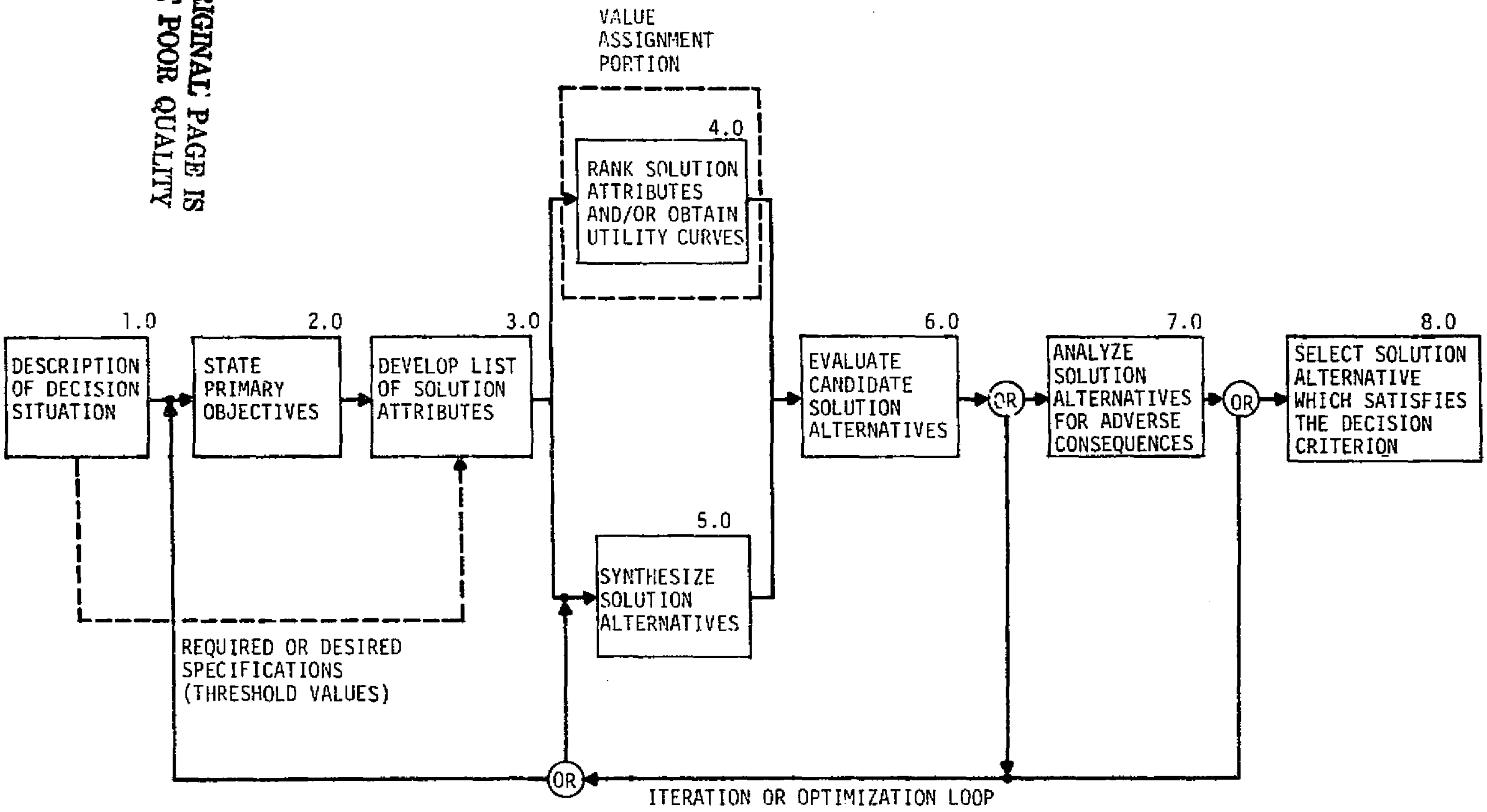


FIGURE 26. APOLLO APPLICATIONS DECISION MODEL

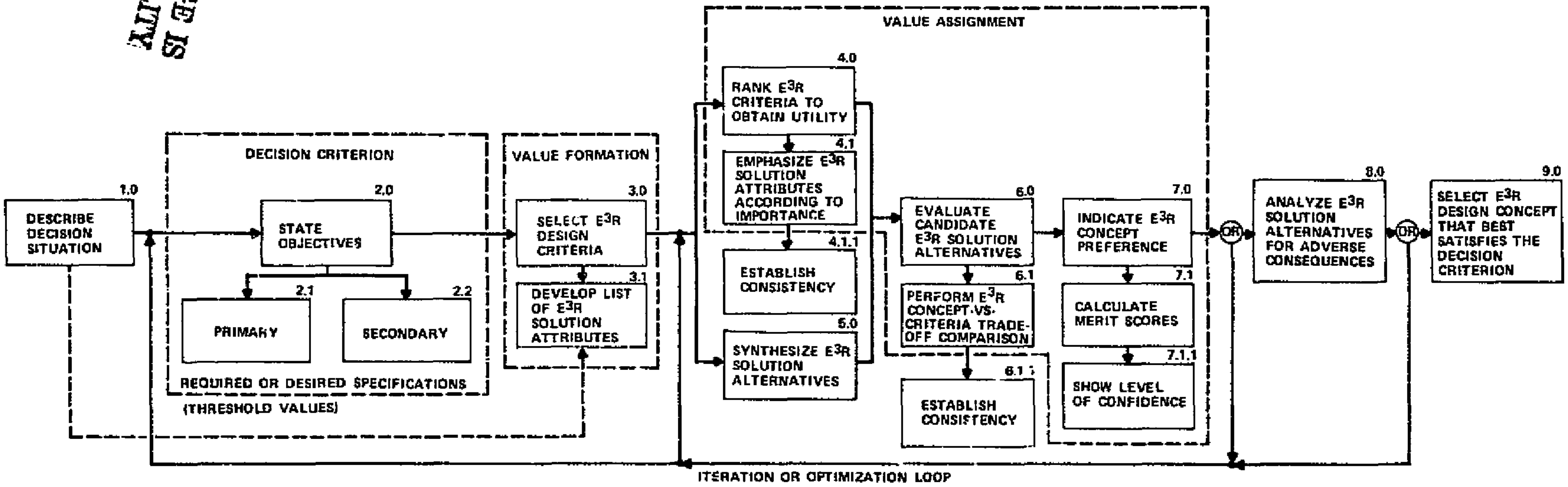


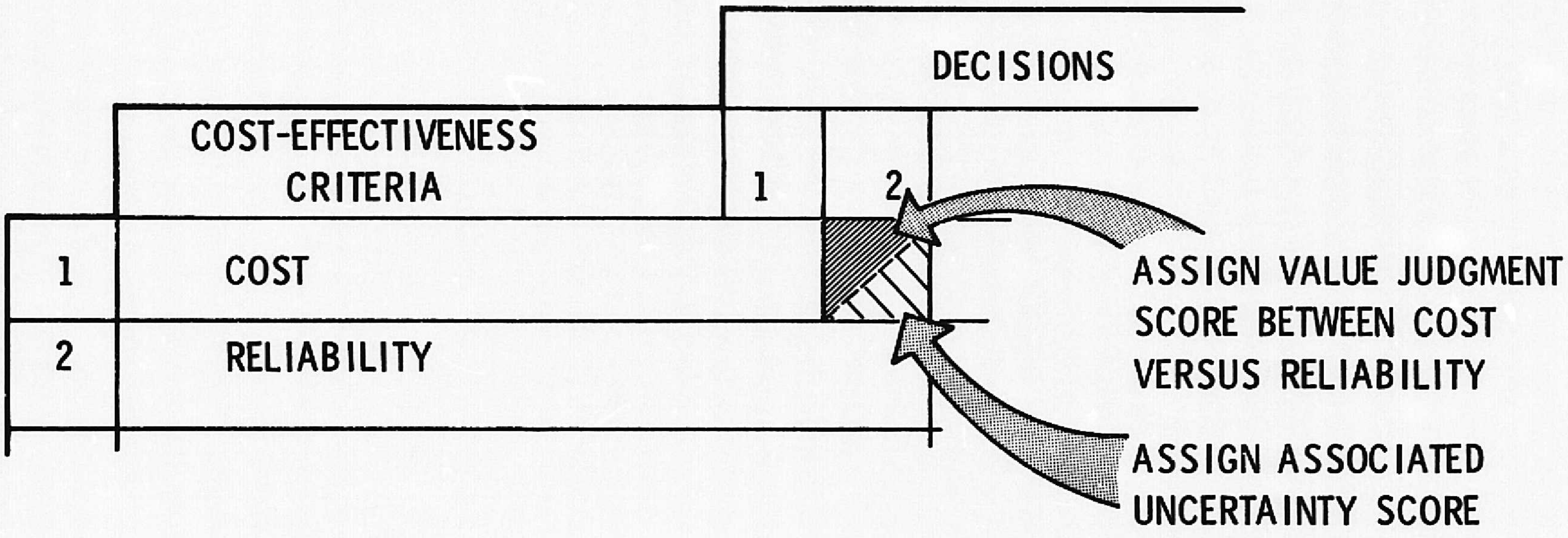
FIGURE 27. ENGINE EXHAUST EMISSION REDUCTION DECISION MODEL

DATE ________________
RUN NO. ______________
PASS NO. _____________

EVALUATOR: ____________________

		DECISIONS														
	COST-EFFECTIVENESS CRITERIA	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Cost		/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	Reliability			/	/	/	/	/	/	/	/	/	/	/	/	/
3	Safety				/	/	/	/	/	/	/	/	/	/	/	/
4	Technology					/	/	/	/	/	/	/	/	/	/	/
5	Performance						/	/	/	/	/	/	/	/	/	/
6	Fuel Economy							/	/	/	/	/	/	/	/	/
7	Weight and Size								/	/	/	/	/	/	/	/
8	Maintainability and Maintenance									/	/	/	/	/	/	/
9	Emissions										/	/	/	/	/	/
10	Operational Characteristics											/	/	/	/	/
11	Cooling												/	/	/	/
12	Adaptability													/	/	/
13	Materials														/	/
14	Integration															/
15	Producibility															

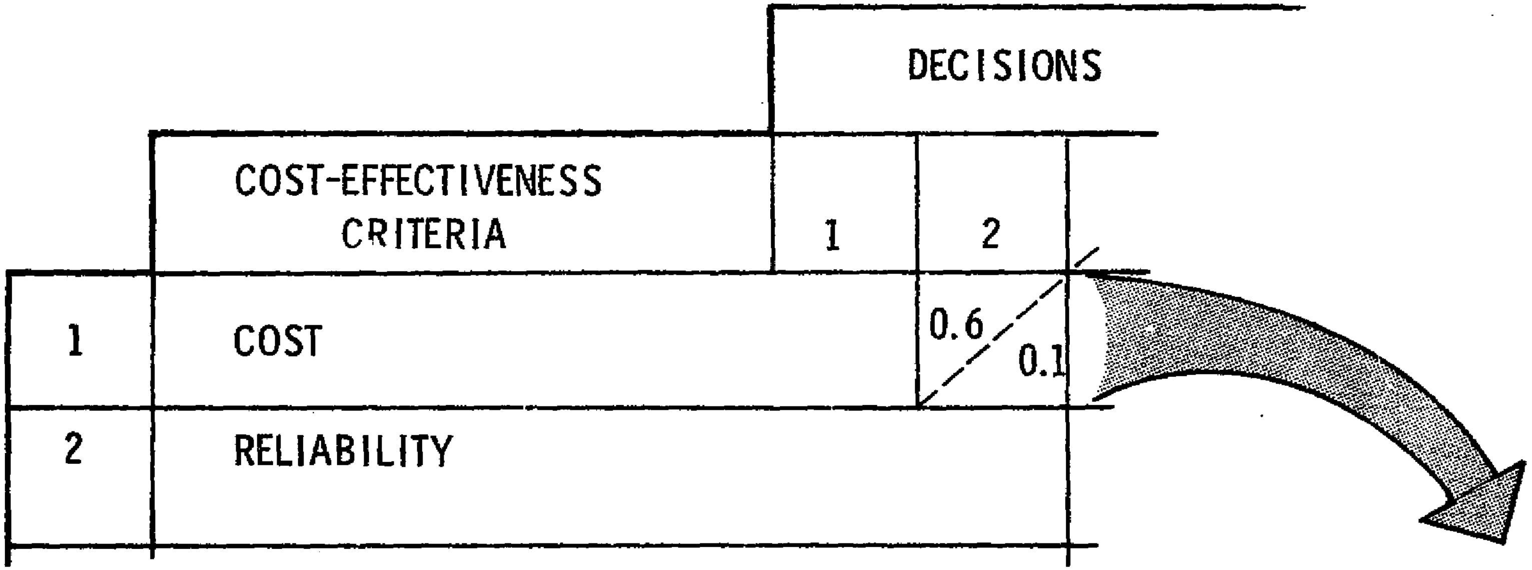
FIGURE 28. DECISION ANALYSIS CRITERIA EMPHASIS WORKSHEET



- QUESTION: WHICH CRITERIA IS MORE IMPORTANT COST OR RELIABILITY?
- SCORE RANGE: NUMERICAL INTERVAL IS BETWEEN [0, 1]
- NUMERICAL DISTRIBUTION:

COST	n_i
RELIABILITY	n_j
ASSOCIATED UNCERTAINTY	n_{ij}
	1.0

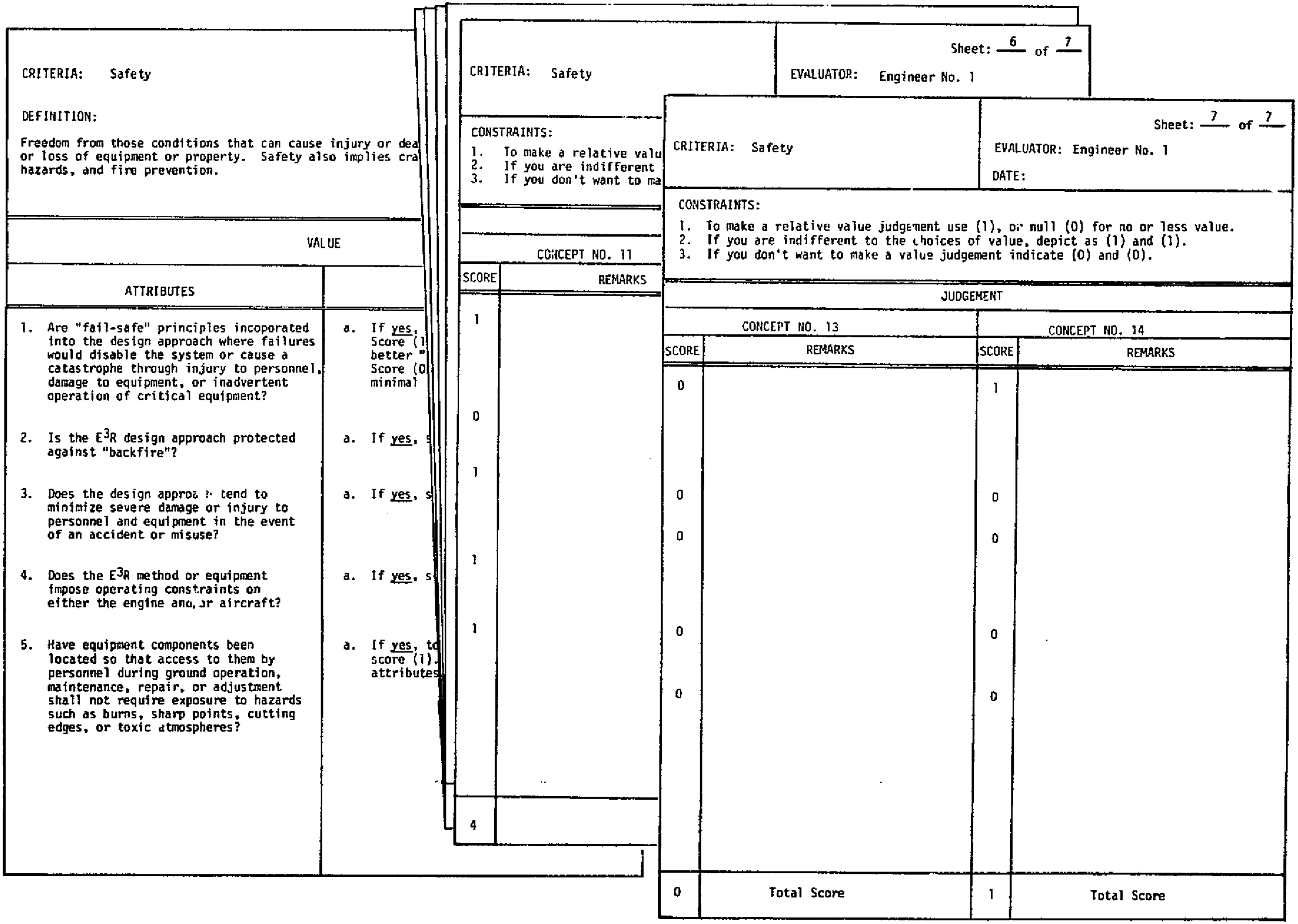
FIGURE 29. VALUE ASSIGNMENT PROCEDURE



NUMERICAL DISTRIBUTION:	COST	n_i		0.6
	RELIABILITY	n_j	OR	0.3
	ASSOCIATED UNCERTAINTY	n_{ij}		0.1
		1.0		1.0

NOTE: THE RELIABILITY VALUE, 0.3, IS ASSIGNED
TO MATRIX CELL 2, 1.

FIGURE 30. ASSIGNMENT OF NUMERICAL VALUES



CRITERIA: Safety

DEFINITION:

Freedom from those conditions that can cause injury or dea
or loss of equipment or property. Safety also implies cra
hazards, and fire prevention.

VALUE

ATTRIBUTES	
1. Are "fail-safe" principles incoporated into the design approach where failures would disable the system or cause a catastrophe through injury to personnel, damage to equipment, or inadvertent operation of critical equipment?	a. If yes, Score (1 better " Score (0 minimal
2. Is the E³R design approach protected against "backfire"?	a. If yes, s
3. Does the design approach tend to minimize severe damage or injury to personnel and equipment in the event of an accident or misuse?	a. If yes, s
4. Does the E³R method or equipment impose operating constraints on either the engine and/or aircraft?	a. If yes, s
5. Have equipment components been located so that access to them by personnel during ground operation, maintenance, repair, or adjustment shall not require exposure to hazards such as burns, sharp points, cutting edges, or toxic atmospheres?	a. If yes, to score (1). attributes

CRITERIA: Safety

Sheet: 6 of 7

EVALUATOR: Engineer No. 1

CONSTRAINTS:
1. To make a relative valu
2. If you are indifferent
3. If you don't want to ma

CONCEPT NO. 11	
SCORE	REMARKS
1	
0	
1	
1	
1	
4	

CRITERIA: Safety

Sheet: 7 of 7

EVALUATOR: Engineer No. 1

DATE:

CONSTRAINTS:
1. To make a relative value judgement use (1), or null (0) for no or less value.
2. If you are indifferent to the choices of value, depict as (1) and (1).
3. If you don't want to make a value judgement indicate (0) and (0).

JUDGEMENT

CONCEPT NO. 13		CONCEPT NO. 14	
SCORE	REMARKS	SCORE	REMARKS
0		1	
0		0	
0		0	
0		0	
0		0	
0	Total Score	1	Total Score

FIGURE 31. SAMPLE OF CRITERIA VERSUS CONCEPT TRADEOFF EVALUATION AND PRELIMINARY ORDERING WORKSHEETS

DATE:____________

RUN NO.:__________

PASS NO.:__________

EVALUATOR: ______________________________

⑨

		DECISIONS													
	CONCEPTS	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Honda Compound Vortex Controlled Combustion		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2	Texaco Controlled Combustion System			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
3	Ford Programmed Combustion				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
4	Improved Cooling Combustion Chamber					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
5	Four-Stroke Diesel, Open Chamber						▨	▨	▨	▨	▨	▨	▨	▨	▨
6	Two-Stroke Diesel - McCulloch							▨	▨	▨	▨	▨	▨	▨	▨
7	Variable Camshaft Timing								▨	▨	▨	▨	▨	▨	▨
8	Improved Fuel Injection System									▨	▨	▨	▨	▨	▨
9	Ultrasonic Fuel Atomization - Autotronic System										▨	▨	▨	▨	▨
10	Thermal Fuel Vaporization - Ethyl Turbulent Flow System											▨	▨	▨	▨
11	Multiple Spark Discharge System - Autotronics												▨	▨	▨
12	Variable Timing Ignition System													▨	▨
13	Hydrogen Enrichment - Jet Propulsion Laboratory														▨
14	Air Injection														

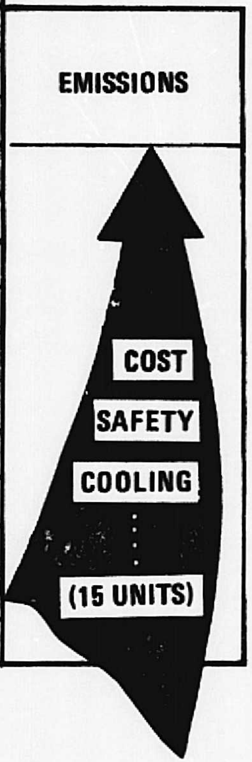
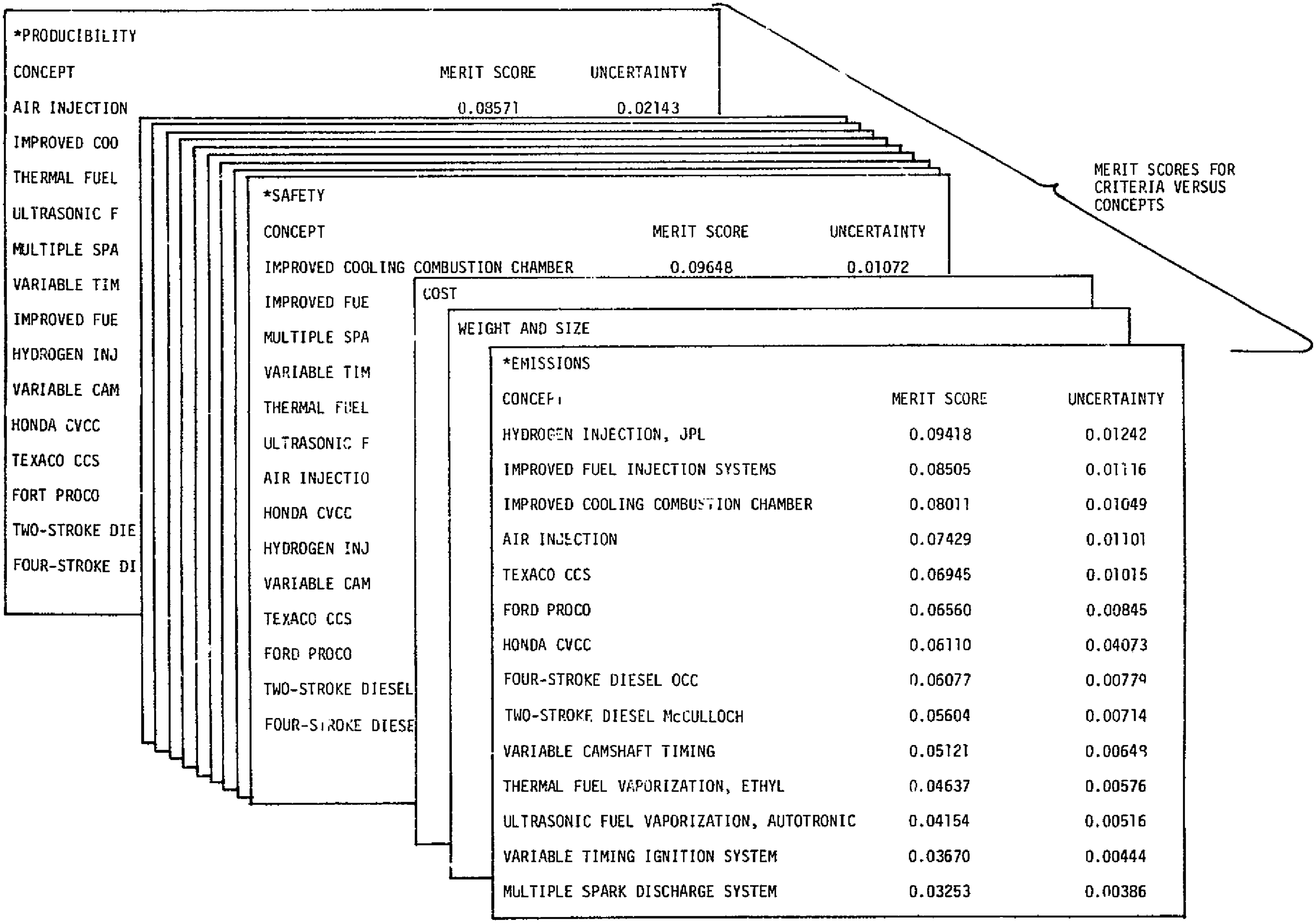


FIGURE 32. DECISION ANALYSIS CONCEPT MERIT WORKSHEET



*PRODUCIBILITY

CONCEPT	MERIT SCORE	UNCERTAINTY
AIR INJECTION	0.08571	0.02143
IMPROVED COO		
THERMAL FUEL		
ULTRASONIC F		
MULTIPLE SPA		
VARIABLE TIM		
IMPROVED FUE		
HYDROGEN INJ		
VARIABLE CAM		
HONDA CVCC		
TEXACO CCS		
FORT PROCO		
TWO-STROKE DIE		
FOUR-STROKE DI		

*SAFETY

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.09648	0.01072
IMPROVED FUE		
MULTIPLE SPA		
VARIABLE TIM		
THERMAL FUEL		
ULTRASONIC F		
AIR INJECTIO		
HONDA CVCC		
HYDROGEN INJ		
VARIABLE CAM		
TEXACO CCS		
FORD PROCO		
TWO-STROKE DIESEL		
FOUR-STROKE DIESE		

COST

WEIGHT AND SIZE

*EMISSIONS

CONCEPT	MERIT SCORE	UNCERTAINTY
HYDROGEN INJECTION, JPL	0.09418	0.01242
IMPROVED FUEL INJECTION SYSTEMS	0.08505	0.01116
IMPROVED COOLING COMBUSTION CHAMBER	0.08011	0.01049
AIR INJECTION	0.07429	0.01101
TEXACO CCS	0.06945	0.01015
FORD PROCO	0.06560	0.00845
HONDA CVCC	0.06110	0.04073
FOUR-STROKE DIESEL OCC	0.06077	0.00779
TWO-STROKE DIESEL McCULLOCH	0.05604	0.00714
VARIABLE CAMSHAFT TIMING	0.05121	0.00648
THERMAL FUEL VAPORIZATION, ETHYL	0.04637	0.00576
ULTRASONIC FUEL VAPORIZATION, AUTOTRONIC	0.04154	0.00516
VARIABLE TIMING IGNITION SYSTEM	0.03670	0.00444
MULTIPLE SPARK DISCHARGE SYSTEM	0.03253	0.00386

FIGURE 33. SAMPLE OUTPUT OF CONCEPT COMPARISON TRADEOFF EVALUATION FOR ENGINEER NUMBER 2

CONCEPT	CRITERIA														
	DOMINANT							SECONDARY				MINOR			
	EMISSIONS	SAFETY	PERFORMANCE	COOLING	WEIGHT AND SIZE	FUEL ECONOMY	COST	RELIABILITY	TECHNOLOGY	OPERATIONAL CHARACTERISTICS	MAINTAINABILITY AND MAINTENANCE	INTEGRATION	MATERIALS	PRODUCIBILITY	ADAPTABILITY
IMPROVED COOLING COMBUSTION CHAMBER	9	1	6	1	1	6	6	3	2	1	1	6	3	2	4
IMPROVED FUEL INJECTION SYSTEMS	3	2	1	14	2	5	7	4	1	6	2	4	2	7	6
AIR INJECTION	4	5	8	9	6	14	1	5	3	3	5	2	6	1	1
MULTIPLE SPARK DISCHARGE SYSTEM	14	3	5	7	3	12	2	6	4	2	3	1	1	5	2
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	12	4	9	11	5	10	4	1	5	5	4	10	4	4	7
VARIABLE TIMING IGNITION SYSTEM	13	6	3	8	4	11	5	7	7	9	6	3	5	6	3
THERMAL FUEL VAPORIZATION, ETHYL	11	7	10	13	7	9	3	2	6	4	7	9	7	3	5
HYDROGEN ENRICHMENT, JPL	1	14	7	4	8	1	12	8	9	12	8	7	14	8	8
TEXACO CCS	5	8	12	2	10	2	10	12	13	10	13	11	13	11	11
TWO-STROKE DIESEL, McCULLOCH	7	11	2	6	13	4	13	9	11	13	9	13	12	13	14
FORD PROCO	6	9	13	3	11	3	9	11	14	11	14	12	9	12	12
VARIABLE CAMSHAFT TIMING	10	13	4	10	9	13	8	14	8	8	10	5	8	9	9
HONDA CVCC	2	12	11	12	12	8	11	13	10	7	11	8	10	10	10
FOUR-STROKE DIESEL, OPEN CHAMBER	8	10	14	5	14	7	14	10	12	14	12	14	11	14	13

FIGURE 34. CONCEPT RANK ORDERING VERSUS CRITERIA IMPORTANCE

TABLES

TABLE I. CONCEPT RANKING FOR EMISSIONS

RANK	CONCEPT	PROJECTED MINIMUM EMISSIONS PERCENT EPA STANDARDS		
		CO	HC	NOx
1	Hydrogen Enrichment, JPL	68.	43.	30.
2	Honda CVCC	36.	22.	76.
3	Improved Fuel Injection Systems	90.	55.	58.
4	Air Injection	97.	65.	34.
5	Texaco CCS	8.	58.	128.
6	Ford PROCO	4.	7.	132.
7	Two-Stroke Diesel, McCulloch	10.	140.	54.
8	Four-Stroke Diesel, Open Chamber	3.	47.	163.
9	Improved Cooling Combustion Chamber	106.	95.	44.
10	Variable Camshaft Timing	127.	48.	33.
11	Thermal Fuel Vaporization, Ethyl	126.	59.	30.
12	Ultrasonic Fuel Atmoization, Autotronic	126.	59.	30.
13	Variable Timing Ignition System	116.	86.	35.
14	Multiple Spark Discharge System	126.	97.	30.
* * * * * * * * * * *				
-	IO-520-D Case 1 (Exhaust Emission Reference Level)	126.	97.	30.

TABLE II. IO-520-D POWER REQUIREMENTS BY OPERATING MODE

MODE	rpm	BHP	FHP	IHP	REMARKS
Idle	600.	1.	5.	6.	BHP per test data
Taxi	1200.	9.	10.	19.	BHP per test data
Take-off	2850.	300.	46.	346.	Maximum rated power at speed
Climb	2565.	240.	39.	270.	80% maximum power/90% speed
Approach	2480.	120.	37.	157.	40% maximum power/87% speed

TABLE III. EXHAUST EMISSIONS FOR ENGINE WITH HYDROGEN ENRICHMENT

MODE	TIME (hr)	IHP	ϕ	EMISSION RATE (lbm/IHP · hr) × 10^3			POLLUTANT PRODUCED/MODE (lbm)		
				NOx	HC	CO	NOx	HC	CO
Idle, Out	0.0167	6.	0.6	2.65	8.82	16.31	0.0003	0.0009	0.0016
Taxi, Out	0.1833	19.	0.6	2.65	8.82	16.31	0.0092	0.0307	0.0568
Take-off	0.0050	346.	1.23	2.08	4.73	361.	0.0044	0.0082	0.625
Climb	0.0833	279.	1.20	1.81	3.23	447.	0.075	0.06	7.6
Approach	0.1000	157.	0.6	2.65	8.82	16.31	0.0416	0.1385	0.2561
Taxi, In	0.0500	19.	0.6	2.65	8.82	16.31	0.0025	0.0084	0.0155
Idle, In	0.0167	6.	0.6	2.65	8.82	16.31	0.0003	0.0009	0.0016
	Total Pollutant Produced/Cycle, lbm						0.1333	0.2476	8.56
	Total Pollutant Produced/ Rated HP/Cycle, (lbm/BHP) × 10^3						0.444	0.825	28.5
	Percent Allowable Standard						29.6	43.4	67.9

TABLE IV. SELECTED COST-EFFECTIVENESS CRITERIA USED TO EVALUATE THE ENGINE EXHAUST EMISSION REDUCTION DESIGN CONCEPTS

- COST
- RELIABILITY
- SAFETY
- TECHNOLOGY
- PERFORMANCE
- COOLING
- ADAPTABILITY
- OPERATIONAL CHARACTERISTICS
- MATERIALS
- INTEGRATION
- PRODUCIBILITY
- FUEL ECONOMY
- WEIGHT AND SIZE
- MAINTAINABILITY AND MAINTENANCE
- EMISSIONS

TABLE V. CRITERIA ELEMENT WITH A PARTIAL LISTING OF SOLUTION ATTRIBUTES

Sheet: 1 of 7

CRITERIA: Cost

DEFINITION:

Cost is the dollars paid by an organization for an end item or service. Cost is the expected expenditure of money for planning, engineering, manufacturing, and supportive services to realize an effective E^3R design solution approach.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. Will the expected cost, to produce the design approach, be high (H), moderate (M), or low (L)? ARBITRARY COST SCALE SCALE — RANGE(S) Low — 0 to 9 Moderate — 100 to 999 High — 1,000 to 9,999	a. Give a ROM cost estimate range per concept unit: If ROM cost estimates cannot be made then indicate L, M, H per concept. Score (1) to the concept that has low cost indication and (0) to moderate or high.
2. Will the concept require considerable engineering analysis, tradeoff study, and evaluation to gain design adaptability/flexibility?	a. If <u>yes</u>, score (0); if <u>no</u>, score (1).
3. Can the concept be developed and integrated into a manufacturer's product line by 1981, 1985, or 1986 (pessimistic cases)? If the concept can be developed before or by 1979 (optimistic case) then indicate the date.	a. If optimistic (developed before or by 1979), score (1). If pessimistic, score (0).
4. What test equipment is needed (large capital expenditures) to verify the E^3R design approach?	a. Itemize mechanical and electrical/electronic equipment required. Estimate the range (L, M, or H) of capital outlay to acquire, rent, lease, and fabricate such equipment.

TABLE V - Continued

Sheet: 1 of 5

CRITERIA: Reliability

DEFINITION:

Reliability is the probability that a system will perform satisfactorily for at least a given period of time when used under stated conditions. This notion can be reduced to the question: Will it work? A reliability function is the same probability expressed as a function of the time period. Reliability relates to the frequency with which failures occur. Failure means "unsatisfactory performance", usually representing a judgment of an operator or a maintenance man. This does not preclude the ....

VALUE

ATTRIBUTES	ASSIGNMENT
1. Is equipment design complexity minimized?	a. Score (1) if design concept is simple, or (0) if complex.
2. Will standardized processes, components, and materials be used to manufacture the E^3R system?	a. If answer is yes to all elements, score (1). If answer is no to any element, score (0).
3. Can E^3R equipment mean life (operational hours) be predicted for the design approach?	a. Score (1) for predicted (ROM) E^3R mean life, or (0) for no E^3R mean life estimate.
4. Can the E^3R system/equipment wearout period, expressed as operational hours, be predicted (warranty implications)?	a. Score (1) for predicted (ROM) E^3R wearout period, or (0) for no estimate available.
5. Can E^3R equipment and/or system failure rates be predicted in terms of MTBF and MTBM?	a. If either MTBF or MTBM can be predicted for a concept, then score (1). If MTBF or MTBM cannot be established, score (0).
6. Can E^3R failure modes and effects, i.e., what can fail, and what are the consequences if it does fail, be identified or predicted?	a. Score (0) for the concept that contains 5 or greater quantity of FMEA. Score (1) for the concept with fewer than 5 FMEA.
7. Does the design approach lend itself to at least univariate life testing (i.e., vary one stress load at a time, or step-stress the load condition until failure occurs)?	a. Score (1) for yes and (0) for no.

TABLE V - Continued

Sheet: 1 of 5

CRITERIA: Safety

DEFINITION:

Freedom from those conditions that can cause injury or death to personnel, damage to or loss of equipment or property. Safety also implies crashworthiness, freedom from hazards, and fire prevention.

VALUE

ATTRIBUTES	ASSIGNMENT
1. Are "fail-safe" principles incoporated into the design approach where failures would disable the system or cause a catastrophe through injury to personnel, damage to equipment, or inadvertent operation of critical equipment?	a. If yes, score (1), if no score (0). Score (1) to the concept that has better "fail-safe" design features. Score (0) for concept that has minimal safety features.
2. Is the E^3R design approach protected against "backfire"?	a. If yes, score (1). If no, score (0).
3. Does the design approach tend to minimize severe damage or injury to personnel and equipment in the event of an accident or misuse?	a. If yes, score (1). If no, score (0).
4. Does the E^3R method or equipment impose operating constraints on either the engine and/or aircraft?	a. If yes, score (0); if no, score (1).
5. Have equipment components been located so that access to them by personnel during ground operation, maintenance, repair, or adjustment shall not require exposure to hazards such as burns, sharp points, cutting edges, or toxic atmospheres?	a. If yes, to most safety attributes, then score (1). If not yes to most safety attributes, then score (0).

TABLE V - Continued

Sheet: 1 of 4

CRITERIA: Technology

DEFINITION:

A technological state may be defined as a given storehouse of hardware; physical man-made systems; human knowledge and skills; methods and standards of performance that exist in time, and are constrained by acceptance and limited by cost. The technology needed to reduce engine exhaust emissions is probably within the state of the art.

VALUE

ATTRIBUTES	ASSIGNMENT
1. Is all necessary basic scientific knowledge available, or are new developments needed to realize the design approach (R&D implications)?	a. If new developments are needed, then indicate (0), of if new developments are not needed, then indicate (1). Indicate what new developments are needed.
2. Can basic materials be used or must fundamental research be initiated to improve or develop new materials for application to the concept?	a. Indicate (1) for basic materials to be used, or (0) for research required.
3. What technologies (welding, machining, turbine manufacturing, pressure vessel, combustion, etc.) are implicit in the concept?	a. Give the name of each discipline. Indicate (1) for the fewest; (0) for the largest.
4. Are advanced manufacturing methods needed to fabricate an E^3R system?	a. Indicate (1) for needed or (0) for not needed.
5. Are the technology disciplines well understood, or are they new within the state of the art?	a. Indicate (1) for "understood" or (0) if any are new.
6. Does TCM have the skill, desire, money, and tooling to pursue advanced manufacturing methods or must we be constrained to use available equipment, facilities, and resources?	a. Score (1) for "will pursue" and (0) for "be constrained".

TABLE V - Continued

Sheet: 1 of 3

CRITERIA: Performance

DEFINITION:

The ability of an aircraft engine to meet the minimum propulsion requirements for a given airframe application.

VALUE

ATTRIBUTES	ASSIGNMENT
1. Which concept has the greater engine horsepower-to-weight ratio?	a. Score (1) for greater hp/lb ratio, and (0) for less hp/lb.
2. For a given rated hp, which concept has the smallest engine frontal area?	a. For smaller, score (1); for larger, score (0).
3. For a given rated hp, which E^3R concept has the smallest engine volume?	a. For larger, score (0); for smaller, score (1).
4. Which concept has the greatest potential for engine acceleration off idle, taxi, and approach?	a. Indicate (1) for greater potential and (0) for less potential
5. Which concept has the greatest potential for easy starting in cold and hot weather?	a. If greater potential, score (1); if less potential, score (0).
6. Which concept has the greatest potential for turbocharging?	a. If greater potential, score (1); if less potential, indicate (0).
7. Which concept has the minimum fuel octane number or performance number, and cetane number requirement?	a. Indicate (1) for concept with lower requirement and (0) for concept with greater requirement.

TABLE V - Continued

Sheet: 1 of 2

CRITERIA: Fuel Economy

DEFINITION:

The fuel economy of an aircraft may be defined as the amount of useful work derived (i.e., moving the mass of the aircraft through a distance) per unit of fuel consumed. The assumption is that in a given airframe, a new concept engine is required to have the same brake horsepower output as the standard piston engine it replaces.

VALUE

ATTRIBUTES	ASSIGNMENT
1. For concepts of the same bhp and weight does one concept run leaner than another?	a. Score (1) for leaner, and (0) for not as lean.
2. For concepts of the same bhp does one concept have a smaller engine frontal area than another?	a. Score (1) for smaller engine frontal area and (0) for a larger engine frontal area.
3. Does one concept have the potential for further reductions in fuel economy with advancing technology over another concept.	a. Score (1) for "shows potential" and (0) for "does not show potential"
4. Can one concept use a larger variety of fuel types than another?	a. If larger variety of fuel types are apparent, score (1); if not apparent, score (0).

TABLE V - Continued

Sheet: 1 of 1

CRITERIA: Emissions

DEFINITION:

Each concept must be evaluated on its projected potential to reduce HC, CO, and NOx per the EPA aircraft cycle regulations.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. What is the projected emissions in percent of EPS Standard for each pollutant?	a. Indicate percent of emissions.
2. Based on the above percent of emissions, which concept has the greatest potential for meeting the EPA Standards?	a. Indicate greatest potential (1), and less potential (0).

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TABLE V - Continued

Sheet: 1 of 3

CRITERIA: . Weight and Size

DEFINITION:

Weight is defined as a unit mass (kg or lb) of a functional subsystem (body) added to any airworthy aircraft system. Size is defined as any increase or decrease of "flat plate" and "wetted" area attributed to aircraft structure growth; addition of fittings, wire, and tubes that influences aerodynamic drag.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. Does the design approach lend itself to specifying an estimate of weight (lb) (±25% error), or can the growth weight be predicted over a three-year period?	a. If response is no, score (0). If response is yes, score (1) and estimate weight.
2. Does the E^{3}R design concept imply that additional equipment must be added to the aircraft system?	a. If yes, indicate (0). If no, indicate (1).
3. Is it necessary to redesign the engine mounts to facilitate the design approach?	a. If yes, score (0). If no, score (1).
4. Is it necessary to increase frontal area of the engine cowling, and/or ram air scoop so that the E^{3}R equipment can be accommodated?	a. If yes, score (1) to the smallest size increase, or no increase in size. Score (0) for the concept that has an increase in size as compared to a concept that has no increase in size.
5. Does the design approach extend the engine cylinder head into the airstream.	a. If yes, indicate (0), and if no, indicate (1).

TABLE V - Continued

Sheet: 1 of 5

CRITERIA: Maintainability and Maintenance

DEFINITION:

Maintainability ($\underline{M}$) is a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources. Maintenance is the consequence of design. Properly applied, maintainability forestalls the requirement of maintenance and alters the course of design to eliminate or reduce the effect. Maintenance (M_*) is all actions necessary for ....

VALUE

ATTRIBUTES	ASSIGNMENT
1. Does the concept lend itself to the principle of frequency-of-use, i.e., positioning the E^3R equipment in preferred locations so that it can be easily maintained? ($\underline{M}$)	a. If <u>yes</u> or relatively better, then score (1), and if <u>no</u> or not as good, score (0).
2. Does the concept require spares during its life cycle? ($\underline{M}$)	a. Indicate what you think the primary hardware spares might be. Score (1) to the concept that is best defined. Score (0) to the concept that is least defined. b. Score (0) to the concept that has the most spares, and (1) to the concept that has the fewest spares.
3. Can you write a comprehensive statement concerning the maintenance policy for each concept? If an E^3R unit experiences equipment failure does the mechanic "remove and replace", or "remove and reinstall"? If he "removes and replaces? what does he do with the old equipment (return to vendor, return to manufacturer, scrap, repair, etc.)? (M_*)	a. Assign a (1) to the concept that has the greatest number of definable maintenance policy characteristics. Indicate (0) for ill-defined maintenance policy.
4. Is the adjustment/alignment automatic (self adjusting), semiautomatic, or manual? (M_*)	a. Indicate type of adjustment/alignment and score relative to each other, i.e., (1) for manual as opposed to (0) .....

TABLE V - Continued

Sheet: 1 of 2

CRITERIA: Operational Characteristics

DEFINITION:

Operational characteristics as used in this study are those responses, changes, and additions that affect pilot ground and flight action.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. Is the starting procedure different from a conventional horizontally opposed and radial engine?	a. Score (1) for less of a change. Score (0) for greater change.
2. Is personnel training required to properly use the concept?	a. If yes, score (0). If no, score (1).
3. Is additional monitoring of temperatures, pressures, rpm, etc., required?	a. Score (1) for less monitoring, and (0) for greater monitoring.
4. Has the engine's controls (throttle, mixture, and propeller pitch) significantly changed from conventional engine equipment designs?	a. Score (1) for no, or less of a change; (0) for a greater change.

TABLE V - Continued

Sheet: 1 of 1

CRITERIA: Cooling

DEFINITION:

Cooling of a cylinder head is presently accomplished by ambient air flowing around the cylinder head, and by rich F/A ratios in the combustion process. In order to reduce CO and HC emissions, it is essential to reduce F/A ratio. However, this reduction could cause cooling problems.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. What is the projected F/A ratios for each mode of operation?	a. Estimate F/A ratio data.
2. Based on the above F/A ratios in question number 1, what are the theoretical flame temperatures (°F) of these mixtures?	a. Estimate temperature data.
3. Based on the above temperatures in question number 2, which concept has the greatest potential for running cooler?	a. Score (1) to indicate greatest potential; (0) to show less potential.

TABLE V - Continued

Sheet: 1 of 1

CRITERIA: Adaptability

DEFINITION:

Adaptability is the quality for a design approach, system, and equipment to be used favorable, in some sense, to continue the functional operation of a system, even though it was not intended for that purpose.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. Is the design concept applicable to: • New TCM engines? • Existing TCM engines? • Competitor's engines?	a. If yes to all, score (1). If relative for pairwise comparison, score (1) to the concept that has the greater application, and (0) for the lesser application. b. If possible, name engine manufacturer and models.

TABLE V - Continued

Sheet: 1 of 2

CRITERIA: Materials

DEFINITION:

A substance that can be classified as either metallic or non-metallic, and whose physical and mechanical properties can be observed and measured. It is desired to address the types of materials to be used in each concept, i.e., metals (ferrous and non-ferrous), and non-metals (wood, plastic, etc.).

VALUE

ATTRIBUTES	ASSIGNMENT
1. Are further developments in materials required, such as increasing the mechanical property of strengths to meet concept design needs?	a. If further developments are needed, score (0). If not needed, score (1).
2. Are exotic materials (e.g., boron fiber reinforced metals, beryllium alloys, etc.) required?	a. If yes, score (0); if no score (1).
3. Is the availability of materials used for the E^3R equipment and concept, likely to decrease?	a. If likely to decrease, score (0). If likely to increase, score (1).
4. Are the materials to be used easy to process and fabricate?	a. If yes to both processes and fabricate, score (1). If no to either or both, score (0).
5. Are additional materials required for one concept over another?	a. If yes, list what the materials are, and score (0). If no, score (1).

TABLE V - Continued

Sheet: 1 of 1

CRITERIA: Integration

DEFINITION:

Integration is the combining of different equipments into subsystems so they work together harmoniously. Integration implies that various skills will be addressed for design, test, manufacturing, and organizational direction.

VALUE	
ATTRIBUTES	ASSIGNMENT
1. Can the design approach subsystems be interchanged, e.g., an induction system from one concept applied to a stratified charge concept, and still be workable?	a. Identify the likely subsystems that are interchangeable. b. Score (1) for the concept that shows the greater interchangeability and (0) for the least interchangeability.
2. What E^3R design interfaces are expected to occur per concept, and how do you consider their relative importance?	a. Identify interfaces in terms of: ELEMENT — RANK • Mechanical ( ) • Electrical ( ) • Fluids ( ) • Instrumentation ( ) • Support Equipment ( ) b. Score (1) to the concept that has the least amount of interfaces and (0) to the concept that has the greatest number of interfaces.

TABLE V - Concluded

CRITERIA: Producibility	Sheet: 1 of 4
DEFINITION: The ability of resources to be technologically converted into functional end items so that needs can be fulfilled. We are concerned with the ease of manufacture and assembly of an end item, including access to its parts, tooling requirements, and realistic tolerances.	
VALUE	
ATTRIBUTES	ASSIGNMENT
1. Do you expect that the design approach would use a greater number of standard parts, rather than specialized parts?	a. If no, score (0); if yes, score (1).
2. Does the concept imply the need to use close fitting manufacturing allowances and rigid true dimensional tolerances?	a. Score (1), if the concept does not require rigid manufacturing dimensional constraints. Score (0) if it does.
3. What retooling is envisaged to manufacture the E^{3}R equipment?	a. Identify and list standard tooling. b. Score (1) for the concept that has the most identifiable machine tools. Score (0) for the least identifiable machine tools.
4. Are standard fabrication and assembly procedures applicable for the concept and the E^{3}R equipment?	a. If yes to both concept and E^{3}R equipment, score (1). If no to either, score (0).

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TABLE VI. NUMBER OF SOLUTION ATTRIBUTES USED FOR DESCRIBING A CRITERIA ELEMENT

CRITERIA	NUMBER OF ATTRIBUTES USED
Cost	15
Reliability	14
Safety	14
Technology	10
Performance	6
Fuel Economy	3
Weight and Size	9
Maintainability and Maintenance	14
Emissions	2
Operational Characteristics	4
Cooling	3
Adaptability	1
Materials	5
Integration	2
Producibility	12

TABLE VII. ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANK FOR ENGINEER NO. 1

Sheet 1 of 4

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
Emissions	0.08000	0.01599
Reliability	0.07429	0.01695
Safety	0.07238	0.01019
Cost	0.06857	0.01842
Fuel Economy	0.06286	0.01390
Materials	0.05810	0.01610
Producibility	0.05333	0.01089
Performance	0.05238	0.02031
Integration	0.04857	0.01371
Maintainability and Maintenance	0.04762	0.01022
Operational Characteristics	0.04381	0.01503
Technology	0.04286	0.01146
Cooling	0.03619	0.01157
Weight and Size	0.03048	0.00986
Adaptability	0.02857	0.00543

TABLE VII. ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANK FOR ENGINEER NO. 2 - Continued

Sheet 2 of 4

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
Emissions	0.09257	0.01485
Performance	0.08400	0.01910
Safety	0.08219	0.01337
Cooling	0.07524	0.01516
Weight and Size	0.07419	0.01033
Cost	0.06286	0.01484
Reliability	0.06267	0.00976
Fuel Economy	0.05667	0.01046
Technology	0.05238	0.00772
Maintainability and Maintenance	0.04428	0.00896
Operational Characteristics	0.03990	0.00825
Producibility	0.03476	0.00903
Integration	0.02876	0.00918
Materials	0.02581	0.00606
Adaptability	0.01981	0.00673

TABLE VII. ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANK FOR ENGINEER NO. 3 - Continued

Sheet 3 of 4

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
Emissions	0.08343	0.01181
Safety	0.07733	0.01410
Reliability	0.07257	0.01410
Fuel Economy	0.06981	0.01971
Operational Characteristics	0.06552	0.01638
Performance	0.06505	0.01495
Weight and Size	0.05867	0.01657
Integration	0.05771	0.01467
Technology	0.05171	0.01495
Adaptability	0.04771	0.01610
Cooling	0.04086	0.01629
Producibility	0.03876	0.01171
Maintainability and Maintenance	0.03676	0.00610
Cost	0.02657	0.00581
Materials	0.01229	0.00200

TABLE VII. ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANK FOR ENGINEER NO. 4 - Concluded

Sheet 4 of 4

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
Emissions	0.10952	0.00138
Safety	0.09667	0.00746
Performance	0.08724	0.00705
Cooling	0.07695	0.00707
Weight and Size	0.07229	0.01152
Fuel Economy	0.06981	0.01019
Cost	0.06781	0.01198
Reliability	0.05933	0.00903
Technology	0.05457	0.00659
Operational Characteristics	0.04200	0.01059
Maintainability and Maintenance	0.04029	0.00924
Integration	0.03324	0.00295
Materials	0.03029	0.00305
Producibility	0.02933	0.00210
Adaptability	0.02781	0.00267

TABLE VIII. ENGINE EXHAUST EMISSION REDUCTION CRITERIA EMPHASIS COEFFICIENTS AND RANKING - OPTIMIZED

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
Emissions	0.10952	0.00138
Safety	0.09676	0.00750
Performance	0.08714	0.00701
Cooling	0.07695	0.00707
Weight and Size	0.07238	0.01159
Fuel Economy	0.06990	0.01020
Cost	0.06771	0.01192
Reliability	0.05933	0.00903
Technology	0.05548	0.00658
Operational Characteristics	0.04200	0.01059
Maintainability and Maintenance	0.04029	0.00924
Integration	0.03324	0.00295
Materials	0.03029	0.00305
Producibility	0.02933	0.00210
Adaptability	0.02781	0.00267

TABLE IX. ENGINE EXHAUST EMISSION REDUCTION CRITERIA ORDERING BASED ON A SIMPLE ARITHMETIC AVERAGE OF THE EVALUATORS' FINAL RANKING

CRITERIA	RANK
Emissions	1
Safety	2
Performance	3
Reliability	4
Fuel Economy	5
Cost	6
Weight and Size	7
Cooling	8
Operational Characteristics	9
Technology	10
Maintainability and Maintenance	11
Materials	12
Integration	13
Producibility	14
Adaptability	15

TABLE X. ENGINE EXHAUST EMISSION REDUCTION CONCEPT PREFERENCE, MERIT SCORE, AND RANK FOR ENGINEER NO. 1

Sheet 1 of 4

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Thermal Fuel Vaporization, Ethyl	1	0.06404	0.03004
Improved Cooling Combustion Chamber	2	0.05618	0.02778
Improved Fuel Injection Systems	3	0.05443	0.03083
Ultrasonic Fuel Atomization, Autotronic	4	0.05264	0.03017
Multiple Spark Discharge System	5	0.05199	0.02832
Texaco CCS	6	0.04931	0.02932
Ford PROCO	7	0.04655	0.02889
Variable Timing System	8	0.04278	0.02735
Air Injection	9	0.04037	0.02452
Two-Stroke Diesel, McCulloch	10	0.03913	0.02425
Honda CVCC	11	0.03853	0.02040
Four-Stroke Diesel, Open Chamber	12	0.03823	0.02291
Variable Camshaft Timing	13	0.03269	0.01890
Hydrogen Enrichment, JPL	14	0.03177	0.01766

TABLE X. ENGINE EXHAUST EMISSION REDUCTION CONCEPT PREFERENCE, MERIT SCORE, AND RANK FOR ENGINEER NO. 2 - Continued

Sheet 2 of 4

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Cooling Combustion Chamber	1	0.06195	0.02917
Air Injection	2	0.05478	0.02845
Improved Fuel Injection Systems	3	0.05416	0.02544
Thermal Fuel Vaporization, Ethyl	4	0.05300	0.02726
Hydrogen Enrichment, JPL	5	0.04922	0.02226
Ultrasonic Fuel Atomization, Autotronic	6	0.04915	0.02525
Multiple Spark Discharge System	7	0.04779	0.02532
Texaco CCS	8	0.04710	0.02186
Variable Timing System	9	0.04553	0.02353
Variable Camshaft Timing	10	0.04528	0.02287
Ford PROCO	11	0.04402	0.02022
Two-Stroke Diesel, McCulloch	12	0.04303	0.01969
Honda CVCC	13	0.04014	0.02260
Four-Stroke Diesel, Open Chamber	14	0.03451	0.01641

TABLE X. ENGINE EXHAUST EMISSION REDUCTION CONCEPT PREFERENCE, MERIT SCORE, AND RANK FOR ENGINEER NO. 3 - Continued

Sheet 3 of 4

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Fuel Injection Systems	1	0.06759	0.03360
Air Injection	2	0.06530	0.03127
Improved Cooling Combustion Chamber	3	0.06402	0.03455
Multiple Spark Discharge System	4	0.05953	0.03096
Ultrasonic Fuel Atomization, Autotronic	5	0.05852	0.03060
Variable Timing System	6	0.05702	0.03189
Thermal Fuel Vaporization, Ethyl	7	0.04695	0.02785
Hydrogen Enrichment, JPL	8	0.04527	0.02627
Variable Camshaft Timing	9	0.03605	0.02434
Honda CVCC	10	0.03024	0.01965
Two-Stroke Diesel, McCulloch	11	0.02898	0.01910
Four-Stroke Diesel, Open Chamber	12	0.02681	0.01684
Texaco CCS	13	0.02518	0.01849
Ford PROCO	14	0.02513	0.01795

TABLE X. ENGINE EXHAUST EMISSION REDUCTION CONCEPT PREFERENCE, MERIT SCORE, AND RANK FOR ENGINEER NO. 4 - Concluded

Sheet 4 of 4

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Cooling Combustion Chamber	1	0.05961	0.02425
Texaco CCS	2	0.05791	0.02657
Multiple Spark Discharge System	3	0.05668	0.02721
Improved Fuel Injection Systems	4	0.05629	0.02337
Ford PROCO	5	0.05219	0.02453
Variable Timing System	6	0.05112	0.02668
Air Injection	7	0.05057	0.02369
Thermal Fuel Vaporization, Ethyl	8	0.04799	0.02215
Variable Camshaft Timing	9	0.04722	0.02542
Two-Stroke Diesel, McCulloch	10	0.04582	0.02532
Honda CVCC	11	0.04083	0.01962
Ultrasonic Fuel Atomization, Autotronic	12	0.03782	0.01985
Four-Stroke Diesel, Open Chamber	13	0.03732	0.01837
Hydrogen Enrichment, JPL	13	0.03410	0.01751

TABLE XI. ENGINE EXHAUST EMISSION REDUCTION CONCEPT PREFERENCE, MERIT SCORE, AND RANK - OPTIMIZED

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Cooling Combustion Chamber	1	0.07294	0.02391
Improved Fuel Injection Systems	2	0.07084	0.02165
Air Injection	3	0.06540	0.02096
Multiple Spark Discharge System	4	0.06485	0.02201
Ultrasonic Fuel Atomization, Autotronic	5	0.05822	0.02018
Variable Timing System	6	0.05761	0.02024
Thermal Fuel Vaporization, Ethyl	7	0.05390	0.01986
Hydrogen Enrichment, JPL	8	0.04974	0.01641
Texaco CCS	9	0.04397	0.01657
Two-Stroke Diesel, McCulloch	10	0.04374	0.01691
Ford PROCO	11	0.04210	0.01549
Variable Camshaft Timing	12	0.04081	0.01659
Honda CVCC	13	0.04057	0.01548
Four-Stroke Diesel, Open Chamber	14	0.03471	0.01432

TABLE XII. ENGINE EXHAUST EMISSION REDUCTION CONCEPT COMPARISON TRADEOFF EVALUATION MERIT SCORES - OPTIMIZED

Sheet 1 of 15

*EMISSIONS

CONCEPT	MERIT SCORE	UNCERTAINTY
HYDROGEN ENRICHMENT, JPL	0.09848	0.01072
HONDA CVCC	0.09143	0.01016
IMPROVED FUEL INJECTION SYSTEMS	0.08659	0.00962
AIR INJECTION	0.08165	0.00907
TEXACO CCS	0.07538	0.00967
FORD PROCO	0.07066	0.00900
TWO-STROKE DIESEL, McCULLOCH	0.06560	0.00865
FOUR-STROKE DIESEL, OPEN CHAMBER	0.06066	0.00796
IMPROVED COOLING COMBUSTION CHAMBER	0.05582	0.00729
VARIABLE CAMSHAFT TIMING	0.05187	0.00576
THERMAL FUEL VAPORIZATION, ETHYL	0.04692	0.00521
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.04209	0.00468
VARIABLE TIMING SYSTEM	0.03714	0.00413
MULTIPLE SPARK DISCHARGE SYSTEM	0.03220	0.00358

TABLE XII - Continued

Sheet 2 of 15

*SAFETY

CONCEPT	MERIT SCOPE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.09901	0.01857
IMPROVED FUEL INJECTION SYSTEMS	0.09824	0.01604
MULTIPLE SPARK DISCHARGE SYSTEM	0.09451	0.01429
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.08934	0.01396
AIR INJECTION	0.08308	0.01143
VARIABLE TIMING SYSTEM	0.07582	0.01319
THERMAL FUEL VAPORIZATION, ETHYL	0.05747	0.01176
TEXACO CCS	0.03626	0.01868
FORD PROCO	0.03582	0.01692
FOUR-STROKE DIESEL, OPEN CHAMBER	0.03495	0.01890
TWO-STROKE DIESEL, McCULLOCH	0.03484	0.01901
HONDA CVCC	0.02813	0.01143
VARIABLE CAMSHAFT TIMING	0.02176	0.00901
HYDROGEN ENRICHMENT, JPL	0.01187	0.00571

TABLE XII - Continued

Sheet 3 of 15

*PERFORMANCE

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED FUEL INJECTION SYSTEMS	0.09703	0.01078
TWO-STROKE DIESEL, McCULLOCH	0.09132	0.01092
VARIABLE TIMING SYSTEM	0.08604	0.01022
VARIABLE CAMSHAFT TIMING	0.08000	0.01081
MULTIPLE SPARK DISCHARGE SYSTEM	0.07615	0.00903
IMPROVED COOLING COMBUSTION CHAMBER	0.06945	0.01020
HYDROGEN ENRICHMENT, JPL	0.06560	0.00858
AIR INJECTION	0.06088	0.00792
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.05462	0.00783
THERMAL FUEL VAPORIZATION, ETHYL	0.04989	0.00714
HONDA CVCC	0.04582	0.00645
TEXACO CCS	0.04022	0.00632
FORD PROCO	0.03549	0.00561
FOUR-STROKE DIESEL, OPEN CHAMBER	0.03209	0.00357

TABLE XII - Continued

Sheet 4 of 15

*COOLING

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.08769	0.01931
TEXACO CCS	0.08264	0.01892
FORD PROCO	0.07835	0.01761
HYDROGEN ENRICHMENT, JPL	0.06802	0.01165
FOUR-STROKE DIESEL, OPEN CHAMBER	0.05934	0.03154
TWO-STROKE DIESEL, McCULLOCH	0.05582	0.02958
MULTIPLE SPARK DISCHARGE SYSTEM	0.04637	0.02785
VARIABLE TIMING SYSTEM	0.04286	0.02595
AIR INJECTION	0.04077	0.02246
VARIABLE CAMSHAFT TIMING	0.03538	0.02229
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.03099	0.02105
HONDA CVCC	0.02901	0.01202
THERMAL FUEL VAPORIZATION, ETHYL	0.02769	0.01915
IMPROVED FUEL INJECTION SYSTEMS	0.02055	0.01512

TABLE XII - Continued

Sheet 5 of 15

*WEIGHT AND SIZE

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.10286	0.01143
IMPROVED FUEL INJECTION SYSTEMS	0.09890	0.01099
MULTIPLE SPARK DISCHARGE SYSTEM	0.09494	0.01055
VARIABLE TIMING SYSTEM	0.09099	0.01011
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.08703	0.00967
AIR INJECTION	0.08308	0.00923
THERMAL FUEL VAPORIZATION, ETHYL	0.07363	0.00989
HYDROGEN ENRICHMENT, JPL	0.04956	0.01198
VARIABLE CAMSHAFT TIMING	0.04692	0.01462
TEXACO CCS	0.03011	0.01275
FORD PROCO	0.02835	0.01011
HONDA CVCC	0.02813	0.00923
TWO-STROKE DIESEL, McCULLOCH	0.02648	0.00978
FOUR-STROKE DIESEL, OPEN CHAMBER	0.01615	0.00253

TABLE XII - Continued

Sheet 6 of 15

*FUEL ECONOMY

CONCEPT	MERIT SCORE	UNCERTAINTY
HYDROGEN ENRICHMENT, JPL	0.09648	0.01072
TEXACO CCS	0.09143	0.01016
FORD PROCO	0.08648	0.00961
TWO-STROKE DIESEL, McCULLOCH	0.08154	0.00906
IMPROVED FUEL INJECTION SYSTEMS	0.07659	0.00851
IMPROVED COOLING COMBUSTION CHAMBER	0.06989	0.00972
FOUR-STROKE DIESEL, OPEN CHAMBER	0.06516	0.00895
HONDA CVCC	0.06176	0.00686
THERMAL FUEL VAPORIZATION, ETHYL	0.05692	0.00632
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.05198	0.00578
VARIABLE TIMING SYSTEM	0.04703	0.00523
MULTIPLE SPARK DISCHARGE SYSTEM	0.04209	0.00468
VARIABLE CAMSHAFT TIMING	0.03714	0.00413
AIR INJECTION	0.03220	0.00358

TABLE XII - Continued

Sheet 7 of 15

*COST

CONCEPT	MERIT SCORE	UNCERTAINTY
AIR INJECTION	0.09648	0.01072
MULTIPLE SPARK DISCHARGE SYSTEM	0.08681	0.01480
THERMAL FUEL VAPORIZATION, ETHYL	0.08231	0.01394
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.07758	0.01302
VARIABLE TIMING SYSTEM	0.07308	0.01216
IMPROVED COOLING COMBUSTION CHAMBER	0.07275	0.00808
IMPROVED FUEL INJECTION SYSTEMS	0.06440	0.00990
VARIABLE CAMSHAFT TIMING	0.05923	0.00909
FORD PROCO	0.05516	0.00792
TEXACO CCS	0.05033	0.00724
HONDA CVCC	0.04484	0.00719
HYDROGEN ENRICHMENT, JPL	0.04209	0.00468
TWO-STROKE DIESEL, McCULLOCH	0.03714	0.00413
FOUR-STROKE DIESEL, OPEN CHAMBER	0.03143	0.00349

TABLE XII - Continued

Sheet 8 of 15

*RELIABILITY

CONCEPT	MERIT SCORE	UNCERTAINTY
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.09011	0.01538
THERMAL FUEL VAPORIZATION, ETHYL	0.08714	0.01615
IMPROVED COOLING COMBUSTION CHAMBER	0.08319	0.02780
IMPROVED FUEL INJECTION SYSTEMS	0.08154	0.01407
AIR INJECTION	0.08088	0.01363
MULTIPLE SPARK DISCHARGE SYSTEM	0.07967	0.01593
VARIABLE TIMING SYSTEM	0.06308	0.01604
HYDROGEN ENRICHMENT, JPL	0.05154	0.01440
TWO-STROKE DIESEL, McCULLOCH	0.04747	0.00967
FOUR-STROKE DIESEL, OPEN CHAMBER	0.04088	0.00857
FORD PROCO	0.03571	0.00714
TEXACO CCS	0.03220	0.00736
HONDA CVCC	0.02692	0.00824
VARIABLE CAMSHAFT TIMING	0.01945	0.00582

TABLE XII - Continued

Sheet 9 of 15

*TECHNOLOGY

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED FUEL INJECTION SYSTEMS	0.10110	0.01648
IMPROVED COOLING COMBUSTION CHAMBER	0.09736	0.01363
AIR INJECTION	0.09473	0.01516
MULTIPLE SPARK DISCHARGE SYSTEM	0.08879	0.01451
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.07857	0.01374
THERMAL FUEL VAPORIZATION, ETHYL	0.07637	0.01374
VARIABLE TIMING SYSTEM	0.06165	0.00978
VARIABLE CAMSHAFT TIMING	0.05231	0.01473
HYDROGEN ENRICHMENT, JPL	0.04407	0.01418
HONDA CVCC	0.03582	0.01363
TWO-STROKE DIESEL, McCULLOCH	0.02516	0.01000
FOUR-STROKE DIESEL, OPEN CHAMBER	0.02275	0.01022
TEXACO CCS	0.02275	0.00912
FORD PROCO	0.02165	0.00802

TABLE XII - Continued

Sheet 10 of 15

*OPERATIONAL CHARACTERISTICS

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.07494	0.03212
MULTIPLE SPARK DISCHARGE SYSTEM	0.07099	0.03042
AIR INJECTION	0.06703	0.02873
THERMAL FUEL VAPORIZATION, ETHYL	0.06330	0.02713
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.05956	0.02553
IMPROVED FUEL INJECTION SYSTEMS	0.05571	0.02388
HONDA CVCC	0.05198	0.02228
VARIABLE CAMSHAFT TIMING	0.04802	0.02058
VARIABLE TIMING SYSTEM	0.04418	0.01893
TEXACO CCS	0.04055	0.01738
FORD PROCO	0.03670	0.01573
HYDROGEN ENRICHMENT, JPL	0.03275	0.01403
TWO-STROKE DIESEL, McCULLOCH	0.02912	0.01248
FOUR-STROKE DIESEL, OPEN CHAMBER	0.02516	0.01078

TABLE XII - Continued

Sheet 11 of 15

*MAINTAINABILITY AND MAINTENANCE

CONCEPT	MERIT SCORE	UNCERTAINTY
IMPROVED COOLING COMBUSTION CHAMBER	0.11769	0.01308
IMPROVED FUEL INJECTION SYSTEMS	0.08527	0.01802
MULTIPLE SPARK DISCHARGE SYSTEM	0.07725	0.02055
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.07121	0.02000
AIR INJECTION	0.06769	0.02022
VARIABLE TIMING SYSTEM	0.06319	0.02912
THERMAL FUEL VAPORIZATION, ETHYL	0.06253	0.01989
HYDROGEN ENRICHMENT, JPL	0.04187	0.01637
TWO-STROKE DIESEL, McCULLOCH	0.03407	0.01538
VARIABLE CAMSHAFT TIMING	0.03132	0.01264
HONDA CVCC	0.02934	0.01901
FOUR-STROKE DIESEL, OPEN CHAMBER	0.02560	0.01396
TEXACO CCS	0.02440	0.01407
FORD PROCO	0.02352	0.01275

TABLE XII - Continued

Sheet 12 of 15

*INTEGRATION

CONCEPT	MERIT SCORE	UNCERTAINTY
MULTIPLE SPARK DISCHARGE SYSTEM	0.09593	0.01136
AIR INJECTION	0.08066	0.02099
VARIABLE TIMING SYSTEM	0.07846	0.01780
IMPROVED FUEL INJECTION SYSTEMS	0.07242	0.01840
VARIABLE CAMSHAFT TIMING	0.06110	0.02407
IMPROVED COOLING COMBUSTION CHAMBER	0.06099	0.01859
HYDROGEN ENRICHMENT, JPL	0.04978	0.02441
HONDA CVCC	0.04747	0.02125
THERMAL FUEL VAPORIZATION, ETHYL	0.04396	0.01913
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.04110	0.01645
TEXACO CCS	0.03934	0.01288
FORD PROCO	0.03429	0.01215
TWO-STROKE DIESEL, McCULLOCH	0.03418	0.00713
FOUR-STROKE DIESEL, OPEN CHAMBER	0.02956	0.00616

TABLE XII - Continued

Sheet 13 of 15

*MATERIALS

CONCEPT	MERIT SCORE	UNCERTAINTY
MULTIPLE SPARK DISCHARGE SYSTEM	0.10483	0.01275
IMPROVED FUEL INJECTION SYSTEMS	0.09769	0.01440
IMPROVED COOLING COMBUSTION CHAMBER	0.08967	0.01253
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.08396	0.01165
VARIABLE TIMING SYSTEM	0.08165	0.01176
AIR INJECTION	0.06934	0.00978
THERMAL FUEL VAPORIZATION, ETHYL	0.05912	0.01341
VARIABLE CAMSHAFT TIMING	0.04044	0.01670
TWO-STROKE DIESEL, McCULLOCH	0.03879	0.01615
HONDA CVCC	0.03868	0.01297
FOUR-STROKE DIESEL, OPEN CHAMBER	0.03440	0.01396
FORD PROCO	0.03143	0.01363
TEXACO CCS	0.03033	0.01253
HYDROGEN ENRICHMENT, JPL	0.02055	0.00692

TABLE XII - Continued

Sheet 14 of 15

*PRODUCIBILITY

CONCEPT	MERIT SCORE	UNCERTAINTY
AIR INJECTION	0.08571	0.02143
IMPROVED COOLING COMBUSTION CHAMBER	0.08132	0.02033
THERMAL FUEL VAPORIZATION, ETHYL	0.07692	0.01923
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.07253	0.01813
MULTIPLE SPARK DISCHARGE SYSTEM	0.06813	0.01703
VARIABLE TIMING SYSTEM	0.06374	0.01593
IMPROVED FUEL INJECTION SYSTEMS	0.05934	0.01484
HYDROGEN ENRICHMENT, JPL	0.05495	0.01374
VARIABLE CAMSHAFT TIMING	0.05055	0.01264
HONDA CVCC	0.04615	0.01154
TEXACO CCS	0.04176	0.01044
FORD PROCO	0.03736	0.00934
TWO-STROKE DIESEL, McCULLOCH	0.03297	0.00824
FOUR-STROKE DIESEL, OPEN CHAMBER	0.02857	0.00714

TABLE XII - Concluded

Sheet 15 of 15

*ADAPTABILITY

CONCEPT	MERIT SCORE	UNCERTAINTY
AIR INJECTION	0.08571	0.02143
MULTIPLE SPARK DISCHARGE SYSTEM	0.08132	0.02033
VARIABLE TIMING SYSTEM	0.07692	0.01923
IMPROVED COOLING COMBUSTION CHAMBER	0.06945	0.02058
THERMAL FUEL VAPORIZATION, ETHYL	0.06560	0.01938
IMPROVED FUEL INJECTION SYSTEMS	0.06154	0.01813
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	0.05747	0.01688
HYDROGEN ENRICHMENT, JPL	0.05330	0.01560
VARIABLE CAMSHAFT TIMING	0.04703	0.01590
HONDA CVCC	0.04330	0.01469
TEXACO CCS	0.03879	0.01327
FORD PROCO	0.03484	0.01201
FOUR-STROKE DIESEL, OPEN CHAMBER	0.03066	0.01067
TWO-STROKE DIESEL, McCULLOCH	0.02659	0.00938

APPENDIX A. RAW EMISSIONS DATA

TABLE OF CONTENTS FOR APPENDIX A

HONDA COMPOUND VORTEX CONTROLLED COMBUSTION

DATA SOURCE: Southwest Research Institute (Ref. 5, p. B-16, Table B-19)

ENGINE DESCRIPTION:

Manufacturer: Honda Motor Co.
Cylinder Arrangement: I-4
Displacement (in^3): 95.2
Aspiration: Natural
Rated (Maximum) Power: 63 hp at 5500 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	1000.
Taxi, In and Out	-	1200.	-	1000.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	50.	100.%

ASSUMPTIONS:

- Equilibrium values of CO_2 and O_2 used for all modes.
- Fuel hydrogen-to-carbon ratio assumed to be 2.0.

```
95 CID HONDA COMPOUND VORTEX CONTROLLED COMBUSTION

 PBARGAV                                FUEL HYDROGEN-    TAMB       RATED      CID         EXHAUST      AVG H2O IN AIR
IN HG ABS                                CARBON RATIO    DEG F        HP      INCH**3    C - H FORMULA      PERCENT
 14.700                                     2.0000       76.00       63.00     95.20     1.000   1.850       0.720

                            UNITS       MODE 1     MODE 2      MODE 3      MODE 4      MODE 5      MODE 6      MODE 7      TOTAL
TIME IN MODE               MINUTES        1.00      11.00        0.30        5.00        6.00        3.00        1.00      27.30
FUEL FLOW                    LB/HR        1.72       1.72       30.83       25.53       20.24        1.72        1.72
AIR  FLOW                    LB/HR       27.78      27.78      367.79      316.20      276.51       27.78       27.78
HYDROCARBON CONC.          PPM-C        636.00     636.00     1872.00     1504.00      100.00      280.00      280.00
OXIDES OF NITROGEN CONC PPM              86.00      86.00      801.00      461.00      962.00       82.00       82.00
CARBON MONOXIDE CONC. PERCENT             0.26       0.26        2.84        2.54        0.46        0.25        0.25
CARBON DIOXIDE CONC.   PERCENT           12.13      12.13        9.45       10.20       11.58       12.13       12.13
OXYGEN CONC.               PERCENT        1.20       1.20        0.0         0.0         0.0         1.20        1.20
PROP.  TORQUE                FT-LB                               60.23       45.17       30.11
PROP.  SPEED                   RPM     1000.00    1000.00     5500.00     5500.00     5500.00     1000.00     1000.00

DRY BULB TEMP                DEG F       68.00      68.00       75.70       75.70       80.20       82.00       82.00
WET BULB TEMP                DEG F       60.00      60.00       60.00       60.00       60.00       60.00       60.00



FUEL AIR RATIO               LB/LB     0.06248    0.06248     0.08445     0.08134     0.07367     0.06229     0.06229     0.06861 TA
FUEL AIR EQUIVALENCE RATIO --             0.92       0.92        1.25        1.20        1.09        0.92        0.92        1.01 TA
ENGINE OBSERVED POWER           HP                               63.07       47.30       31.53
OBS BMEP                       PSI                               95.41       71.55       47.70
OBS BSFC                LBM/BHP-HR                               0.489       0.540       0.642
EXHAUST MOLE. WT.  LB/LB-MOLE            28.91      28.91       27.57       27.80       28.41       28.91       28.91
WET CORRECTION FACTOR          --      0.85066    0.85066     0.90985     0.89910     0.89713     0.85582     0.85582
HC EMISSION RATE             LB/HR     0.00900    0.00900     0.37557     0.25648     0.01449     0.00396     0.00396
HC MASS / MODE               LB        0.00015    0.00165     0.00188     0.02137     0.00145     0.00020     0.00007     0.02677
HC MASS / RATED HP           LB/HP                                                                                      0.00042
 HC - PERCENT OF EPA STANDARD                                                                                             22.36
CO EMISSION RATE             LB/HR     0.07466    0.07466    11.51486     8.76120     1.34572     0.07005     0.07005
CO MASS / MODE               LB        0.00124    0.01369     0.05757     0.73010     0.13457     0.00350     0.00117     0.94185
CO MASS / RATED HP           LB/HP                                                                                      0.01495
 CO - PERCENT OF EPA STANDARD                                                                                             35.60
NOX EMISSION RATE            LB/HR     0.00404    0.00404     0.53287     0.26068     0.46237     0.00385     0.00385
NOX MASS / MODE              LB        0.00007    0.00074     0.00266     0.02172     0.04624     0.00019     0.00006     0.07169
NOX MASS / RATED HP          LB/HP                                                                                      0.00114
 NOX- PERCENT OF EPA STANDARD                                                                                             75.86

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO          LB/LB     0.06465    0.06465     0.07747     0.07594     0.06904     0.06438     0.06438     0.06778 TA
DIFF. MEAS & CAL. F/A PERCENT             3.47       3.47       -8.27       -6.64       -6.28        3.37        3.37       -1.20 TA
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FORD PROGRAMMED COMBUSTION

DATA SOURCE: Southwest Research Institute (Ref. 5, p. B-10, Table B-13)

ENGINE DESCRIPTON:

Manufacturer: Ford (Capri)
Cylinder Arrangement: I-4
Displacement (in^3): 141
Aspiration: Natural
Rated (Maximum) Power: 73 hp at 4000 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	900.
Taxi, In and Out	-	1200.	-	900.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	50.	100.%

ASSUMPTIONS:

- Equilibrium values of CO_2 and O_2 used for all modes.
- Fuel hydrogen-to-carbon ratio assumed to be 2.0.

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141 CID CAPRI WITH FORD PROCO

PBARCAV IN HG ABS	FUEL HYDROGEN-CARBON RATIO	TAMB DEG F	RATED HP	CID INCH**3	EXHAUST C - H FORMULA		AVG H2O IN AIR PERCENT
29.000	2.0000	60.00	73.40	141.00	1.000	1.850	0.917

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
TIME IN MODE	MINUTES	1.00	11.00	0.30	5.00	6.00	3.00	1.00	27.30
FUEL FLOW	LB/HR	0.53	0.53	41.41	33.87	26.46	0.53	0.53	
AIR FLOW	LB/HR	58.21	58.21	504.06	497.45	388.96	58.21	58.21	
HYDROCARBON CONC.	PPM-C	67.00	67.00	5664.00	50.00	30.00	14.00	14.00	
OXIDES OF NITROGEN CONC	PPM	80.00	80.00	384.00	1116.00	944.00	68.00	68.00	
CARBON MONOXIDE CONC.	PERCENT	0.00	0.00	4.41	0.00	0.00	0.00	0.00	
CARBON DIOXIDE CONC.	PERCENT	1.88	1.88	9.75	12.75	12.76	1.88	1.88	
OXYGEN CONC.	PERCENT	17.75	17.75	0.01	0.01	0.01	17.75	17.75	
PROP. TORQUE	FT-LB			96.46	86.57	74.91			
PROP. SPEED	RPM	900.00	900.00	4000.00	4000.00	4000.00	900.00	900.00	
DRY BULB TEMP	DEG F	69.00	69.00	66.50	66.50	65.00	65.00	65.00	
WET BULB TEMP	DEG F	60.00	60.00	60.00	60.00	60.00	60.00	60.00	

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
FUEL AIR RATIO	LB/LB	0.00917	0.00917	0.08293	0.06873	0.06870	0.00918	0.00918	0.03397 TA
FUEL AIR EQUIVALENCE RATIO	--	0.14	0.14	1.23	1.02	1.02	0.14	0.14	0.50 TA
ENGINE OBSERVED POWER	HP			73.47	65.94	57.05			
OBS BMEP	PSI			103.17	92.59	80.12			
OBS BSFC	LBM/BHP-HR			0.564	0.514	0.464			
EXHAUST MOLE. WT.	LB/LB-MOLE	28.96	28.96	27.68	28.81	28.81	28.96	28.96	
WET CORRECTION FACTOR	--	0.96034	0.96034	0.86632	0.86604	0.86511	0.96049	0.96049	
HC EMISSION RATE	LB/HR	0.00189	0.00189	1.54854	0.01279	0.00600	0.00039	0.00039	
HC MASS / MODE	LB	0.00003	0.00035	0.00774	0.00107	0.00060	0.00002	0.00001	0.00981
HC MASS / RATED HP	LB/HP								0.00013
HC - PERCENT OF EPA STANDARD									7.04
CO EMISSION RATE	LB/HR	0.00136	0.00136	24.32472	0.01085	0.01090	0.00136	0.00136	
CO MASS / MODE	LB	0.00002	0.00025	0.12162	0.00090	0.00109	0.00007	0.00002	0.12398
CO MASS / RATED HP	LB/HP								0.00169
CO - PERCENT OF EPA STANDARD									4.02
NOX EMISSION RATE	LB/HR	0.00747	0.00747	0.34813	0.94696	0.62623	0.00635	0.00635	
NOX MASS / MODE	LB	0.00012	0.00137	0.00174	0.07891	0.06262	0.00032	0.00011	0.14519
NOX MASS / RATED HP	LB/HP								0.00198
NOX- PERCENT OF EPA STANDARD									131.87

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
CAL. FUEL AIR RATIO	LB/LB	0.00933	0.00933	0.08387	0.06771	0.06770	0.00931	0.00931	0.03367 TA
DIFF. MEAS & CAL. F/A	PERCENT	1.79	1.79	1.13	-1.48	-1.45	1.40	1.40	-0.89 TA

TEXACO CONTROLLED COMBUSTION SYSTEM

CASE 1

DATA SOURCE: Texaco, Incorporated (Ref. 54)

ENGINE DESCRIPTION:

Type: Military Engine
Cylinder Arrangement: I-4
Displacement (in^3): 183
Aspiration: Natural
Rated (Maximum) Power: 82 hp at 3500 rpm
Fuel: Gasoline

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	725.
Taxi, In and Out	-	1200.	13.	1500.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	78.	86.%
Approach	40.	87.%	39.	86.%

ASSUMPTIONS:

None

Engine Description: Stratified Charge, Multifuel, 4-Cylinder, Water Cooled, 4 Cycle, In Line, OHC
Engine Displacement: 183 CID
Engine Rated Brake H.P.: 82 at 3500 rpm
Fuel Hydrogen-Carbon Ratio: 0.157 (by weight)

	ENGINE CONDITIONS REQUIRED		DATA REQUIRED WET												ACTUAL ENGINE CONDITIONS		
						INDUCTION AIR UPSTREAM											
MODE NAME	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr)	OR MASS FUEL-AIR RATIO	TEMPERATURE (°F)	PRESSURE (in. Hg abs)	SPECIFIC HUMIDITY (lb/lb)	HC (ppm)	NOx (ppm)	CO (ppm)	CO_2 (%)	O_2 (%)	* MANIFOLD PRESSURE (in. Hg abs)	ENGINE POWER (H.P.)	ENGINE SPEED (rpm)	INDICATED H.P.
Idle	-	600 rpm	1.00	132	0.0076	78	29.85	0.00857	224	46	1000	1.45	19.0		0	725	2.6
Taxi	-	1200 rpm	5.63	305	0.018	78	29.95	0.00914	329	166	1200	3.55	16.0		11	1500	18.8
Take-Off	100	100%	39.3	643	0.061	80	29.99	0.00572	2	1420	1000	13.8	1.6		82	3500	107.2
Climb	80	90% of Max.	29.4	539	0.055	78	29.22	0.01021	8	1300	2000	12.0	5.2		64	3000	83.2
Approach	40	87% of Max.	16.0	575	0.028	78	29.22	0.01021	100	340	1400	6.3	12.5		32	3000	52.7

*Engine operates unthrottled

NOTES:

HC	- Total hydrocarbons in ppm Cx Hy by volume	- Undiluted	(or) gm/hr of Cx Hy	(define x and y) x = 6, y = 14
NOx	- Total oxides of nitrogen in ppm by volume	- Undiluted	(or) gm/hr of NOx	(define x) x = 2
CO	- Carbon monoxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO	PPM
CO_2	- Carbon dioxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO_2	% Volume
O_2	- Oxygen in ppm or % by volume	- Undiluted	(or) gm/hr of O_2	% Volume

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183 CID MILITARY ENGINE WITH TEXACO CCS

PBARLAV IN HG ABS	FUEL HYDROGEN-CARBON RATIO	TAMB DEG F	RATED HP	CID INCH**3	EXHAUST C - H FORMULA	AVG H2O IN AIR PERCENT
29.720	1.8700	78.30	82.00	183.00	1.000 1.850	0.867

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
TIME IN MODE	MINUTES	1.00	11.00	0.30	5.00	6.00	3.00	1.00	27.30
FUEL FLOW	LB/HR	1.00	5.63	39.30	29.40	16.00	5.63	1.00	
AIR FLOW	LB/HR	132.00	305.00	643.00	539.00	575.00	305.00	132.00	
HYDROCARBON CONC.	PPM-C	1344.00	1974.00	12.00	48.00	600.00	1974.00	1344.00	
OXIDES OF NITROGEN CONC	PPM	46.00	166.00	1420.00	1300.00	340.00	166.00	46.00	
CARBON MONOXIDE CONC.	PERCENT	0.10	0.12	0.10	0.20	0.14	0.12	0.10	
CARBON DIOXIDE CONC.	PERCENT	1.45	3.55	13.80	12.00	6.30	3.55	1.45	
OXYGEN CONC.	PERCENT	19.00	16.00	1.60	5.20	12.50	16.00	19.00	
PROP. TORQUE	FT-LB		38.51	123.05	112.04	56.02	38.51		
PROP. SPEED	RPM	725.00	1500.00	3500.00	3000.00	3000.00	1500.00	725.00	
DRY BULB TEMP	DEG F	78.00	78.00	80.00	78.00	78.00	78.00	78.00	
WET BULB TEMP	DEG F	63.00	63.90	59.00	65.10	65.10	63.90	63.00	
FUEL AIR RATIO	LB/LB	0.00764	0.01863	0.06148	0.05511	0.02811	0.01863	0.00764	0.02706 TA
FUEL AIR EQUIVALENCE RATIO	--	0.11	0.27	0.90	0.80	0.41	0.27	0.11	0.40 TA
ENGINE OBSERVED POWER	HP		11.00	82.00	64.00	32.00	11.00		
OBS BMEP	PSI		31.74	101.40	92.33	46.16	31.74		
OBS BSFC	LBM/BHP-HR		0.512	0.479	0.459	0.500	0.512		
EXHAUST MOLE. WT.	LB/LB-MOLE	28.96	28.95	28.91	28.92	28.94	28.95	28.96	
WET CORRECTION FACTOR	--	0.95206	0.96010	0.84575	0.88462	0.89471	0.96010	0.95206	
HC EMISSION RATE	LB/HR	0.08564	0.29388	0.00393	0.01309	0.17000	0.29388	0.08564	
HC MASS / MODE	LB	0.00143	0.05388	0.00002	0.00109	0.01700	0.01469	0.00143	0.08954
HC MASS / RATED HP	LB/HP								0.00109
HC - PERCENT OF EPA STANDARD									57.47
CO EMISSION RATE	LB/HR	0.12864	0.36065	0.66103	1.10114	0.80077	0.36065	0.12864	
CO MASS / MODE	LB	0.00214	0.06612	0.00331	0.09176	0.08008	0.01803	0.00214	0.26358
CO MASS / RATED HP	LB/HP								0.00321
CO - PERCENT OF EPA STANDARD									7.65
NOX EMISSION RATE	LB/HR	0.00972	0.08195	1.54180	1.17564	0.31943	0.08195	0.00972	
NOX MASS / MODE	LB	0.00016	0.01502	0.00771	0.09797	0.03194	0.00410	0.00016	0.15707
NOX MASS / RATED HP	LB/HP								0.00192
NOX- PERCENT OF EPA STANDARD									127.70

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS

CAL. FUEL AIR RATIO	LB/LB	0.00805	0.01833	0.06381	0.05352	0.03002	0.01833	0.00805	0.02709 TA
DIFF. MEAS & CAL. F/A	PERCENT	5.31	-1.64	3.80	-2.87	6.77	-1.64	5.31	0.10 TA

TEXACO CONTROLLED COMBUSTION SYSTEM

CASE 2

DATA SOURCE: Southwest Research Institute (Ref. 5, p. B-14, Table B-18)

ENGINE DESCRIPTION:

Manufacturer: Plymouth (Cricket)
Cylinder Arrangement: I-4
Displacement (in^3): 141
Aspiration: Natural
Rated (Maximum) Power: 67 hp at 3000 rpm
Fuel: Gasoline

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	900.
Taxi, In and Out	-	1200.	17.	1800.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	50.	100.%

ASSUMPTIONS:

- Equilibrium values of CO_2 and O_2 used for all modes.
- Fuel hydrogen to carbon ratio assumed to be 2.0.

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141 CID PLYMOUTH CRICKET WITH TEXACO CCS (GASOLINE)

 PBAROAV                          FUEL HYDROGEN-    TAMB     RATED      CIO        EXHAUST      AVG H2O IN AIR
IN HG ABS                          CARBON RATIO    DEG F       HP     INCH**3   C - H FORMULA      PERCENT
 29.000                               2.0000       64.00     67.10     141.00   1.000   1.850       1.039

                             UNITS     MODE 1     MODE 2     MODE 3     MODE 4     MODE 5     MODE 6     MODE 7      TOTAL
TIME IN MODE               MINUTES       1.00      11.00       0.30       5.00       6.00       3.00       1.00      27.30
FUEL FLOW                    LB/HR       1.46       7.54      24.48      19.98      15.48       7.54       1.46
AIR  FLOW                    LB/HR     101.87     316.20     612.55     563.60     550.37     316.20     101.87
HYDROCARBON CONC.         PPM-C       1440.00     270.00      17.00      17.00      65.00     270.00    1808.00
OXIDES OF NITROGEN CONC PPM            108.00     231.00     924.00     660.00     406.00     231.00      98.00
CARBON MONOXIDE CONC. PERCENT            0.03       0.00       0.00       0.00       0.00       0.00       0.04
CARBON DIOXIDE CONC.  PERCENT            2.94       4.85       8.06       7.18       5.71       4.85       2.94
OXYGEN CONC.           PERCENT          16.10      13.15       8.10       9.55      11.85      13.15      16.10
PROP.  TORQUE            FT-LB                     33.58     117.57      88.12      58.90      33.58
PROP.  SPEED               RPM         900.00    1800.00    3000.00    3000.00    3000.00    1800.00     900.00

DRY BULB TEMP            DEG F          63.00      63.00      70.20      63.00      63.00      63.00      63.00
WET BULB TEMP            DEG F          60.00      60.00      65.00      60.00      60.00      60.00      60.00
COOLING AIR TEMP         DEG F          64.00      64.00      64.00      64.00      64.00      64.00      64.00
INDUCTION AIR TEMP       DEG F          64.00      64.00      64.00      64.00      64.00      64.00      64.00

FUEL AIR RATIO           LB/LB        0.01448    0.02409    0.04044    0.03582    0.02842    0.02409    0.01448    0.02666 TA
FUEL AIR EQUIVALENCE RATIO --            0.21       0.36       0.60       0.53       0.42       0.36       0.21       0.39 TA
ENGINE OBSERVED POWER       HP                     11.51      67.16      50.34      33.64      11.51
OBS BMEP                   PSI                     35.92     125.74      94.25      62.99      35.92
OBS BSFC           LBM/BHP-HR                      0.655      0.365      0.397      0.460      0.655
EXHAUST MOLE. WT.  LB/LB-MOLE           28.95      28.94      28.93      28.93      28.94      28.94      28.95
WET CORRECTION FACTOR    --           0.92702    0.93317    0.90097    0.91219    0.92715    0.93317    0.92044
HC EMISSION RATE         LB/HR        0.07130    0.04190    0.00519    0.00476    0.01763    0.04190    0.08953
HC MASS / MODE           LB           0.00119    0.00768    0.00003    0.00040    0.00176    0.00210    0.00149    0.01464
HC MASS / RATED HP       LB/HP                                                                                 0.00022
 HC - PERCENT OF EPA STANDARD                                                                                    11.49
CO EMISSION RATE         LB/HR        0.03459    0.00470    0.02282    0.01977    0.01588    0.00470    0.04348
CO MASS / MODE           LB           0.00058    0.00086    0.00011    0.00165    0.00159    0.00023    0.00072    0.00575
CO MASS / RATED HP       LB/HP                                                                                 0.00009
 CO - PERCENT OF EPA STANDARD                                                                                     0.20
NOX EMISSION RATE        LB/HR        0.01773    0.11887    0.93609    0.61245    0.36522    0.11887    0.01609
NOX MASS / MODE          LB           0.00030    0.02179    0.00468    0.05104    0.03652    0.00594    0.00027    0.12054
NOX MASS / RATED HP      LB/HP                                                                                 0.00180
 NOX- PERCENT OF EPA STANDARD                                                                                   119.76

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO      LB/LB        0.01550    0.02428    0.04058    0.03592    0.02846    0.02428    0.01574    0.02687 TA
DIFF. MEAS & CAL. F/A PERCENT            7.02       0.77       0.34       0.29       0.17       0.77       8.72       0.79 TA
```

TEXACO CONTROLLED COMBUSTION SYSTEM

CASE 3

DATA SOURCE: Southwest Research Institute (Ref. 5, p. B-12, Table B-16)

ENGINE DESCRIPTION:

Manufacturer: Plymouth (Cricket)
Cylinder Arrangement: I-4
Displacement (in^3): 141
Aspiration: Natural
Rated (Maximum) Power: 76 hp at 3000 rpm
Fuel: Diesel Fuel

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	900.
Taxi, In and Out	-	1200.	19.	1800.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	50.	100.%

ASSUMPTIONS:

- Equilibrium values of CO_2 and O_2 used for all modes.
- Fuel hydrogen to carbon ratio assumed to be 2.0.

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141 CID PLYMOUTH CRICKET WITH TEXACO CCS (DIESEL FUEL)
 PBARDAV                          FUEL HYDROGEN-   TAMB      RATED     CID          EXHAUST      AVG H2O IN AIR
IN HG ABS                          CARBON RATIO    DEG F      HP      INCH**3    C - H FORMULA      PERCENT
 29.000                               2.0000       73.00     76.40    141.00    1.000    1.850      0.794

                             UNITS     MODE 1     MODE 2     MODE 3     MODE 4     MODE 5     MODE 6     MODE 7     TOTAL
TIME IN MODE               MINUTES       1.00      11.00       0.30       5.00       6.00       3.00       1.00      27.30
FUEL FLOW                    LB/HR       1.85       8.47      28.84      22.49      16.93       8.47       1.72
AIR  FLOW                    LB/HR     101.87     314.87     633.72     586.09     549.04     314.87     101.87
HYDROCARBON CONC.         PPM-C       2624.00    1184.00      72.00      37.00      52.00    1184.00    1968.00
OXIDES OF NITROGEN CONC PPM             73.00     230.00    1140.00     849.00     614.00     230.00     110.00
CARBON MONOXIDE CONC. PERCENT            0.13       0.01       0.01       0.01       0.01       0.01       0.13
CARBON DIOXIDE CONC.  PERCENT            3.71       5.47       9.10       7.74       6.25       5.47       3.48
OXYGEN CONC.          PERCENT           14.90      12.20       6.15       8.60      10.95      12.20      15.30
PROP.  TORQUE            FT-LB                     42.36     133.88     100.38      66.94      42.36
PROP.  SPEED               RPM         900.00    1800.00    3000.00    3000.00    3000.00    1800.00     900.00

DRY BULB TEMP            DEG F          70.60      71.00      72.00      74.90      74.90      71.00      75.70
WET BULB TEMP            DEG F          60.00      60.00      60.00      60.00      60.00      60.00      60.00


FUEL AIR RATIO           LB/LB        0.01834    0.02712    0.04589    0.03867    0.03108    0.02712    0.01701    0.02962 TA
FUEL AIR EQUIVALENCE RATIO --            0.27       0.40       0.68       0.57       0.46       0.40       0.25       0.44 TA
ENGINE OBSERVED POWER       HP                     14.52      76.48      57.34      38.24      14.52
OBS BMEP                   PSI                     45.31     143.19     107.35      71 59      45.31
OBS BSFC           LBM/BHP-HR                      0.583      0.377      0.392      0.443      0.583
EXHAUST MOLE. WT.  LB/LB-MOLE           28.95      28.94      28.92      28.93      28.94      28.94      28.95
WET CORRECTION FACTOR   --            0.90483    0.92153    0.89044    0.90919    0.92401    0.92153    0.91008
HC EMISSION RATE         LB/HR        0.13044    0.18353    0.02288    0.01080    0.01411    0.18353    0.09770
HC MASS / MODE           LB           0.00217    0.03365    0.00011    0.00090    0.00141    0.00918    0.00163    0.04905
HC MASS / RATED HP       LB/HP                                                                                  0.00064
 HC - PERCENT OF EPA STANDARD                                                                                        79
CO EMISSION RATE         LB/HR        0.12926    0.01815    0.04684    0.03771    0.03013    0.01815    0.12959
CO MASS / MODE           LB           0.00215    0.00333    0.00023    0.00314    0.00301    0.00091    0.00216    0    .94
CO MASS / RATED HP       LB/HP                                                                                      .020
 CO - PERCENT OF EPA STANDARD                                                                                      0.47
NOX EMISSION RATE        LB/HR        0.01203    0.11822    1.20141    0.82165    0.55250    0.11822    0.01811
NOX MASS / MODE          LB           0.00020    0.02167    0.00601    0.06847    0.05525    0.00591    0.00030    0.15781
NOX MASS / RATED HP      LB/HP                                                                                  0.00207
 NOX- PERCENT OF EPA STANDARD                                                                                    137.71

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO      LB/LB        0.02045    0.02790    0.04676    0.03895    0.03129    0.02790    0.01889    0.03027 TA
DIFF. MEAS & CAL. F/A PERCENT           11.50       2.66       1.89       0.74       0.69       2.88      11.08       2.21 TA
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FOUR-STROKE DIESEL
CASE 1

DATA SOURCE: Southwest Research Institute (Ref. 10, pp. C-20 and C-25)
(Ref. 52)

ENGINE DESCRIPTION:

Manufacturer: International Harvester Company
Cylinder Arrangement: I-6
Displacement (in^3): 407
Aspiration: Natural
Rated (Maximum) Power: 112 hp at 2400 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	700.
Taxi, In and Out	-	1200.	11.	1800.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	73.	92.%
Approach	40.	87.%	47.	84.%

ASSUMPTIONS:

None

407 CID INTERNATIONAL FOUR-STROKE DIESEL

PBARCAV IN HG ABS	FUEL HYDROGEN-CARBON RATIO	TAMB DEG F	RATED HP	CID INCH**3	EXHAUST C - H FORMULA	AVG H2O IN AIR PERCENT
29.200	2.0000	74.00	113.00	407.00	1.000 1.850	1.161

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
TIME IN MODE	MINUTES	1.00	11.00	0.30	5.00	6.00	3.00	1.00	27.30
FUEL FLOW	LB/HR	1.70	9.10	46.60	34.10	22.40	9.10	1.70	
AIR FLOW	LB/HR	282.00	728.00	945.00	892.00	845.00	728.00	282.00	
HYDROCARBON CONC.	PPM-C	575.00	555.00	1040.00	660.00	630.00	555.00	575.00	
OXIDES OF NITROGEN CONC	PPM	116.00	177.00	1440.00	1154.00	538.00	177.00	116.00	
CARBON MONOXIDE CONC.	PERCENT	0.03	0.04	0.22	0.07	0.04	0.04	0.03	
CARBON DIOXIDE CONC.	PERCENT	1.41	2.51	8.73	7.62	5.40	2.51	1.41	
OXYGEN CONC.	PERCENT	18.30	17.50	6.30	9.10	12.50	17.50	18.30	
PROP. TORQUE	FT-LB		35.01	237.39	189.07	131.30	35.01		
PROP. SPEED	RPM	700.00	1800.00	2500.00	2300.00	2100.00	1800.00	700.00	
DRY BULB TEMP	DEG F	74.00	74.00	74.00	75.00	75.00	74.00	74.00	
WET BULB TEMP	DEG F	65.00	65.00	65.00	67.00	67.00	65.00	65.00	
INDUCTION'AIR TEMP	DEG F	74.00	74.00	74.00	75.00	75.0	74.00	74.00	
FUEL AIR RATIO	LB/LB	0.00610	0.01264	0.04986	0.03870	0.02684	0.01264	0.00610	0.02046 TA
FUEL AIR EQUIVALENCE RATIO	--	0.09	0.19	0.74	0.57	0.40	0.19	0.09	0.30 TA
ENGINE OBSERVED POWER	HP		12.00	113.00	82.80	52.50	12.00		
OBS BMEP	PSI		12.97	87.96	70.05	48.65	12.97		
OBS BSFC	LBM/BHP-HR		0.758	0.412	0.412	0.427	0.758		
EXHAUST MOLE. WT.	LB/LB-MOLE	28.96	28.96	28.92	28.93	28.94	28.96	28.96	
WET CORRECTION FACTOR	--	0.87436	0.96516	0.92018	0.91042	0.92337	0.96516	0.87436	
HC EMISSION RATE	LB/HR	0.07815	0.19603	0.49474	0.29313	0.26197	0.19603	0.07815	
HC MASS / MODE	LB	0.00130	0.03594	0.00247	0.02443	0.02620	0.00980	0.00130	0.10144
HC MASS / RATED HP	LB/HP								0.00090
HC - PERCENT OF EPA STANDARD									47.25
CO EMISSION RATE	LB/HR	0.08698	0.26454	2.09646	0.63121	0.32151	0.26454	0.08698	
CO MASS / MODE	LB	0.00145	0.04850	0.01048	0.05260	0.03215	0.01323	0.00145	0.15986
CO MASS / RATED HP	LB/HP								0.00141
CO - PERCENT OF EPA STANDARD									3.37
NOX EMISSION RATE	LB/HR	0.05228	0.20730	2.27151	1.69953	0.74183	0.20730	0.05228	
NOX MASS / MODE	LB	0.00087	0.03801	0.01136	0.14163	0.07418	0.01037	0.00087	0.27728
NOX MASS / RATED HP	LB/HP								0.00245
NOX- PERCENT OF EPA STANDARD									163.59
CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS									
CAL. FUEL AIR RATIO	LB/LB	0.00751	0.01243	0.04707	0.03833	0.02713	0.01243	0.00751	0.02043 TA
DIFF. MEAS & CAL. F/A PERCENT		23.29	-1.63	-5.60	-0.97	1.09	-1.63	23.29	-0.18 TA

FOUR-STROKE DIESEL

CASE 2

DATA SOURCE: Southwest Research Institute (Ref. 10, pp. C-48 and C-55) (Ref. 52)

ENGINE DESCRIPTION:

Manufacturer: Perkins Engines, Incorporated
Cylinder Arrangement: I-4
Displacement (in^3): 236
Aspiration: Natural
Rated (Maximum) Power: 76 hp at 2500 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	600.
Taxi, In and Out	-	1200.	9.	1450.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	67.	88.%
Approach	40.	87.%	45.	88.%

ASSUMPTIONS:

- Airflow for climb and approach modes determined as function of rpm.
- Equilibrium values of O_2 used for all modes.

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236 CID PERKINS FOUR-STROKE DIESEL

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 PBARCAV                      FUEL HYDROGEN-    TAMB      RATED      CID         EXHAUST      AVG H2O IN AIR
 IN HG ABS                     CARBON RATIO     DEG F      HP      INCH**3   C - H FORMULA       PERCENT
 29.300                           2.0000        72.30     75.60     236.00   1.000   1.850       1.161

                            UNITS     MODE 1     MODE 2     MODE 3     MODE 4     MODE 5     MODE 6     MODE 7      TOTAL
TIME IN MODE              MINUTES       1.00      11.00       0.30       5.00       6.00       3.00       1.00      27.30
FUEL FLOW                   LB/HR       0.70       4.20      30.20      18.60      12.80       4.20       0.70
AIR  FLOW                   LB/HR     157.00     385.00     580.00     522.00     522.00     385.00     157.00
HYDROCARBON CONC.         PPM-C       280.00     194.00      38.00     180.00     210.00     194.00     280.00
OXIDES OF NITROGEN CONC PPM            74.00     177.00    1793.00    1618.00     814.00     177.00      74.00
CARBON MONOXIDE CONC. PERCENT           0.02       0.03       0.34       0.01       0.02       0.03       0.02
CARBON DIOXIDE CONC.  PERCENT           1.18       2.10       9.99       7.51       5.21       2.10       1.18
OXYGEN CONC.          PERCENT          19.20      17.20       4.56       9.54      13.01      17.20      19.20
PROP.  TORQUE           FT-LB                    24.99     165.44     127.30      85.28      24.99
PROP.  SPEED              RPM         600.00    1450.00    2400.00    2100.00    2100.00    1450.00     600.00

DRY BULB TEMP           DEG F          75.00      75.00      75.00      73.00      73.00      75.00      75.00
WET BULB TEMP           DEG F          67.00      67.00      67.00      65.00      65.00      67.00      67.00

INDUCTION AIR TEMP      DEG F          75.00      75.00      75.00      73.00      73.00      75.00      75.00

FUEL AIR RATIO          LB/LB        0.00451    0.01104    0.05271    0.03604    0.02480    0.01104    0.00451    0.01862 TA
FUEL AIR EQUIVALENCE RATIO --           0.07       0.16       0.78       0.53       0.37       0.16       0.07       0.28 TA
ENGINE OBSERVED POWER      HP                     6.90      75.60      50.90      34.10       6.90
OBS BMEP                  PSI                    15.97     105.71      81.34      54.49      15.97
OBS BSFC           LBM/BHP-HR                    0.609      0.399      0.365      0.375      0.609
EXHAUST MOLE. WT.  LB/LB-MOLE          28.56      28.96      28.92      28.93      28.94      28.96      28.96
WET CORRECTION FACTOR   --           0.83060    0.97354    0.87977    0.89975    0.91705    0.97354    0.83060
HC EMISSION RATE        LB/HR        0.02115    0.03618    0.01113    0.04666    0.05384    0.03618    0.02115
HC MASS / MODE          LB           0.00035    0.00663    0.00006    0.00389    0.00538    0.00181    0.00035    0.01847
HC MASS / RATED HP      LB/HP                                                                                  0.00024
 HC - PERCENT OF EPA STANDARD                                                                                    12.86
CO EMISSION RATE        LB/HR        0.02791    0.10090    1.98881    0.06542    0.10972    0.10090    0.02791
CO MASS / MODE          LB           0.00047    0.01850    0.00994    0.00545    0.01097    0.00504    0.00047    0.05084
CO MASS / RATED HP      LB/HP                                                                                  0.00067
 CO - PERCENT OF EPA STANDARD                                                                                     1.60
NOX EMISSION RATE       LB/HR        0.01854    0.10945    1.74064    1.39085    0.69197    0.10945    0.01854
NOX MASS / MODE         LB           0.00031    0.02007    0.00870    0.11590    0.06920    0.00547    0.00031    0.21996
NOX MASS / RATED HP     LB/HP                                                                                  0.00291
 NOX- PERCENT OF EPA STANDARD                                                                                   193.97

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO     LB/LB        0.00598    0.01071    0.05305    0.03682    0.02562    0.01071    0.00598    0.01889 TA
DIFF. MEAS & CAL. F/A PERCENT          32.56      -3.01       0.64       2.17       3.31      -3.01      32.56       1.42 TA
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FOUR-STROKE DIESEL

CASE 3

DATA SOURCE: Southwest Research Institute (Ref. 5, p. B-2, Table B-3)

ENGINE DESCRIPTION:

Manufacturer: Nissan Motors - Datsun
Cylinder Arrangement: I-4
Displacement (in^3): 132
Aspiration: Natural
Rated (Maximum) Power: 70 hp at 4000 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	-	1150.
Taxi, In and Out	-	1200.	-	1150.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	50.	100.%

ASSUMPTIONS:

- Equilibrium values of CO_2 and O_2 used for all modes.
- Fuel hydrogen to carbon ratio assumed to be 2.0.

132 CID DATSUN FOUR-STROKE DIESEL

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 PBARUAV                         FUEL HYDROGEN-    TAMB       RATED      CID         EXHAUST      AVG H2O IN AIR
IN HG ABS                         CARBON RATIO     DEG F       HP       INCH**3   C - H FORMULA       PERCENT
 14.700                              2.0000        80.00      70.00     132.40    1.000    1.850       0.621

                           UNITS     MODE 1      MODE 2      MODE 3      MODE 4      MODE 5      MODE 6      MODE 7      TOTAL
TIME IN MODE             MINUTES       1.00       11.00        0.30        5.00        6.00        3.00        1.00      27.30
FUEL FLOW                  LB/HR       1.72        1.72       32.55       27.25       21.70        1.85        1.85
AIR  FLOW                  LB/HR     153.47      153.47      537.14      522.59      534.49      154.79      154.79
HYDROCARBON CONC.        PPM-C        24.00       24.00      160.00      128.00       80.00       48.00       48.00
OXIDES OF NITROGEN CONC PPM           98.00       98.00      441.00      488.00      437.00       78.00       78.00
CARBON MONOXIDE CONC. PERCENT          0.01        0.01        0.20        0.05        0.03        0.02        0.02
CARBON DIOXIDE CONC.  PERCENT          2.30        2.30       11.90       10.35        8.18        2.46        2.46
OXYGEN CONC.          PERCENT         17.10       17.10        1.65        4.30        7.95       16.90       16.90
PROP.  TORQUE            FT-LB                                91.96       69.01       45.98
PROP.  SPEED               RPM     1150.00     1150.00     4000.00     4000.00     4000.00     1150.00     1150.00

DRY BULB TEMP            DEG F        80.50       80.50       79.10       79.10       79.10       80.30       80.30
WET BULB TEMP            DEG F        60.00       60.00       60.00       60.00       60.00       60.00       60.00



FUEL AIR RATIO           LB/LB      0.01128     0.01128     0.06100     0.05249     0.04087     0.01203     0.01203     0.02599 TA
FUEL AIR EQUIVALENCE RATIO --          0.17        0.17        0.90        0.78        0.60        0.18        0.18        0.38 TA
ENGINE OBSERVED POWER       HP                                70.04       52.56       35.02
OBS BMEP                   PSI                               104.74       78.60       52.37
OBS BSFC           LBM/BHP-HR                                 0.465       0.518       0.620
EXHAUST MOLE. WT.  LB/LB-MOLE         28.96       28.96       28.91       28.92       28.93       28.96       28.96
WET CORRECTION FACTOR    --         0.96163     0.96163     0.86024     0.88111     0.90502     0.95887     0.95887
HC EMISSION RATE         LB/HR      0.00178     0.00178     0.04374     0.03377     0.02134     0.00360     0.00360
HC MASS / MODE           LB         0.00003     0.00033     0.00022     0.00281     0.00213     0.00018     0.00006     0.00576
HC MASS / RATED HP       LB/HP                                                                                      0.00008
 HC - PERCENT OF EPA STANDARD                                                                                          4.33
CO EMISSION RATE         LB/HR      0.01907     0.01907     1.09062     0.28918     0.15294     0.02288     0.02288
CO MASS / MODE           LB         0.00032     0.00350     0.00545     0.02410     0.01529     0.00114     0.00038     0.05018
CO MASS / RATED HP       LB/HP                                                                                      0.00072
 CO - PERCENT OF EPA STANDARD                                                                                          1.71
NOX EMISSION RATE        LB/HR      0.02416     0.02416     0.39980     0.42688     0.38654     0.01941     0.01941
NOX MASS / MODE          LB         0.00040     0.00443     0.00200     0.03557     0.03865     0.00097     0.00032     0.08235
NOX MASS / RATED HP      LB/HP                                                                                      0.00118
 NOX- PERCENT OF EPA STANDARD                                                                                         78.43

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO      LB/LB      0.01144     0.01144     0.06265     0.05328     0.04125     0.01223     0.01223     0.02633 TA
DIFF. MEAS & CAL. F/A PERCENT          1.47        1.47        2.70        1.50        0.92        1.72        1.72        1.34 TA
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TWO-STROKE DIESEL

DATA SOURCE: McCulloch Corporation (Ref. 53)

ENGINE DESCRIPTION:

Manufacturer: McCulloch Corporation
Cylinder Arrangement: Radial-4
Displacement (in^3): 180
Aspiration: Turbocharged
Rated (Maximum) Power: 116 hp at 2500 rpm

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	1.	770.
Taxi, In and Out	-	1200.	6.	1800.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	75.	100.%
Approach	40.	87.%	44.	72.%

ASSUMPTIONS:

- Engine rated at 180 hp at 2500 rpm but emissions data taken only up to 116 hp at 2500 rpm; assumed 116 hp at 2500 rpm as 100% BHP/100% rpm take-off mode.
- Equilibrium value of O_2 used for all modes.

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180 CID MC CULLOCH TWO-STROKE DIESEL

PBARO IN HG ABS	TDRY DEG F	TWET DEG F	FUEL HYDROGEN-CARBON RATIO	TAMB DEG F	RATED HP	CID INCH**3	EXHAUST C - H FORMULA		H2O IN AIR PERCENT
30.050	72.00	56.00	1.8000	72.00	116.00	180.00	1.000	1.650	0.700

	UNITS	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 7	TOTAL
TIME IN MODE	MINUTES	1.00	11.00	0.30	5.00	6.00	3.00	1.00	27.30
FUEL FLOW	LB/HR	2.61	8.07	55.20	40.40	28.30	8.07	2.61	
AIR FLOW	LB/HR	145.00	430.00	2256.00	1763.00	1006.00	430.00	145.00	
HYDROCARBON CONC.	PPM-C W	42.00	3360.00	760.00	846.00	1056.00	3360.00	42.00	
OXIDES OF NITROGEN CONC PPM W		86.00	65.00	220.00	209.00	179.00	65.00	86.00	
CARBON MONOXIDE CONC.	PERCENT	0.03	0.15	0.06	0.03	0.36	0.15	0.03	
CARBON DIOXIDE CONC.	PERCENT	3.80	3.90	5.00	4.70	5.60	3.90	3.80	
OXYGEN CONC.	PERCENT	15.60	15.60	13.60	14.40	12.80	15.60	15.80	
PROP. TORQUE	FT-LB	6.00	19.00	244.00	183.00	150.00	19.00	6.00	
PROP. SPEED	RPM	770.00	1800.00	2500.00	2500.00	1800.00	1800.00	770.00	
COOLING AIR TEMP	DEG F	72.00	72.00	72.00	72.00	72.00	72.00	72.00	
INDUCTION AIR TEMP	DEG F	72.00	72.00	72.00	72.00	72.00	72.00	72.00	
FUEL AIR RATIO	LB/LB	0.01813	0.01890	0.02464	0.02308	0.02833	0.01890	0.01813	0.07174 TA
FUEL AIR EQUIVALENCE RATIO	--	0.26	0.27	0.36	0.33	0.41	0.27	0.26	0.32 TA
ENGINE OBSERVED POWER	HP	0.88	6.51	116.15	87.11	51.41	6.51	0.88	
OBS BMEP	PSI	2.51	7.96	102.21	76.66	62.83	7.96	2.51	
OBS BSFC	LBM/BHP-HR	2.967	1.239	0.475	0.464	0.550	1.239	2.967	
EXHAUST MOLE. WT.	LB/LB-MOLE	28.95	28.95	28.94	28.95	28.94	28.95	28.95	
WET CORRECTION FACTOR	--	0.95967	0.91900	0.95030	0.95574	0.93133	0.91900	0.95967	
HC EMISSION RATE	LB/HR	0.00297	0.70545	0.86415	0.73131	0.82114	0.70545	0.00297	
HC MASS / MODE	LB	0.00005	0.12935	0.00432	0.06094	0.08211	0.03527	0.00005	0.31208
HC MASS / RATED HP	LB/HP								0.00269
HC - PERCENT OF EPA STANDARD									141.60
CO EMISSION RATE	LB/HR	0.04112	0.58427	1.27592	0.50036	3.35801	0.58427	0.04112	
CO MASS / MODE	LB	0.00069	0.10712	0.00638	0.04170	0.33580	0.02921	0.00069	0.52158
CO MASS / RATED HP	LB/HP								0.00450
CO - PERCENT OF EPA STANDARD									10.71
NOX EMISSION RATE	LB/HR	0.02017	0.04525	0.80821	0.59908	0.29432	0.04525	0.02017	
NOX MASS / MODE	LB	0.00034	0.00830	0.00404	0.04992	0.02943	0.00226	0.00034	0.09463
NOX MASS / RATED HP	LB/HP								0.00082
NOX- PERCENT OF EPA STANDARD									54.38
CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS									
CAL. FUEL AIR RATIO	LB/LB	0.01800	0.02069	0.02441	0.02272	0.02897	0.02069	0.01800	0.02272 TA
DIFF. MEAS & CAL. F/A PERCENT		-0.70	9.45	-0.95	-1.55	2.28	9.45	-0.70	4.51 TA

THERMAL FUEL VAPORIZATION

CASE 1

DATA SOURCE: Ethyl Corporation (Ref. 51)

ENGINE DESCRIPTION:

Manufacturer: Chevrolet
Cylinder Arrangement: V-8
Displacement (in^3): 350
Aspiration: Natural
Rated (Maximum) Power: 176 hp at 3600 rpm - standard induction system
183 hp at 3600 rpm - Ethyl TFS

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	2.	600.
Taxi, In and Out	-	1200.	3.	1200.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	80.	90.%
Approach	40.	87.%	40.	78.%

ASSUMPTIONS:

- NOx emission data not provided for take-off mode - used approach mode value.
- No data provided for climb mode - used take-off mode emission data and fuel-air ratio. Calculated climb mode air and fuel flows based on engine horsepower.

Engine Description: 1975 Chevrolet - 8.5 C.R. - Standard 4-Barrel Induction System

Engine Displacement: 350 CID

Engine Rated Brake H.P.:

Fuel Hydrogen-Carbon Ratio: 1.855 - Indolene + 3 gm/gal TEL

MODE NAME	ENGINE CONDITIONS REQUIRED		DATA REQUIRED													ACTUAL ENGINE CONDITIONS		
	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr) OR	MASS FUEL-AIR RATIO	INDUCTION AIR UPSTREAM			HC (ppm)	NOx (ppm)	CO (%)	CO_2 (%)	O_2 (%)	MANIFOLD PRESSURE (in. Hg abs)	ENGINE TORQUE (ft/lb)	ENGINE SPEED (rpm)	INDICATED H.P. OR FRICTIONAL H.P.
						TEMPERATURE (°F)	PRESSURE (in. Hg abs)	SPECIFIC HUMIDITY (grains/lb)									
Idle	-	600 rpm	5.0		17.11	97	29.46	48	299	50	0.09	12.80	3.60	15.1	29.7	596	
Taxi	-	1200 rpm	7.6		17.63	103	29.33	62	228	85	0.12	12.10	4.05	10.8	24.0	1204	
Take-Off	100	100%	98.4		12.46	94	29.22	80	396	-	5.35	11.85	0.18	27.8	257.1	3600	
Climb	80	90% of Max.															
Approach	50	77% of Max.	38.0		15.89	106	29.34	58	164	2525	0.28	13.50	2.15	18.4	137.6	2800	

NOTES:

HC - Total hydrocarbons in ppm Cx Hy by volume - Undiluted (or) gm/hr of Cx Hy (define x and y) x = 6
NOx - Total oxides of nitrogen in ppm by volume - Undiluted (or) gm/hr of NOx (define x) x = 1
CO - Carbon monoxide in ppm or % by volume - Undiluted (or) gm/hr of CO
CO_2 - Carbon dioxide in ppm or % by volume - Undiluted (or) gm/hr of CO_2
O_2 - Oxygen in ppm or % by volume - Undiluted (or) gm/hr of O_2

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350 CID CHEVROLET WITH STANDARD INTAKE MANIFOLD

  PBARO      TDRY       TWET   FUEL HYDROGEN-    TAMB      RATED      CID         EXHAUST        H2O IN AIR
IN HG ABS   DEG F      DEG F    CARBON RATIO    DEG F        HP     INCH**3    C - H FORMULA       PERCENT
 29.300    100.00      70.20       1.8550      100.00     176.20     350.00    1.000   1.850        0.890

                             UNITS     MODE 1     MODE 2     MODE 3     MODE 4     MODE 5     MODE 6     MODE 7      TOTAL
TIME IN MODE               MINUTES       1.00      11.00       0.30       5.00       6.00       3.00       1.00      27.30
FUEL FLOW                    LB/HR       5.00       7.60      98.40      81.96      38.00       7.60       5.00
AIR  FLOW                    LB/HR      85.55     133.99    1226.06    1021.00     603.82     133.99      85.55
HYDROCARBON CONC.         PPM-C       1794.00    1368.00    2376.00    2376.00     984.00    1368.00    1794.00
OXIDES OF NITROGEN CONC PPM             50.00      85.00    2525.00    2525.00    2525.00      85.00      50.00
CARBON MONOXIDE CONC. PERCENT            0.09       0.12       5.35       5.35       0.28       0.12       0.09
CARBON DIOXIDE CONC.  PERCENT           12.80      12.10      11.85      11.85      13.50      12.10      12.80
OXYGEN CONC.          PERCENT            3.60       4.05       0.18       0.18       2.15       4.05       3.60
PROP.  TORQUE            FT-LB          29.70      24.00     257.10     228.53     137.60      24.00      29.70
PROP.  SPEED               RPM         596.00    1204.00    3600.00    3240.00    2800.00    1204.00     596.00
MFLD PRESSURE   IN HG ABS DRY           15.10      10.80      27.80      27.80      18.40      10.80      15.10


INDUCTION AIR TEMP       DEG F         100.00     100.00     100.00     100.00     100.00     100.00     100.00

FUEL AIR RATIO           LB/LB        0.05897    0.05723    0.08098    0.08099    0.06350    0.05723    0.05897    0.06335 TA
FUEL AIR EQUIVALENCE RATIO --            0.86       0.83       1.18       1.18       0.93       0.83       0.86       0.92 TA
ENGINE OBSERVED POWER       HP           3.37       5.50     176.23     140.98      73.36       5.50       3.37
OBS BMEP                   PSI          12.80      10.34     110.77      96.46      59.29      10.34      12.80
OBS BSFC            LBM/BHP-HR          1.484      1.381      0.558      0.581      0.518      1.381      1.484
EXHAUST MOLE. WT.  LB/LB-MOLE           28.91      28.92      27.92      27.92      28.91      28.92      28.91
WET CORRECTION FACTOR    --           0.88391    0.88957    0.86911    0.86919    0.88059    0.88957    0.88391
HC EMISSION RATE         LB/HR        0.06890    0.08268    1.35925    1.13208    0.26691    0.08268    0.06890
HC MASS / MODE           LB           0.00115    0.01516    0.00680    0.09434    0.02669    0.00413    0.00115    0.14942
HC MASS / RATED HP       LB/HP                                                                                 0.00085
 HC - PERCENT OF EPA STANDARD                                                                                    44.63
CO EMISSION RATE         LB/HR        0.06978    0.14641   61.78664   51.46022    1.53327    0.14641    0.06978
CO MASS / MODE           LB           0.00116    0.02684    0.30893    4.28835    0.15333    0.00732    0.00116    4.78710
CO MASS / RATED HP       LB/HP                                                                                 0.02717
 CO - PERCENT OF EPA STANDARD                                                                                    64.69
NOX EMISSION RATE        LB/HR        0.00637    0.01703    4.78986    3.98933    2.27112    0.01703    0.00637
NOX MASS / MODE          LB           0.00011    0.00312    0.02395    0.33244    0.22711    0.00085    0.00011    0.58769
NOX MASS / RATED HP      LB/HP                                                                                 0.00334
 NOX- PERCENT OF EPA STANDARD                                                                                   222.36

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO      LB/LB        0.05862    0.05682    0.08051    0.08051    0.06300    0.05682    0.05862    0.06291 TA
DIFF. MEAS & CAL. F/A PERCENT           -0.59      -0.72      -0.58      -0.60      -0.78      -0.72      -0.59      -0.69 TA
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Engine Description: 1975 Chevrolet - 8.5 C.R. - TFM with 4-Barrel Carburetor
Engine Displacement: 350 CID
Engine Rated Brake H.P.:
Fuel Hydrogen-Carbon Ratio: 1.967 - Indolene + 3 gm/gal TEL

MODE NAME	ENGINE CONDITIONS REQUIRED		DATA REQUIRED												ACTUAL ENGINE CONDITIONS		
						INDUCTION AIR UPSTREAM											
	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr) OR	MASS FUEL-AIR RATIO	TEMPERATURE (°F)	PRESSURE (in. Hg abs)	SPECIFIC HUMIDITY (grains/lb)	HC (ppm)	NOx (ppm)	CO (%)	CO_2 (%)	O_2 (%)	MANIFOLD PRESSURE (in. Hg abs)	ENGINE TORQUE (ft/lb)	ENGINE SPEED (rpm)	INDICATED H.P. OR FRICTIONAL H.P.
Idle	-	600 rpm	5.1		17.26	96	29.18	37	228	60	0.10	12.50	3.50	14.7	29.8	602	
Taxi	-	1200 rpm	7.7		17.62	94	29.18	21	141	83	0.11	12.25	4.00	10.7	24.3	1202	
Take-Off	100	100%	96.5		12.26	98	28.98	28	275	-	5.9	11.60	0.10	27.9	266.2	3603	
Climb	90	90% of Max.															
Approach	50	77% of Max.	36.8		16.06	104	29.60	14	77	2800	0.13	13.40	2.00	18.8	137.3	2800	

NOTES:

HC - Total hydrocarbons in ppm Cx Hy by volume - Undiluted (or) gm/hr of Cx Hy (define x and y) x = 6
NOx - Total oxides of nitrogen in ppm by volume - Undiluted (or) gm/hr of NOx (define x) x = 1
CO - Carbon monoxide in ppm or % by volume - Undiluted (or) gm/hr of CO
CO_2 - Carbon dioxide in ppm or % by volume - Undiluted (or) gm/hr of CO_2
O_2 - Oxygen in ppm or % by volume - Undiluted (or) gm/hr of O_2

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350 CID CHEVROLET WITH ETHYL TURBULENT FLOW MANIFOLD

  PBARO      TDRY       TWET   FUEL HYDROGEN-    TAMB       RATED      CID        EXHAUST        H2O IN AIR
IN HG ABS   DEG F      DEG F    CARBON RATIO     DEG F       HP      INCH**3    C - H FORMULA     PERCENT
 29.200     58.00      62.00      1.9670         98.00      182.60    350.00   1.000    1.850      0.365

                             UNITS     MODE 1      MODE 2      MODE 3      MODE 4      MODE 5      MODE 6      MODE 7      TOTAL
TIME IN MODE               MINUTES       1.00       11.00        0.30        5.00        6.00        3.00        1.00      27.30
FUEL FLOW                    LB/HR       5.10        7.70       96.50       80.85       36.80        7.70        5.10
AIR  FLOW                    LB/HR      88.03      135.67     1183.09      991.00      591.01      135.67       88.03
HYDROCARBON CONC.         PPM-C       1368.00      846.00     1650.00     1650.00      462.00      846.00     1368.00
OXIDES OF NITROGEN CONC PPM            60.00       83.00     2800.00     2800.00     2800.00       83.00       60.00
CARBON MONOXIDE CONC. PERCENT           0.10        0.11        5.90        5.90        0.13        0.11        0.10
CARBON DIOXIDE CONC.  PERCENT          12.50       12.25       11.60       11.60       13.40       12.25       12.50
OXYGEN CONC.          PERCENT           3.50        4.00        0.10        0.10        2.00        4.00        3.50
PROP.  TORQUE            FT-LB         29.80       24.30      266.20      236.62      137.30       24.30       29.80
PROP.  SPEED               RPM        602.00     1202.00     3603.00     3242.70     2800.00     1202.00      602.00
MFLD PRESSURE    IN HG ABS DRY         14.70       10.70       27.90       27.90       18.80       10.70       14.70


INDUCTION AIR TEMP        DEG F        98.00       98.00       98.00       98.00       98.00       98.00       98.00

FUEL AIR RATIO            LB/LB      0.05815     0.05696     0.08186     0.08188     0.06249     0.05696     0.05815    0.06310 TA
FUEL AIR EQUIVALENCE RATIO --           0.86        0.84        1.21        1.21        0.92        0.84        0.86       0.93 TA
ENGINE OBSERVED POWER        HP         3.42        5.56      182.62      146.09       73.20        5.56        3.42
OBS BMEP                    PSI        12.84       10.47      114.69      101.95       59.16       10.47       12.84
OBS BSFC            LBM/BHP-HR         1.493       1.385       0.528       0.553       0.503       1.385       1.493
EXHAUST MOLE. WT.  LB/LB-MOLE          28.91       28.91       27.78       27.78       28.91       28.91       28.91
WET CORRECTION FACTOR     --         0.88612     0.89110     0.87178     0.87186     0.88202     0.89110     0.88612
HC EMISSION RATE          LB/HR      0.05417     0.05186     0.91919     0.77007     0.12278     0.05186     0.05417
HC MASS / MODE            LB         0.00090     0.00951     0.00460     0.06417     0.01228     0.00259     0.00090    0.09495
HC MASS / RATED HP        LB/HP                                                                                   0.00052
 HC - PERCENT OF EPA STANDARD                                                                                       27.37
CO EMISSION RATE          LB/HR      0.07994     0.13614    66.35297    55.56820     0.69745     0.13614     0.07994
CO MASS / MODE            LB         0.00133     0.02496     0.33176     4.63235     0.06975     0.00681     0.00133    5.06829
CO MASS / RATED HP        LB/HP                                                                                   0.02776
 CO - PERCENT OF EPA STANDARD                                                                                       66.09
NOX EMISSION RATE         LB/HR      0.00788     0.01687     5.17234     4.33320     2.46745     0.01687     0.00788
NOX MASS / MODE           LB         0.00013     0.00309     0.02586     0.36110     0.24675     0.00084     0.00013    0.63791
NOX MASS / RATED HP       LB/HP                                                                                   0.00349
 NOX- PERCENT OF EPA STANDARD                                                                                      232.90

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO       LB/LB      0.05806     0.05638     0.08076     0.08076     0.06225     0.05638     0.05806    0.06253 TA
DIFF. MEAS & CAL. F/A PERCENT          -0.15       -1.02       -1.35       -1.37       -0.39       -1.02       -0.15      -0.91 TA
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THERMAL FUEL VAPORIZATION

CASE 2

DATA SOURCE: Ethyl Corporation (Ref. 51)

ENGINE DESCRIPTION:

Manufacturer: BMW
Cylinder Arrangement: I-4
Displacement (in^3): 121.3
Aspiration: Natural
Rated (Maximum) Power: 100 hp at 5200 rpm - Standard induction system
103 hp at 5200 rpm - Ethyl TFS

OPERATING CONDITIONS:

MODE	REQUIRED		ACTUAL	
	BHP (%)	rpm	BHP (%)	rpm
Idle, In and Out	-	600.	1.	950.
Taxi, In and Out	-	1200.	6.	1600.
Take-Off	100.	100.%	100.	100.%
Climb	80.	90.%	80.	90.%
Approach	40.	87.%	31.	69.%

ASSUMPTIONS:

- NOx emission data not provided for take-off mode - used approach mode value.
- No emission data provided for climb mode - used take-off mode data and fuel-air ratio. Calculated climb mode air and fuel flows based on engine horsepower.

Engine Description: 1973 BMW 4-Cylinder - 9.0 C.R. - Production Intake System with Staged 2-Barrel Carburetor
Engine Displacement: 121.3 CID (1988 CC)
Engine Rated Brake H.P.:
Fuel Hydrogen-Carbon Ratio: 1.855 - Indolene + 3 gm/gal TEL

MODE NAME	ENGINE CONDITIONS REQUIRED		DATA REQUIRED												ACTUAL ENGINE CONDITIONS		
	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr) OR	MASS FUEL-AIR RATIO	INDUCTION AIR UPSTREAM TEMPERATURE (°F)	INDUCTION AIR UPSTREAM PRESSURE (in. Hg abs)	INDUCTION AIR UPSTREAM SPECIFIC HUMIDITY (grains/lb)	HC (ppm)	NOx (ppm)	CO (%)	CO_2 (%)	O_2 (%)	MANIFOLD PRESSURE (in. Hg abs)	ENGINE TORQUE (ft/lb)	ENGINE SPEED (rpm)	INDICATED H.P. OR FRICTIONAL H.P.
Idle	-	600 rpm	2.5		13.98	89	29.17	38	561	90	2.00	13.65	0.70	10.17	2.5	950	
Taxi	-	1200 rpm	5.0		13.35	89	29.17	38	604	245	2.90	13.90	0.30	11.17	18.0	1600	
Take-Off	100	100%	49.2		12.93	92	28.81	46	407	-	4.05	12.80	0.15	27.01	101.4	5200	
Climb	90	90% of Max.															
Approach	40	69% of Max.	17.3		14.48	95	29.40	22	414	1950	1.30	13.80	0.95	16.80	45.6	3600	

NOTES:

HC	- Total hydrocarbons in ppm Cx Hy by volume	- Undiluted	(or) gm/hr of Cx Hy	(define x and y)	x = 6
NOx	- Total oxides of nitrogen in ppm by volume	- Undiluted	(or) gm/hr of NOx	(define x)	x = 1
CO	- Carbon monoxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO		
CO_2	- Carbon dioxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO_2		
O_2	- Oxygen in ppm or % by volume	- Undiluted	(or) gm/hr of O_2		

121 CID BMW WITH STANDARD INTAKE MANIFOLD

```
  PBARO      TDRY       TWET    FUEL HYDROGEN-      TAMB       RATED       CID          EXHAUST          H2O IN AIR
IN HG ABS   DEG F      DEG F     CARBON RATIO      DEG F        HP       INCH**3     C - H FORMULA        PERCENT
 29.140     91.30      62.20       1.8550          91.30      100.40      121.30     1.000    1.850         0.528

                             UNITS      MODE 1      MODE 2      MODE 3      MODE 4      MODE 5      MODE 6      MODE 7       TOTAL
TIME IN MODE               MINUTES        1.00       11.00        0.30        5.00        6.00        3.00        1.00       27.30
FUEL FLOW                    LB/HR        2.50        5.00       49.20       41.81       17.30        5.00        2.50
AIR  FLOW                    LB/HR       34.95       66.75      636.16      541.00      250.50       66.75       34.95
HYDROCARBON CONC.           PPM-C      3366.00     3624.00     2442.00     2442.00     2484.00     3624.00     3366.00
OXIDES OF NITROGEN CONC PPM              90.00      245.00     1950.00     1950.00     1950.00      245.00       90.00
CARBON MONOXIDE CONC. PERCENT             2.00        2.90        4.05        4.05        1.30        2.90        2.00
CARBON DIOXIDE CONC.  PERCENT            13.65       12.90       12.80       12.80       13.80       12.90       13.65
OXYGEN CONC.          PERCENT             0.70        0.30        0.15        0.15        0.95        0.30        0.70
PROP.  TORQUE           FT-LB             2.50       18.00      101.40       90.14       45.60       18.00        2.50
PROP.  SPEED              RPM           950.00     1600.00     5200.00     4680.00     3600.00     1600.00      950.00
MFLD PRESSURE   IN HG ABS DRY            10.17       11.17       27.01       27.01       16.80       11.17       10.17


INDUCTION AIR TEMP       DEG F           91.30       91.30       91.30       91.30       91.30       91.30       91.30

FUEL AIR RATIO           LB/LB         0.07191     0.07530     0.07775     0.07769     0.06943     0.07530     0.07191   0.07423 TA
FUEL AIR EQUIVALENCE RATIO --             1.05        1.10        1.13        1.13        1.01        1.10        1.05      1.08 TA
ENGINE OBSERVED POWER       HP            0.45        5.48      100.40       80.32       31.26        5.48        0.45
OBS BMEP                   PSI            3.11       22.38      126.06      112.06       56.69       22.38        3.11
OBS BSFC            LBM/BHP-HR           5.528       0.912       0.490       0.521       0.553       0.912       5.528
EXHAUST MOLE. WT.  LB/LB-MOLE            28.63       28.36       28.17       28.17       28.83       28.36       28.63
WET CORRECTION FACTOR     --           0.87083     0.87227     0.87036     0.87011     0.87495     0.87227     0.87083
HC EMISSION RATE         LB/HR         0.05320     0.11097     0.71755     0.60991     0.28011     0.11097     0.05320
HC MASS / MODE           LB            0.00089     0.02034     0.00359     0.05083     0.02801     0.00555     0.00089     0.11009
HC MASS / RATED HP       LB/HP                                                                                          0.00110
 HC - PERCENT OF EPA STANDARD                                                                                             57.71
CO EMISSION RATE         LB/HR         0.63814     1.79266    24.02402    20.42030     2.95937     1.79266     0.63814
CO MASS / MODE           LB            0.01064     0.32865     0.12012     1.70169     0.29594     0.08963     0.01064     2.55730
CO MASS / RATED HP       LB/HP                                                                                          0.02547
 CO - PERCENT OF EPA STANDARD                                                                                             60.65
NOX EMISSION RATE        LB/HR         0.00472     0.02488     1.89996     1.61496     0.72914     0.02488     0.00472
NOX MASS / MODE          LB            0.00008     0.00456     0.00950     0.13458     0.07291     0.00124     0.00008     0.22296
NOX MASS / RATED HP      LB/HP                                                                                          0.00222
 NOX- PERCENT OF EPA STANDARD                                                                                            148.04

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO      LB/LB         0.07201     0.07544     0.07760     0.07760     0.06943     0.07544     0.07201   0.07429 TA
DIFF. MEAS & CAL. F/A PERCENT             0.13        0.18       -0.19       -0.12        0.01        0.18        0.13      0.08 TA
```

Engine Description: 1973 BMW - 4-Cylinder - 9.0 C.R. - TFM with Staged 2-Barrel Carburetor

Engine Displacement: 121.3 CID (1988 CC)

Engine Rated Brake H.P.:

Fuel Hydrogen-Carbon Ratio: 1.855 - Indolene + 3 gm/gal TEL

	ENGINE CONDITIONS REQUIRED		DATA REQUIRED												ACTUAL ENGINE CONDITIONS		
						INDUCTION AIR UPSTREAM											
MODE NAME	ENGINE BRAKE HORSEPOWER (%)	ENGINE SPEED	FUEL FLOW (lb/hr)	AIR FLOW (lb/hr) OR	MASS FUEL-AIR RATIO	TEMPERATURE (°F)	PRESSURE (in. Hg abs)	SPECIFIC HUMIDITY (grains/lb)	HC (ppm)	NOx (ppm)	CO (%)	CO_2 (%)	O_2 (%)	MANIFOLD PRESSURE (in. Hg abs)	ENGINE TORQUE (ft/lb)	ENGINE SPEED (rpm)	INDICATED H.P. OR FRICTIONAL H.P.
Idle	-	600 rpm	2.5		15.86	93	29.40	25	190	135	0.17	13.8	2.00	12.10	3.2	950	
Taxi	-	1200 rpm	5.0		15.18	94	29.40	25	360	620	0.30	14.25	1.25	12.20	16.4	1600	
Take-Off	100	100%	49.5		12.88	83	29.30	34	372	-	4.15	12.10	2.30	27.00	103.5	5200	
Climb	80	90% of Max.															
Approach	40	87% of Max.	17.6		18.19	96	29.39	53	243	600	0.16	11.75	4.60	20.89	44.6	3600	

NOTES:

HC	- Total hydrocarbons in ppm Cx Hy by volume	- Undiluted	(or) gm/hr of Cx Hy	(define x and y)	x = 6
NOx	- Total oxides of nitrogen in ppm by volume	- Undiluted	(or) gm/hr of NOx	(define x)	x = 1
CO	- Carbon monoxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO		
CO_2	- Carbon dioxide in ppm or % by volume	- Undiluted	(or) gm/hr of CO_2		
O_2	- Oxygen in ppm or % by volume	- Undiluted	(or) gm/hr of O_2		

```
121 CID BMW WITH ETHYL TURBULENT FLOW MANIFOLD

  PBARO      TDRY       TWET   FUEL HYDROGEN-    TAMB       RATED      CID         EXHAUST        H2O IN AIR
IN HG ABS   DEG F      DEG F    CARBON RATIO     DEG F        HP      INCH**3    C - H FORMULA      PERCENT
 29.400     91.50      62.00      1.8550         91.50      102.50    123.30     1.000   1.850       0.511

                                   UNITS      MODE 1      MODE 2      MODE 3      MODE 4      MODE 5      MODE 6      MODE 7       TOTAL
TIME IN MODE                     MINUTES        1.00       11.00        0.30        5.00        6.00        3.00        1.00       27.30
FUEL FLOW                          LB/HR        2.50        5.00       49.50       46.33       17.60        5.00        2.50
AIR  FLOW                          LB/HR       39.65       75.90      637.56      597.00      320.14       75.90       39.65
HYDROCARBON CONC.                  PPM-C     1140.00     2160.00     2232.00     2232.00     1458.00     2160.00     1140.00
OXIDES OF NITROGEN CONC PPM                   135.00      620.00      620.00      620.00      600.00      620.00      135.00
CARBON MONOXIDE CONC.            PERCENT        0.17        0.30        4.15        4.15        0.16        0.30        0.17
CARBON DIOXIDE CONC.             PERCENT       13.80       14.25       12.10       12.10       11.75       14.25       13.80
OXYGEN CONC.                     PERCENT        2.00        1.25        2.30        2.30        4.60        1.25        2.00
PROP.  TORQUE                      FT-LB        3.20       18.40      103.50       92.00       44.60       18.40        3.20
PROP.  SPEED                         RPM      950.00     1600.00     5200.00     4680.00     3600.00     1600.00      950.00
MFLD PRESSURE              IN HG ABS DRY       12.10       12.20       27.00       27.00       20.89       12.20       12.10


INDUCTION AIR TEMP                 DEG F       91.50       91.50       91.50       91.50       91.50       91.50       91.50

FUEL AIR RATIO                     LB/LB     0.06338     0.06621     0.07804     0.07800     0.05526     0.06621     0.06338  0.06589 TA
FUEL AIR EQUIVALENCE RATIO --                   0.92        0.97        1.14        1.14        0.81        0.97        0.92     0.96 TA
ENGINE OBSERVED POWER                 HP        0.58        5.61      102.48       81.98       30.57        5.61        0.58
OBS BMEP                             PSI        3.91       22.50      126.58      112.52       54.55       22.50        3.91
OBS BSFC                      LBM/BHP-HR       4.319       0.892       0.483       0.565       0.576       0.892       4.319
EXHAUST MOLE. WT.             LB/LB-MOLE       28.91       28.91       28.14       28.15       28.92       28.91       28.91
WET CORRECTION FACTOR            --          0.87942     0.87496     0.90742     0.90726     0.89490     0.87496     0.87942
HC EMISSION RATE                   LB/HR     0.02028     0.07339     0.68601     0.64217     0.21144     0.07339     0.02028
HC MASS / MODE                     LB        0.00034     0.01345     0.00343     0.05351     0.02114     0.00367     0.00034     0.09589
HC MASS / RATED HP                 LB/HP                                                                                     0.00094
 HC - PERCENT OF EPA STANDARD                                                                                                  49.24
CO EMISSION RATE                   LB/HR     0.06105     0.20576    25.74953    24.10400     0.46842     0.20576     0.06105
CO MASS / MODE                     LB        0.00102     0.03772     0.12875     2.00867     0.04684     0.01029     0.00102     2.23430
CO MASS / RATED HP                 LB/HP                                                                                     0.02180
 CO - PERCENT OF EPA STANDARD                                                                                                  51.90
NOX EMISSION RATE                  LB/HR     0.00796     0.06985     0.63188     0.59150     0.28853     0.06985     0.00796
NOX MASS / MODE                    LB        0.00013     0.01281     0.00316     0.04929     0.02885     0.00349     0.00013     0.09787
NOX MASS / RATED HP                LB/HP                                                                                     0.00095
 NOX- PERCENT OF EPA STANDARD                                                                                                  63.65

CALCULATED FUEL AIR RATIO FROM EXHAUST GAS ANALYSIS
CAL. FUEL AIR RATIO                LB/LB     0.06337     0.06639     0.07095     0.07095     0.05526     0.06639     0.06337  0.06461 TA
DIFF. MEAS & CAL. F/A PERCENT                  -0.01        0.26       -9.08       -9.04       -0.00        0.26       -0.01    -1.95 TA
```

Additional firms were contacted (Refs. 55 through 66) but were unable to provide emissions data due to proprietary reasons or lack of suitable data.

APPENDIX B. EXHAUST EMISSIONS CALCULATION PROCEDURE

I. THE COMBUSTION EQUATION

The chemical equation for the combustion of a hydrocarbon fuel in air can be represented symbolically by:

Fuel + Air ⟶ Products of Combustion

To be able to deal mathematically with the combustion equation, it must be written in a form such that the coefficients, representing the quantities of each constituent, are known by virtue of measurement or are calculable using the principles of mass conservation or chemical equilibrium.

The combustion equation used as the basis for the emissions calculations is:

$$(M_f)\cdot\overbrace{C_x\,H_y}^{\text{Fuel}} + (M_a)\,\overbrace{[O_2 + (3.72744)\,N_2 + (0.04451)\,Ar]}^{\text{Air}} + (M_w)\cdot\overbrace{H_2O}^{\text{Atmospheric Humidity}} \longrightarrow$$

$$\longrightarrow (M_1)\cdot H_2O + (M_2)\cdot CO_2 + (M_3)\cdot CO + (M_4)\cdot NO + (M_5)\cdot O_2 +$$

$$+ (M_6)\cdot C_p\,H_q + (M_7)\cdot H_2 + (M_8)\cdot N_2 + (M_9)\cdot Ar + (M_{10})\cdot NO_2 +$$

$$+ (M_{11})\cdot C$$

where

M_i is the number of lbm-moles of the ith constituent. One lbm-mole (pound-mass mole) of a substance is a quantity of that substance in pounds-mass, numerically equal to the molecular weight of the substance in atomic mass units. One lbm-mole of water (H_2O), therefore, would have a mass of (2) (1.008) + 16 = 18.016 lbm.

$C_x\,H_y$ - a pure hydrocarbon fuel containing x atoms of carbon and y atoms of hydrogen in each molecule

O_2 - oxygen

N_2 - nitrogen

Ar - argon

H_2O - water (vapor)

CO_2 - carbon dioxide

CO - carbon monoxide

NO - nitric oxide

NO_2 - nitrogen dioxide

$C_p H_q$ - unburned hydrocarbon exhaust product containing p atoms of carbon and q atoms of hydrogen in each molecule

H_2 - hydrogen

C - solid carbon

TCM represents the fuel, C_xH_y, as a pure hydrocarbon molecule. Fuel additives containing elements other than hydrogen and carbon such as antiknock agents, deposit modifiers, detergents, etc. are ignored in the combustion equation since they are deemed negligible. The fuel molecule, C_xH_y, then is representative of a nominal or average hydrocarbon molecule with a ratio of hydrogen to carbon atoms of y/x. Although the actual values of y and x for the gasoline vary considerably and no specific values can be assigned to them in our simplified fuel molecule, the ratio of hydrogen to carbon atoms in 100/130 octane aviation gasoline can be measured and remains relatively constant at a value of about 2.125.

Likewise, the unburned hydrocarbon constituent in the exhaust may contain several species of hydrocarbons, but a ratio of q/p of 1.85 has been suggested to represent the average ratio of hydrogen to carbon in the exhaust hydrocarbon pollutant. This value, however, for the purpose of this analysis will be considered unknown.

II. BALANCING THE COMBUSTION EQUATION

By the principle of conservation of mass, we know that the atomic quantities introduced into the engine induction system must also be present in the exhaust even though they are rearranged into different molecules by the combustion chemical reaction. Hence, all the carbon atoms entering the engine in the form of hydrocarbon fuel molecules must be present in the exhaust in the form of CO, CO_2, and $C_p H_q$. This atom-balancing technique provides us with a system of equations by which we may solve for unknown quantities.

Going back to the original combustion equation, we eliminate solid carbon, C, and nitrogen dioxide, NO_2 (it has been found that NO_2 does not exist in any significant quantity for our engines), and then divide each molar value on both sides of the equation by the sum of the molar values on the right-hand side. The equation then becomes

$$(m_f) \cdot C_x H_y + (m_a) [O_2 + (3.72744) N_2 + (0.04451) Ar] + (m_w) \cdot H_2O \longrightarrow$$

$$(m_1) \cdot H_2O + (m_2) \cdot CO_2 + (m_3) \cdot CO + (m_4) \cdot NO + (m_5) \cdot O_2 +$$

$$(m_6) \cdot C_p H_q + (m_7) \cdot H_2 + (m_8) \cdot N_2 + (m_9) \cdot Ar$$

where

$$m_i = \frac{M_i}{M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9}\ .$$

Thus, every molar coefficient on the right-hand side of the equation is now expressed in mole fractions such that

$$m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9 = 1.0.$$

This is done for convenience, and the reason for it will be demonstrated later.

The nine products of combustion represent an estimated 99.998% of the chemical composition of an equilibrium mixture at exhaust gas temperatures below 3,000°R.

An oxygen balance results in Equation (1):

$$2\ m_a + m_w = m_1 + 2m_2 + m_3 + m_4 + 2m_5$$

or

$$m_1 = 2m_a + m_w - 2m_2 - m_3 - m_4 - 2m_5 \qquad (1)$$

A carbon balance gives Equation (2):

$$x \cdot m_f = m_2 + m_3 + p \cdot m_6$$

or

$$m_f = \frac{m_2 + m_3 + p \cdot m_6}{x} \qquad (2)$$

Since our measurement of $C_p\ H_q$ is in parts per million carbon equivalent, we can represent $C_p\ H_q$ as $CH_{q/p}$. Equation (2) then becomes

$$m_f = \frac{m_2 + m_3 + m_6}{x} \qquad (2)$$

The remaining atomic balances are as follows:

Hydrogen Balance: $y \cdot m_f + 2m_w = 2m_1 + \frac{q}{p} m_6 + 2m_7$ (3)

Nitrogen Balance: $(3.72744)\ (2)\ m_a = m_4 + 2m_8$ (4)

Argon Balance: $(0.04451)\ m_a = m_9.$ (5)

III. THE WATER CORRECTION FACTOR

Since CO, CO_2, and O_2 are measured on a dry volumetric basis (the water vapor being removed from the exhaust sample before measurement), and HC and NO are measured on a wet volumetric basis, we must determine the amount of water vapor removed from the dry sample in order to correct all measured values to either a dry or a wet volumetric basis for calculative purposes. In doing this, we are solving for one of the unknowns, i.e., m_1 (H_2O).

We can define the fuel to dry air mass ratio as

$$\frac{f}{A} = \frac{m_f\ (12.011\ x + 1.008\ y)}{m_a\ (138.2689)} \tag{6}$$

where

(12.011 x + 1.008 y) = fuel molecular weight

and

138.2689 = pounds-mass of air
per lbm-mole of oxygen.

The specific humidity, or water vapor to dry air mass ratio is

$$\frac{W}{A} = \frac{m_w\ (18.016)}{m_a\ (138.2689)} \quad . \tag{7}$$

By substituting Equations (2), (6), and (7) into Equation (1) and rearranging the terms, we have

$$m_1 = \left[2 + 7.67478\ \frac{W}{A}\right] \frac{(m_2 + m_3 + m_6)\ (12.011 + 1.008\ \frac{y}{x})}{138.2689\ (f/A)}$$

$$- 2m_2 - m_3 - m_4 - 2m_5 \quad . \tag{8}$$

For clarity, Equation (8) may be rewritten using chemical symbols to represent the mole fraction for each constituent

$$H_2O = \left[2 + 7.67478\ \frac{W}{A}\right] \left[\frac{(CO_2 + CO + HC)\ (12.011 + 1.008\ \frac{y}{x})}{138.2689\ (f/A)}\right]$$

$$- 2CO_2 - CO - NO - 2O_2 \ . \tag{9}$$

Equation (9) then represents the total water vapor (humidity plus water of combustion) contained in the exhaust gas with each constituent measured on a wet basis.

Defining the water correction factor as

$$C_w = 1.0 - H_2O \tag{10}$$

we can convert the entire Equation (9) to dry basis measurements by dividing by $(1.0 - H_2O)$

$$\frac{H_2O}{1-H_2O} = \left[2 + 7.67478\,\frac{W}{A}\right]\left[\frac{\left(CO_{2_{dry}} + CO_{dry} + \frac{HC_{wet}}{1-H_2O}\right)\left(12.011 + 1.008\,\frac{y}{x}\right)}{138.2689\ (f/A)}\right]$$

$$- 2CO_{2_{dry}} - CO_{dry} - \frac{NO_{wet}}{1-H_2O} - 2O_{2_{dry}} \tag{11}$$

where

$$CO_{2_{dry}} = \frac{CO_{2_{wet}}}{1 - H_2O}\text{, etc.}$$

The solution to Equation (11) may be obtained iteratively by assuming a value for H_2O on the right-hand side of the equation, solving for H_2O on the left-hand side, using this new value for H_2O on the right-hand side, and repeating the process until satisfactory agreement has been obtained between the assumed and calculated values. Using this scheme, convergence is obtained usually within four iterations, starting with H_2O equalling zero on the right-hand side of the equation.

A more expansive chemical equilibrium calculation was made over the normal range of fuel air ratios, considering the products of combustion to include: C, A, CO, CO_2, H_2, H_2O, N_2, O_2, O, OH, H, NO, N, NH_3, and CH_4. The maximum error determined in the calculation of water vapor using our abbreviated product of combustion equation was less than one-half of 1 percent.

The solution to the wet correction factor then was obtained by using five equations [(1), (2), (6), (7), and (10)] involving five unknowns: m_a, m_w, m_l, m_f, and C_w. The assumptions made in order to effect a solution to the water correction factor are:

- The combustion equation represents all of the elemental constituents involved in the actual combustion process.

- The ratio of hydrogen to carbon atoms for all 100/130 octane aviation gasolines remains constant at (y/x).

While there are similar methods which can be used to calculate the water correction factor, it is believed that this method involves the use of the least number of assumptions leading to the most accurate estimate of C_w based on the quantities currently being measured.

IV. CALCULATION OF MASS EMISSION VALUES

As mentioned previously, the raw emissions are measured on a volumetric basis in percent or parts per million. In order to determine the emissions based on the requirements of the EPA Standards, these volumetric values must be converted to volumetric flow rate and then to mass flow values in accordance with Equation (12).

$$\begin{array}{c}\text{pollutant}\\\text{mass}\\\text{emission}\\\text{rate}\end{array} = \begin{array}{c}\text{exhaust}\\\text{volumetric}\\\text{flow}\\\text{rate}\end{array} \times \begin{array}{c}\text{pollutant}\\\text{volumetric}\\\text{concentration}\end{array} \times \begin{array}{c}\text{pollutant}\\\text{density}\end{array} . \qquad (12)$$

For this equation, the pollutant densities are specified in the Federal Register at a standard pressure and temperature of 760 mm Hg and 68°F. The values of pollutant volumetric concentrations (CO, HC, NOx) are measured, and, in order to calculate the mass emission rates, the exhaust volumetric flow rate must be known.

The EPA Standards state that the exhaust volumetric flow rate "shall be calculated in accordance with good engineering practices".

TCM calculates the exhaust volumetric flow rate at the standard pressure and temperature of 760 mm Hg and 68°F, using the assumption that the exhaust gas follows the ideal gas equation of state.

$$\dot{V}_{EXH} = \frac{R\,\dot{m}\,T}{M_{EXH}\,P} = \frac{R\,(f + A')\,T}{M_{EXH}\,P} \qquad (13)$$

where

$\dot{V}_{EXH}$ - exhaust volumetric flow rate, ft^3/hr

R - universal gas constant 1545.33 $\frac{\text{ft-lbf}}{\text{lbm-mole R}}$

$\dot{m}$ - total exhaust gas mass flow (also equal to total induction mass flow of fuel and air by principle of mass conservation), lbm/hr

T - absolute temperature, 528°R (68°F)

M_{EXH} - exhaust gas molecular weight

P - exhaust pressure, 2116 $\frac{\text{lbf}}{\text{ft}^2}$ (760 mm Hg)

f - fuel mass flow, lbm/hr

A' - humid air mass flow, lbm/hr.

In Equation (13), R, T, and P are given values and $\dot{m}$ is measured. The value of the exhaust gas molecular weight can be calculated from exhaust products as follows:

$$M_{EXH} = \sum m_i M_i \qquad (14)$$

where

M_{EXH} - the "apparent molecular weight" of the exhaust gas

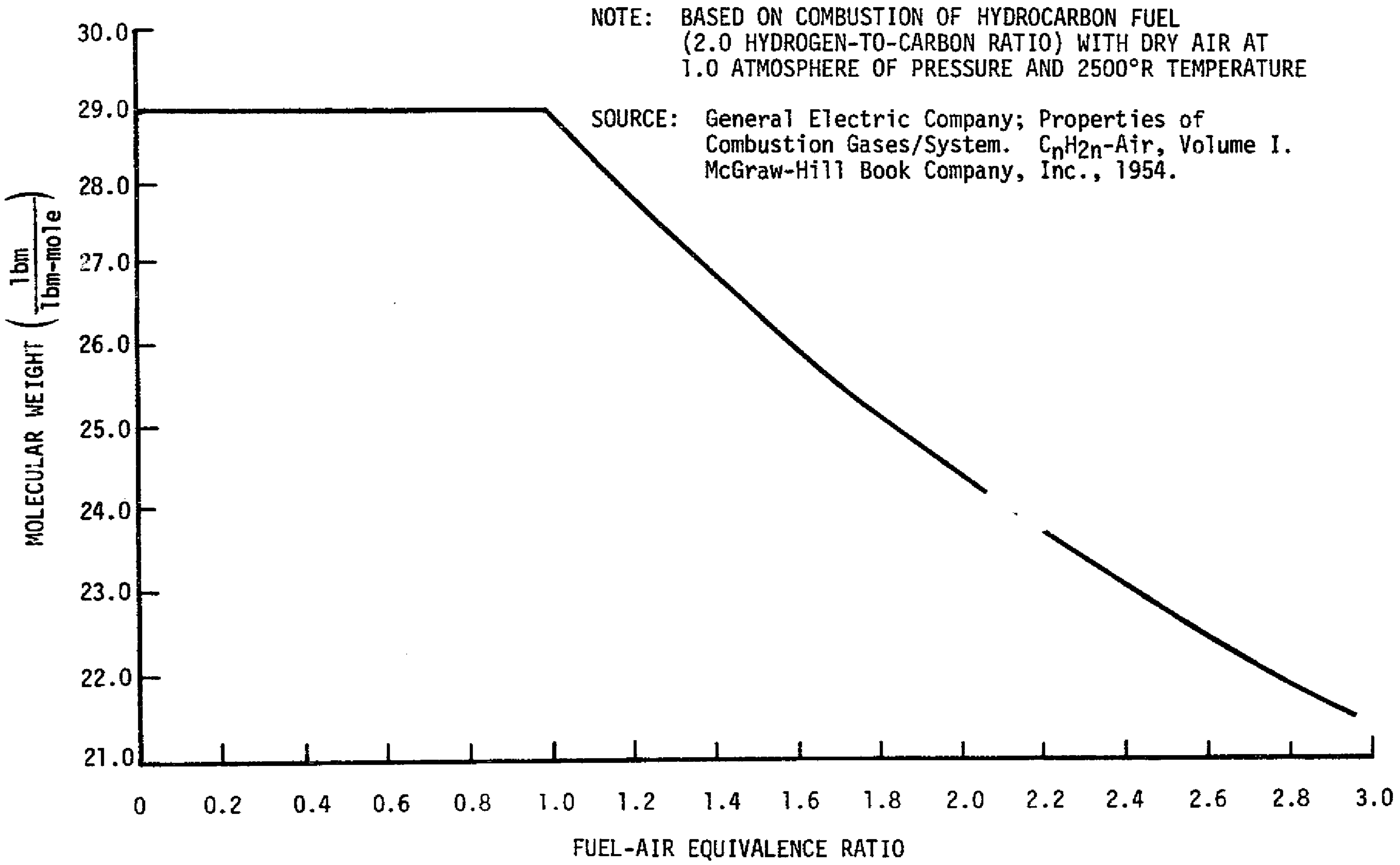
M_i - the molecular weight of each constituent

m_i - the mole fraction of each constituent which can be determined from measured concentrations and solution of Equations (2) through (7).

The solution of Equation (14) further requires an assumption of exhaust hydrocarbon hydrogen to carbon ratio, q/p. Studies have indicated however that extremely unreasonable values of calculated fuel-air ratio are obtained when the sum of the exhaust gas mole fractions are constrained to unity.

Therefore the method used by TCM for estimating the exhaust gas molecular weight is based on chemical equilibrium calculations and assumes that chemical equilibrium exists among the exhaust products for a given measured fuel-air equivalence ratio, Figure B-1. This assumption is reasonable since the major constituents which contribute to the exhaust molecular weight (e.g., N_2, CO_2, H_2O, CO) do not vary significantly from equilibrium predictions. The calculation of mass emissions of carbon monoxide as an example would be as follows, by substituting Equation (13) into Equation (12):

$$\dot{m}_{co} = \left[\frac{R\ (f + A')\ T}{M_{EXH}\ P}\right] \times [\rho_{co}] \times [CO]\ . \qquad (15)$$



NOTE: BASED ON COMBUSTION OF HYDROCARBON FUEL (2.0 HYDROGEN-TO-CARBON RATIO) WITH DRY AIR AT 1.0 ATMOSPHERE OF PRESSURE AND 2500°R TEMPERATURE

SOURCE: General Electric Company; Properties of Combustion Gases/System. C_nH_{2n}-Air, Volume I. McGraw-Hill Book Company, Inc., 1954.

FIGURE B-1. CHEMICAL EQUILIBRIUM MOLECULAR WEIGHT AS A FUNCTION OF FUEL-AIR EQUIVALENCE RATIO

Since, by the ideal gas assumption

$$\rho_{co} = \frac{M_{co}\ P}{RT} \tag{16}$$

substitution of Equation (16) into (15) yields

$$\dot{m}_{co} = \left[\frac{R\ (f + A')\ T}{M_{EXH}\ P}\right] \times \left[\frac{M_{co}\ P}{RT}\right] \times [CO]$$

or

$$\boxed{\dot{m}_{co} = \left(\frac{M_{co}}{M_{EXH}}\right)\ (f + A')\ (CO)} \tag{17}$$

where

$\dot{m}_{co}$ - mass emission rate of CO, lbm/hr

M_{co} - molecular weight of CO, 28.011 $\frac{\text{lbm}}{\text{lbm-mole}}$

M_{EXH} - exhaust gas molecular weight, $\frac{\text{lbm}}{\text{lbm-mole}}$

$(f + A')$ - total induction mass flow rate, $\frac{\text{lbm}}{\text{hr}}$

CO - wet volume fraction of CO in exhaust.

V. THE EXHAUST EMISSIONS STANDARDS

Once the mass emission rates of CO, HC, and NO have been determined for the modes, the calculation of exhaust emissions relative to the EPA standards is straightforward.

A Five-Mode Landing/Take-Off (LTO) cycle, as defined by the EPA, is shown in Table B-1. In each mode, run consecutively, the mass emissions are calculated in lbm/mode. The sum of these values, lbm/cycle, is then divided by the engine rated brake horsepower so that the final emissions values are in lbm/BHP/cycle. The maximum allowable values specified by the Standards are:

- CO - 0.042 lbm/BHP/cycle
- HC - 0.0019 lbm/BHP/cycle
- NOx - 0.0015 lbm/BHP/cycle.

TABLE B-1. EPA EMISSIONS REGULATIONS REQUIREMENTS

MODE NO.	MODE NAME	TIME IN MODE (min)	POWER (%)	ENGINE RPM (%)
1	Taxi/Idle-Out	12.0	***	
2	Take-Off	0.3	100	(100)
3	Climb	5.0	75 to 100	***
4	Approach	6.0	40	***
5	Taxi/Idle-In	4.0	***	
	TOTAL CYCLE	27.3		

***Manufacturer's Recommendation

To compare emissions from different types of engines, the EPA Five-Mode LTO cycle was expanded into a seven-mode cycle by separating the Idle-Taxi mode and further defining the power-speed conditions. Table B-2 presents the seven-mode cycle which was used as the standard for all engines investigated.

TABLE B-2. TCM SEVEN-MODE AIRCRAFT LANDING/TAKE-OFF OPERATIONAL CYCLE

MODE NO.	MODE NAME	TIME IN MODE (min)	POWER (%)	PROPELLER RPM
1	Idle-Out	1.0	-	600
2	Taxi-Out	11.0	-	1,200*
3	Take-Off	0.3	100	100% of Maximum
4	Climb	5.0	80	90% of Maximum
5	Approach	6.0	40	87% of Maximum
6	Taxi-In	3.0	-	1,200*
7	Idle-In	1.0	-	600
	TOTAL CYCLE	27.3		

*900 RPM on geared engines

VI. CALCULATED FUEL-AIR RATIO FROM EXHAUST PRODUCTS

The Environmental Protection Agency (20) requires a check on the accuracy of measured data by calculating the fuel-air ratio from exhaust gas constituents. The requirement is for the calculated and measured values to agree within ±5%. Teledyne Continental Motors employs a method developed by R.S. Spindt (67) which requires the use of the fuel hydrogen-to-carbon ratio, y/x, rather than molecular form as required by many alternative methods investigated. The Spindt equation requires values for O_2, CO, CO_2, HC, y/x, and an assumption for the water-gas equilibrium constant, Kp. Equation (18) is the Spindt equation.

$$\frac{f}{A} = \frac{1.0}{FB\left[(11.492)\ FC\ \frac{1.0 + E/2 + D}{1 + E} + \frac{120\ (1-FC)}{(K_p + E)}\right]} \qquad (18)$$

where

f/A - calculated fuel-air ratio

FB - $(CO + CO_2)/(CO + CO_2 + HC)$

FC - (12.011)/(12.011 + 1.008 y/x), the fraction of carbon in fuel, $C_x\ H_y$

E - CO/CO_2

D - O_2/CO_2

K_p - $(H_2O)\ (CO)/(H_2)\ (CO_2)$, the value of K_p was assigned by Spindt as 3.5.

LIST OF DEFINITIONS AND SYMBOLS

Abs	Absolute
Baseline	An engine operating condition defined as the average fuel flow rate (as established by the fuel system's production tolerance band) when operated with the mixture control set at full rich position
Bbl	Barrel
BHP	Brake Horsepower
BMW	Bavarian Motor Works
BTDC	Before Top Dead Center
Case I	The minimum allowable fuel flow rate as established by the engine type certificate (approximately best power for most modal conditions)
Case II	The fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety hazard occurs with the engine operating on a propeller test stand
CID	Cubic Inches Displacement
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO Standard	0.042 lbm/rated horsepower/cycle
CVCC	Compound Vortex Controlled Combustion
EGT	Exhaust Gas Temperature
EPA	Environmental Protection Agency
E^3R	Engine Exhaust Emission Reduction
FEMA	Failure Effects and Modes Analysis
FHP	Friction Horsepower
Fuel-Air	Ratio of Fuel Mass Flow to Dry Air Mass Flow
gm	Gram

LIST OF DEFINITIONS AND SYMBOLS - Continued

H	High
H_2	Hydrogen
HC	Unburned Hydrocarbons
HC Standard	0.0019 lbm/rated horsepower/cycle
Hg	Mercury
HP	Horsepower
I	Inline cylinder configuration (followed by number of cylinders)
IHP	Indicated Horsepower
IO-520-D	Fuel-injected six-cylinder opposed engine, 520 CID, D Model, with 300 Maximum Rated Horsepower
JPL	Jet Propulsion Laboratory
kHz	Kilohertz or (cycles per second) × 10^3
L	Low
lb	Pound (mass)
M	Medium
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
NACA	National Advisory Committee for Aeronautics
NTIS	National Technical Information Service
NOx	Oxides of Nitrogen
NOx Standard	0.0015 lbm/rated horsepower/cycle
ppm	Parts per Million
rpm	Revolutions per Minute
R&D	Research and Development
ROM	Rough Order Magnitude
SAE	Society of Automotive Engineers

LIST OF DEFINITIONS AND SYMBOLS - Concluded

Safety buttline	Fuel/air ratio leaned to the verge of safety problems, excessive cylinder head temperature or inadequate acceleration
SFC	Specific Fuel Consumption
S/N	Serial Number
SWRI	Southwest Research Institute
TA	Time Average
TCCS	Texaco Controlled Combustion System
TCM	Teledyne Continental Motors
TEL	Tetraethyllead
TFM	Turbulent Flow Manifold (Ethyl)
Tiara 6-285-B	Fuel-injected six-cylinder opposed engine, 285 Maximum Rated Horsepower, B-Model, with 406 CID
V-8	Eight Cylinders Arranged in a V Configuration
WOT	Wide Open Throttle
(0)	Binary number indicating "no value" or "less value"
(1)	Binary number indicating "value" or "greater value"
→ and >	Greater than ...
← and <	Less than ...
ϕ	Equivalence Ratio. The ratio of actual fuel/air to stoichiometric fuel/air ratio.

REFERENCES

1. A Systems Engineering Decision Algorithm with Application to Apollo Applications Program Integration Problems. NASA TM X-53992, Marshall Space Flight Center, Alabama, February 2, 1970.
2. Rezy, B. J.: Exhaust Emission Reduction for Intermittent Combustion Aircraft Engines; Technical Work Plan. Contract NAS3-19755, January 20, 1976, revised February 20, 1976.
3. Menard, Wesley A.; Moynihan, Phillip I.; and Rupe, Jack H.: New Potentials for Conventional Aircraft When Powered by Hydrogen Enriched Gasoline. Technical Memorandum No. 33-760, Jet Propulsion Laboratory, January 1976.
4. Date, Tasuku; Fijii, Isao; Ishizuya, Akira; and Yagi, Shizue: Research and Development of the Honda CVCC Engine. Paper 740605, SAE, August 1974.
5. Springer, Karl J.: Emissions from Diesel and Stratified Charge Powered Cars. Report No. EPA-460/3-75-001-a, Southwest Research Institute, December 1974.
6. Choma, M. A.; Repko, L. L.; and Simko, A.: Exhaust Emission Control by the Ford Programmed Combustion Process - PROCO. Paper 720052, SAE, January 1972.
7. Alperstein, M.; Schafer, G. H.; and Villforth, F. J., III: Texaco's Stratified Charge Engine - Multifuel, Efficient, Clean and Practical. Paper 740563, SAE, May 1974.
8. Alperstein, Martin; Coppoc, William J.; and Mitchell, Edward: Texaco Controlled Combustion System Provides an Engine with Clean Exhaust and Good Fuel Economy. Swedish Engineering Society, March 27, 1973.
9. Adams, W. E.; Hamilton, J. C.; Marsee, F. J.; and Olree, R. M.: Emission, Fuel Economy, and Durability of Lean Burn Systems. Paper 760227, SAE, February 1976.
10. Hare, Charles T., and Springer, Karl J.: Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines; Final Report, Part 5, Heavy-Duty Form, Construction, and Industrial Engines. Report No. AR-898, Southwest Research Institute, October 1973.
11. Kruckenberg, P. L.: The McCulloch Diesel Combustion System. McCulloch publication, February 3, 1975.

REFERENCES - Continued

12. McCulloch Corporation: The Model TRAD 4180 Light Aircraft Engine - A Radial Two-Stroke Diesel. McCulloch publication, May 9, 1975.

13. Bennethum, James E.; De Nagel, Stephen F.; and Schiele, Carl A.: Design and Development of a Variable Valve Timing (VVT) Camshaft. Paper 740102, SAE February and March 1974.

14. Freeman, Max A., and Nicholson, Roy C.: Valve Timing for Control of Oxides of Nitrogen (NO_X). Paper 720121, SAE, January 1972.

15. Daniel, W. A.: Engine Variable Effects on Exhaust Hydrocarbon Formations (Single Cylinder Engine Study with Propane as Fuel. Paper 670124, SAE, 1967; Vol. 76.

16. Simmonds Aerocessories, Inc.: Simmonds SU Series Fuel Injection Systems. Preliminary Bulletin, 1952.

17. Stephenson, R. Rhoads: Should We Have a New Engine? An Automobile Power System Evaluation, Volume II. Report No. JPL SP 43-17, Jet Propulsion Laboratory, August 1975.

18. Asik, J. R.; Harrington, J. A.; and Shishu, R. C.: A Study of Ignition Systems Effects on Power, Emission, Lean Misfire Limit and EGR Tolerance of a Single-Cylinder Engine - Multiple Spark versus Conventional Single Spark Ignition. Paper 740188, SAE, February and March 1974.

19. Blatter, A.; Datwyler, W. F.; and Hasson, S. T.: Control of Emissions from Light Piston-Engine Aircraft. Report No. APTD-1521, Bendix Corporation, May 1973.

20. Environmental Protection Agency: Control of Air Pollution from Aircraft and Aircraft Engines. Federal Register, Volume 38, Number 136, Part II, Tuesday, July 17, 1973.

21. Airworthiness Standards: Aircraft Engines. FAR Part 33, Federal Aviation Administration, August 1974 (latest revisions).

22. Aircraft Powerplant Handbook. CAA Technical Manual No. 107, U.S. Department of Commerce, January 1949.

23. Obert, E. F.: Internal Combustion Engines and Air Pollution. Intext Educational Publishers, New York, N. Y., 1973.

24. Airframe and Powerplant Mechanics - Powerplant Handbook. AC 65-12, Federal Aviation Administration, 1971.

25. Asimow, M.: Introduction to Design. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962.

REFERENCES - Continued

26. Hall, A. D.: A Methodology for Systems Engineering. D. Van Nostrand Company, Inc., New York, N. Y., 1965.

27. English, J. M., et al.: Cost-Effectiveness. John Wiley and Sons, Inc., New York, N. Y., 1968.

28. Seiler, K.: Introduction to Systems Cost-Effectiveness. Wiley-Interscience, New York, N. Y., 1969.

29. English, M. J.: Economics of Engineering and Social Systems. John Wiley and Sons, Inc., New York, N. Y., 1972.

30. Hajek, V. G.: Project Engineering. McGraw-Hill Book Company, New York, N. Y., 1965.

31. Hackney, J. W.: Control and Management of Capital Projects. John Wiley and Sons, Inc., New York, N. Y., 1965.

32. Von Alven, W. H.: Reliability Engineering. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1964.

33. Rodgers, W. P.: Introduction to System Safety Engineering. John Wiley and Sons, Inc., New York, N. Y., 1971.

34. Bursk, E. C., et al.: New Decision-Making Tools for Managers. Harvard University Press, Cambridge, Massachusetts, 1963.

35. Miles, R. F., Jr.: Systems Concepts. John Wiley and Sons, New York, N. Y., 1973.

36. Forrester, J. W.: Industrial Dynamics. The MIT Press, Cambridge, Massachusetts, 1961.

37. Jones, B.: Elements of Practical Aerodynamics. John Wiley and Sons, Inc., New York, N. Y., 1958.

38. Wood, K. D.: Aircraft Design. Johnson Publishing Company, Boulder, Colorado, 1968.

39. Aircraft Performance Engineering. AF Manual 51-9, U.S. Air Force, December 1954.

40. Blanchard, B. S., Jr., and Lowery, E. E.: Maintainability. McGraw-Hill Book Company, New York, N. Y., 1969.

41. Goldman, A. S., and Slattery, T. B.: Maintainability. John Wiley and Sons, Inc., New York, N. Y., 1967.

REFERENCES - Continued

42. Blanchard, B. S.: Logistics Engineering and Management. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

43. Maintainability Program Requirements for Systems and Equipments. MIL-STD-470, U.S. Air Force, March 21, 1966 (latest revision).

44. Aircraft Engine, Reciprocating, General Specifications. MIL-E-25109, U.S. Air Force, February 7, 1955 (latest revision).

45. Samaras, T. T., and Czerwinski, F. L.: Fundamentals of Configuration Management. Wiley-Interscience, New York, N.Y., 1971.

46. Leech, D. J.: Management of Engineering Design. John Wiley and Sons, Inc., New York, N.Y., 1972.

47. Clapp, W. H., and Clark, D.S.: Engineering Materials and Processes. International Textbook Company, Scranton, Pennsylvania, 1954.

48. Titterton, G. F.: Aircraft Materials and Processes. Pitman Publishing Corp., New York, N. Y., 1956.

49. Chase, W. P.: Management of Systems Engineering. Wiley-Interscience, New York, N. Y., 1974.

50. Mesarovic, M. D., et al.: Theory of Hierarchical, Multilevel Systems. Academic Press, New York, N. Y., 1970.

51. Personal Communication, R. M. Olree to B. J. Rezy, Re: Ethyl Turbulent Flow System, March 23, 1976.

52. Personal Communication, Charles T. Hare to J. Ronald Tucker, Re: Diesel Engine Exhaust Emissions Studies by Southwest Research Institute, April 14, 1976.

53. Personal Communication, B. J. Rezy to George Maffey, Re: McCulloch 2-Stroke Combustion System.

54. Personal Communication, W. T. Tierney to J. Ronald Tucker, Re: Texaco Controlled Combustion System, April 8, 1976.

55. Personal Communication, Jack C. Priegel to B. J. Rezy, Re: Autotronic Controls Corporation Fuel Control System and Associated Data, April 23, 1976.

56. Personal Communication, J. Ronald Tucker to Bill Felker, Re: Bendix Corporation Electronic Fuel Injection, April 27, 1976.

57. Personal Communication, J. Ronald Tucker to J. W. Hallberg, Re: Borg-Warner Fluid Jet Carburetion, April 27, 1976.

REFERENCES - Concluded

58. Personal Communication, J. Ronald Tucker to P. R. Angell, Re: Chrysler Lean Burn System, March 17, 1976.

59. Personal Communication, K. J. Stuckas to Tom Cackette, Re: EPA Emissions Data.

60. Personal Communication, J. Ronald Tucker to Aladan Simko, Re: Ford Programmed Combustion Process, March 19, 1976.

61. Personal Communication, B. J. Rezy to Bill Garrity, Re: Honda CVCC, April 7, 1976.

62. Personal Communication, Wesley A. Merand to B. J. Rezy, Re: J.P.L. Hydrogen Enrichment Concept and Lean Mixture Engine Testing and Evaluation Program, March 18, 1976.

63. Personal Communication, B. J. Rezy to Michael Skorobatckyi, Re: NASA/ Lewis Emissions Data.

64. Personal Communication, B. J. Rezy to David Collins, Re: Emission Data Request to Ricardo and Company Engineers.

65. Personal Communication, H. Shimada to J. Ronald Tucker, Re: Toyota Lean-Burn Engine, April 23, 1976

66. Personal Communication, B. J. Rezy to Charlie Brown, Re: White Engines, Inc., Emission Data.

67. Spindt, R. S.; Gulf Research and Development Company: Air-Fuel Ratios from Exhaust Gas Analysis. Paper 650507, SAE, 1965.

BIBLIOGRAPHY

1. Adams, W. E.; Marsee, F. J ; Olree, R. M.; and Hamilton, J. C.; Ethyl Corporation: Emissions, Fuel Economy, and Durability of Lean Burn Systems. Paper 760227, SAE, February 1976.

2. Adams, W. E.; and Kerley, R. V.; Ethyl Corp.: The Next Decade for Piston Engines. Paper 670685, SAE, 1967.

3. Aiman, William R.; Research Labs., General Motors Corp.: Engine Speed and Load Effects on Charge Dilution and Nitric Oxide Emission. Paper 720256, SAE, January, 1972.

4. Alperstein, M.; and Bradow, R. L.; Texaco, Inc.: Exhaust Emissions Related to Engine Combustion Reactions. Paper 660781, SAE, 1966, Vol. 75.

5. Amano, M.; Sami, H.; Nakagawa, S.; and Yoshizaki, H.; Toyota Motor Co., Ltd. (Japan).: Approaches to Low Emission Levels for Light-Duty Diesel Vehicles. Paper 760211, SAE, February, 1976.

6. Asik, Joseph R.; and Bates, Bradford; Engineering and Research Staff, Ford Motor Co.: The Ferroresonant Capacitor Discharge Ignition (FCDI) System: A Multiple Firing CD Ignition with Spark Discharge Sustaining Between Firings. Paper 760266, SAE, February, 1976.

7. Bascom, C.; Broering, Louis C.; and Wulfhorst, David E.; Cummins Engine Co., Inc.: Design Factors that Affect Diesel Emissions. Paper 710484 (SP-365), SAE, 1971.

8. Beaudoin, G. L.; Laud, K. R.; Logothetis, E. M.; Meitzler, A. H.; and Park, K.; Engineering & Research Staff, Ford Motor Co.: CoO Sensors for Measurement and Control of Exhaust from Lean-Burn Engines. Paper 760312, SAE, February, 1976.

9. Bellan, J. R.: A Theory of Turbulent Combustion and Nitric Oxide Formation for Dual-Carbureted Stratified-Charge Engines. Princeton University, Publication Number 75-20, 612, August, 1974.

10. Bishop, I. N.; and Simok, Aladar; Ford Motor Co.: New Concept of Stratified Charge Combustion - The Ford Combustion Process (FCP). Paper 680041, SAE, 1968, Vol. 77.

11. Blair, G. P.; and McConnell, J. H.; Department of Mechanical Engineering, The Queen's University of Belfast (Northern Ireland): Unsteady Gas Flow through High-Specific-Output 4-Stroke Cycle Engines. Paper 740736, SAE, September, 1974.

BIBLIOGRAPHY - Continued

12. Boekhaus, K. L.; and Copeland, L. C.: Performance Characteristics of Stratified Charge Vehicles with Conventional Fuels and Gasoline Blended with Alcohol and Water. Paper 760197, SAE, February, 1976.

13. Bosecker, R. E.; and Webster, D. F.; Caterpillar Tractor Co.: Precombustion Chamber Diesel Engine Emissions - A Progress Report. Paper 710672, SAE, August, 1971.

14. Brandstetter, W. R.; Decker, G.; Schafer, H. J.; and Steinke, D.; Volkswagenwerk AG (Germany): The Volkswagen PCI Stratified Charge Concept - Results from the 1.6 Liter Air Cooled Engine. Paper 741173, SAE, November, 1974.

15. Breisacher, P.; Nichols, R. J.; and Hicks, W. A.: Exhaust Emission Reduction through Two-Stage Combustion. Combustion Science and Technology, Volume 6, pages 191 - 201, 1972.

16. Bright, C.; et al: Comparison of Air Pollution from Aircraft and Automobiles (Project Eagle). Report No. FAA-NO-70-14, Rutgers University, September, 1970.

17. Brisson, B.; Societe d'Etude des Marchines Thermiques,: and Ecomard, A.; and Eyzat, P.; Institut Francais due Petrole: A New Diesel Combustion Chamber - The Variable-Throat Chamber. Paper 730167, SAE, January, 1973.

18. Camp, John; and Rachel, Todd; Bendix Corp.: Closed-Loop Electronic Fuel and Air Control of Internal Combustion Engines. Paper 750369, SAE, February, 1975.

19. Campau, R. M.; Stefan, A.; and Hancock, E. E.; Ford Motor Co.: Ford Durability Experience on Low Emission Concept Vehicles. Paper 720488 (SP-370), SAE, 1972.

20. Chiu, W. S.; Shahed, S. M.; and Lyn, W. T.; Cummins Engine Co., Inc.: A Transient Spray Mixing Model for Diesel Combustion. Paper 760128, SAE, February, 1976.

21. Coffin, K. P.: Effect of Timed Secondary - Air Injection on Automotive Emissions. NASA TM X-2737, March, 1970.

22. Date, Tasuku; and Yagi, Shizuo; Honda Research and Development Co., Ltd.: Research and Development of the Honda CVCC Engine. Paper 740605, SAE, August, 1974.

23. Davis, G. C.; Krieger, R. B.; and Tabaczynski, R. J.; Research Labs., div., General Motors Corp.: Analysis of the Flow and Combustion Processes of a Three-Valve Stratified Charge Engine with a Small Prechamber. Paper 741170, SAE, November, 1974.

BIBLIOGRAPHY - Continued

24. Dowdy, M. W.; Hoen, F. W.; and Vanderburg, T. G.: Lean Mixture Engine Testing and Evaluation Program, Volumes I, II, and III. Report Number DOT-TSC-OST-75-26, JPL, November, 1975.

25. Evers, L. W.; Myers, P. S.; and Uyehara, O. A.; Univ. of Wisconsin: A Search for a Low Nitric Oxide Engine. Paper 741172, November, 1974.

26. Eyzat, P.; and Guibet, J. C.; Institut Francais du Petrole: New Look at Nitrogen Oxides Formation in Internal Combustion Engines. Paper 680124, SAE, 1968, Vol. 77.

27. Fay, James A.; and Heywood, John B.; Massachusetts Institute of Technology: The Dispersion of Pollutants from Aircraft. Paper 710322 (P-37), SAE, 1971, Vol. 80.

28. Felt, A. E.; and Krause, S. R.; Ethyl Corp.: Effects of Compression Ratio Changes on Exhaust Emissions. Paper 710831, SAE, 1971, Vol. 80.

29. Gast, Richard A.; Res. Labs., General Motors Corp.: Pulsair - A Method for Exhaust System Induction of Secondary Air for Emission Control. Paper 750172, SAE, February, 1975.

30. Gompf, H. L.: Evaluation of the Texaco Stratified Charge (TCP) M-151 Army Vehicle. Report Number APTD-1378, EPA, August, 1972.

31. Griffin, J. R.; Chevron Research Co.; and Wittek, H. L.; List-Rosen-Wittek Associates Inc.: Versatile Single-Cylinder Diesel Test Engine for Lubricant, Emissions, and Fuel Research. Paper 730831, SAE, September, 1973.

32. Grigg, H. C.; CAV Ltd.: The Role of Fuel Injection Equipment in Reducing 4-Stroke Diesel Engine Emissions. Paper 760126, SAE, February, 1976.

33. Grundy, J. R.; Kiley, L. R.; and Brevick, E. A., Teledyne Continental Motors, General Products Division: AVCR 1360-2 High Specific Output-Variable Compression Ratio Diesel Engine. Paper 760051, SAE, February, 1976.

34. Hansel, James G.; Esso Research and Engineering Co.: Lean Automobile Engine Operation - Hydrocarbon Exhaust Emissions and Combustion Characteristics. Paper 710164, SAE, 1971, Vol. 80.

35. Hansel, James G.; Esso Research and Engineering Co.: Low NOx Emissions from Automotive Engine Combustion. Paper 720509, SAE, May, 1972.

36. Hamburg, D. R.; and Hyland, J. E.; Engineering and Research Staff, Ford Motor Co.: A Vaporized Gasoline Metering System for Internal Combustion Engines. Paper 760288, SAE, February, 1976.

BIBLIOGRAPHY - Continued

37. Harrington, J. A.; Shishu, R. C.; and Asik, J. R.; Ford Motor Co.: A Study of Ignition System Effects on Power, Emissions, Lean Misfire Limit, and EGR Tolerance of a Single Cylinder Engine - Multiple Spark versus Conventional Single Spark Ignition. Paper 740188, SAE, March, 1974.

38. Herrin, Ronald J.; General Motors Research Labs: The Importance of Secondary Air Mixing in Exhaust Thermal Reactor Systems. Paper 750174, SAE, February, 1975.

39. Hires, S. D.; Ford Motor Company; and Ekchian, A.; Heywood, J. B.; Tabaczynski, R. J.; and Wall, J. C.; Massachusetts Institute of Technology: Performance and NOx Emissions Modeling of a Jet Ignition Prechamber Stratified Charge Engine. Paper 760161, SAE, February, 1976.

40. Hiroyasu, H.; and Kadota, T.; University of Hiroshima: Models for Combustion and Formation of Nitric Oxide and Soot in Direct Injection Diesel Engines. Paper 760129, SAE, February, 1976.

41. Hittler, D. L.; and Hamkins, L. R.; American Motors Corp.: Emission Control by Engine Design and Development. Paper 680110, SAE, January, 1968.

42. Hoehn, F. W.; Baisley, R. L.; and Dowdy, M. W.: Advances in Ultraclean Combustion Technology Using Hydrogen-Enriched Gasoline. Presentation Paper, Intersociety Energy Conversion Engineering Conference, August, 1975.

43. Houseman, John; and Cerini, D. J.; California Institute of Technology: On-Board Hydrogen Generator for a Partial Hydrogen Injection Internal Combustion Engine. Paper 740600, SAE, August, 1974.

44. Houseman, John; and Hoehn, Frank W.; Jet Propulsion Laboratory, California Institute of Technology: A Two-Charge Engine Concept: Hydrogen Enrichment. Paper 741169, SAE, November, 1974.

45. Houseman, J.; Molinari, L. F.; and Dowdy, M. W.: Lean Combustion of Hydrogen/Gasoline Mixtures. Presentation Paper, American Chemical Society, April, 1975.

46. Hubbard, M.; University of California at Davis; and Bonilla, J. J.; Randall, K. W.; and Powell, J. D.; Stanford University: Closed Loop Control of Lean Fuel-Air Ratios Using a Temperature Compensated Zirconia Oxygen Sensor. Paper 760287, SAE, February, 1976.

47. Hughes, D. W.; and Goulburn, J. R.; Ashby Institute. Queen's University of Belfast (Northern Ireland).: Economy with Reduced Exhaust Emissions - A Simple Technique. Paper 760140, SAE, February, 1976.

BIBLIOGRAPHY - Continued

48. Huls, T. A.; Ford Motor Co.; and Myers, P. S.; and Uyehara, O. A.; Wisconsin Univ.: Spark Ignition Engine Operation and Design for Minimum Exhaust Emission. Paper 660405, SAE, June, 1966, Vol. 75.

49. Huls, T. A.; and Nickol, H. A.; Ford Motor Co.: Influence of Engine Variables on Exhaust Oxides of Nitrogen Concentrations from a Multi-Cylinder Engine. Paper 670482, SAE, May, 1967.

50. Isley, W. F.: The Application of Fuel Injection to Ordnance Gasoline Engines. Continental Aviation and Engineering Corp., November, 1956.

51. Jackson, M. W.; Wiese, W. M.; and Wentworth, J. T.: The Influence of Air-Fuel Ratio, Spark Timing, and Combustion Chamber Deposits on Exhaust Hydrocarbon Emissions. Paper 486-A, SAE, March, 1962.

52. Jet Propulsion Laboratory: Hydrogen-Enrichment-Concept Preliminary Evaluation - Final Report. Document 1200-237, JPL, December 15, 1975.

53. Jo, Souk Hong; Japan Automobile Research Institute, Inc.; Jo, Pan Do; Institute of Industrial Science, Tokyo University; Gomi, Tsutomu; Sophia University; and Ohnishi, Shigeru; Nippon Clean Engine Research Institute: Development of a Low-Emission and High-Performance 2-Stroke Gasoline Engine (NiCE). Paper 730463, SAE, May, 1973.

54. John, J. E. A., et al: Emission Control of Engine Systems. NTIS Report Number PB-242097, National Research Council, September, 1974.

55. Johnson, Steven A.; Onan Div., Onan Corp.; and Kittelson, David B.; and Murphy, Thomas E.; University of Minnesota: An Ionization Probe Study of Small Engine Combustion Chambers. Paper 760170, SAE, February, 1976.

56. Johnson, P. R.; Genslak, S. L.; and Nicholson, R. C.; Engineering Staff, General Motors Corp.: Vehicle Emission Systems Utilizing a Stratified Charge Engine. Paper 741157, SAE, November, 1974.

57. Kant, F. H.; et al: Feasibility Study of Alternative Fuels for Automotive Transportation, Vol. II - Technical Section. Report No. EPA-460/3-74-009-b, Exxon Research and Engineering Co., June, 1974.

58. Keranen, T. W.; and Wertheimer, H. P.; The Bendix Corp.: Spark Ignition Engine Control Variables Study, Paper 730004, SAE, January, 1973.

59. Khan, I. M.; Greeves, G.; and Wang, C. H. T.; CAV Ltd.: Factors Affecting Smoke and Gaseous Emissions from Direct Injection Engines and a Method of Calculation. Paper 730169, SAE, January, 1973.

60. Kirwin, J. M.; and Hasse, E. A.; The Bendix Corp.: Fuel System Requirements for Light Aircraft Turbocharged Reciprocating Engines. Paper 740382, SAE, April, 1974.

BIBLIOGRAPHY - Continued

61. Klomp, Edward D.; and Deboy, Gail R.; Research Labs., General Motors Corp.: The Effects of Fluid Motions on Combustion in a Prechamber Bomb. Paper 760162, SAE, February, 1976.

62. Killman, R. E.; Lestz, S. S.; and Meyer, W. E.; The Pennsylvania State University: Exhaust Emission Characteristics of a Small 2-Stroke Cycle Spark Ignition Engine. Paper 730159, SAE, January, 1973.

63. Komiyama, Kunihiko; Komatsu, Ltd. (Japan) and Massachusetts Institute of Technology; and Heywood, John B.; Massachusetts Institute of Technology: Predicting NOx Emissions and Effects of Exhaust Gas Recirculation in Spark-Ignition Engines. Paper 730475, SAE, May, 1973.

64. LaMasters, G. D.; Marvel-Schebler/Tillotson Div., Borg Warner Corp.: Fuel Injection - Another Tool for Emission Control. Paper 720679, November, 1971.

65. Lancaster, David R.; Research Labs., General Motors Corp.: Effects of Engine Variables on Turbulence in a Spark-Ignition Engine. Paper 760159, SAE, February, 1976.

66. Lancaster, David R.; and Krieger, Roger B.; Research Labs., General Motors Corp.; and Sorenson, Spencer C.; and Hull, William L.; Mechanical Engineering Dept., University of Illinois: Effects of Turbulence on Spark-Ignition Engine Combustion. Paper 760160, SAE, February, 1976.

67. Lee, R. C.; Phillips Petroleum Co.: Effect of Compression Ratio, Mixture Strength, Spark Timing, and Coolant Temperature Upon Exhaust Emissions and Power. Paper 710832, SAE, October, 1971.

68. Lestz, S. S.; Meyer, W. E.; and Colony, C. M.: Emissions from a Direct-Cylinder Water-Injected Spark-Ignition Engine. Paper 720113, SAE, January, 1972.

69. Lord, H. A.; Sondreal, E. A.; Kadlec, R. H.; and Patterson, D. J.; The University of Michigan: Reactor Studies for Exhaust Oxidation Rates. Paper 730203, SAE, January, 1973.

70. Lucas, Albert G.; General Motors Corp.: Spark Ignition Engine Progress. Paper 670199, SAE, May, 1966.

71. Lucas, G. G.; and Varde, K.; University of Technology, Leicestershire (England): Analysis of Nitric Oxide Formation in Spark Ignition Engine with Heat Transfer and Effect of Ignition Point. Paper 740189, SAE, March, 1974.

72. Lucas, G. G.; and Varde, K. S.; Loughborough Univ. of Tech. (United Kingdom): Off-Stoichiometry Operation of an SI Engine - A Model of Formation and Control of Nitric Oxide. Paper 750352, SAE, February, 1975.

BIBLIOGRAPHY - Continued

73. MacDonald, J. Scott; Research Labs., General Motors Corp.: Evaluation of the Hydrogen-Supplemented Fuel Concept with an Experimental Multi-cylinder Engine. Paper 760101, SAE, February, 1976.

74. Malliaris, A. C.; Trella, T.; and Gould, H.; U. S. Dept. of Transportation: Engine Cycle Simulations and Comparisons to Real Engine Performance. Paper 760155, SAE, February, 1976.

75. Malliaris, A. C.; Withjack, E.; and Gould, H.; U. S. Dept. of Transportation: Simulated Sensitivities of Auto Fuel Economy, Performance and Emissions. Paper 760157, SAE, February, 1976.

76. Manger, Hansjoerg: Robert Bosch GmbH (West Germany): Digital Electronic Spark Advance Systems. Paper 760265, SAE, February, 1976.

77. Matthes, William R.; and McGill, Ralph N.; Research Labs., General Motors Corp.: Effects of the Degree of Fuel Atomization on Single-Cylinder Engine Performance. Paper 760017, SAE, February, 1976.

78. May, Hans; and Schulz, Harry; Technical University Aachen, Germany: New Distributing Injection System and Its Potential for Improving Exhaust Gas Emissions. Paper 680043, SAE, January, 1968.

79. Mayo, J.; Combustion Engineering Dept., Ford Motor Co.: The Effect of Engine Design Parameters on Combustion Rate in Spark-Ignited Engines. Paper 750355, SAE, February, 1975.

80. Megonnel, William H.; Environmental Protection Agency: Regulation of Pollutant Emissions from Aircraft - Today and Tomorrow. Paper 710337, SAE Transactions, Volume 80, 1971.

81. Menard, W. A.; Moynihan, P. I.; and Rupe, J. H.; Jet Propulsion Lab., California Institute of Technology: New Potentials for Conventional Aircraft when Powered by Hydrogen-Enriched Gasoline. Paper 760469, SAE, April, 1976.

82. Milkins, E. E.; Watson, H. C.; Goldsworthy, L. C.; and Hallworth, R. J.; Dept. of Mechanical Engineering, Univ. of Melbourne: Cycle by Cycle Variability in Emissions of a Spark Ignition Engine. Paper 741034, SAE, October, 1974.

83. Milks, David; and Matula, Richard A.; Mechanical Engineering and Mechanics Dept., Drexel University: Emissions and Fuel Economy Test Methods and Procedures for Light Duty Motor Vehicles - a Critique. Paper 760141, SAE, February, 1976.

84. Mitchell, E.; Cobb, J. M.; and Frost, R. A.; Texaco Inc., Res. Center: Design and Evaluation of a Stratified Charge Multifuel Military Engine. Paper 680042, SAE Transactions, Vol. 77, January, 1968.

BIBLIOGRAPHY - Continued

85. Mitchell, E.; Alperstein, M.; Cobb, J. M.; and Faist, C. H.; Texaco Research Center: A Stratified Charge Multifuel Military Engine - A Progress Report. Paper 720051, SAE, January, 1972.

86. Miyake, Masataka; Mitsubishi Heavy Industries, Ltd.: Developing a New Stratified Charge Combustion System with Fuel Injection for Reducing Exhaust Emissions in Small Farm and Industrial Engines. Paper 720196, SAE Transactions, Volume 81, 1972.

87. Morgan, C. R.; and Hetrick, S. S.: The Effects of Engine Variables and Exhaust Gas Recirculation on Emissions, Fuel Economy, and Knock - Part II. Paper 760198, SAE, February, 1976.

88. Motoyoshi, Eiichi; Yamada, Tadashi; and Mori, Mitsuyoshi; Yanmar Diesel Engine Co., Ltd. (Japan): The Combustion and Exhaust Emission Characteristics and Starting Ability of Y. P. C. Combustion System. Paper 760215, SAE, February, 1976.

89. Myers, P. S.; Uyehara, O. A.; and Newhall, H. K.: The ABC's of Engine Exhaust Emissions. Paper 710481, SAE, 1971.

90. Nakagawa, Hiroshi; and Tateishi, Mataji; Mitsubishi Heavy Industries, Ltd. (Japan); and Sekino, Masaaki; Mitsubishi Motors Corp. (Japan): Application of Fuel Spray Theory to Exhaust Emission Control in a D. I. Diesel Engine. Paper 760214, SAE, February, 1976.

91. Newhall, H. K.; and El-Messiri, I. A.; the University of Wisconsin: A Combustion chamber Designed for Minimum Engine Exhaust Emissions. Paper 700491, SAE Transactions, Volume 79, 1970.

92. Nicholson, Roy C.; and Niepoth, George W.: Effect of Emission Constraints on Optimum Engine Size and Fuel Economy. Paper 760046, SAE, February, 1976.

93. Ospring, Michael; Karnopp, Kean; and Margolis, Donald; Dept. of Mechanical Engineering, University of California at Davis: Comparison of Computer Predictions and Experimental Tests for Two-Stroke Engine Exhaust Systems. Paper 760172, SAE, February, 1976.

94. Parks, Fred B.; Research Labs., General Motors Corp.: A Single-Cylinder Engine Study of Hydrogen-Rich Fuels. Paper 760099, SAE, February, 1976.

95. Patterson, D. J.; General Motors Corp.: Cylinder Pressure Variations, A Fundamental Combustion Problem. Paper 660129, SAE Transactions, Volume 75, January, 1966.

96. Perez, J. M.; and Landen, E. W.; Caterpillar Tractor Co.: Exhaust Emissions Characteristics of precombustion Chamber Engines. Paper 680421, SAE Transactions, Volume 77, 1968.

BIBLIOGRAPHY - Continued

97. Pischinger, F. F.; and Klocher, K. J.; Lehrstuhl fur Angewandte Thermodynamik an der Rheinisch-Westfalischen Technischen Hochschule Aachen: Single-Cylinder Study of Stratified Charge Process with Prechamber-Injection. Paper 751162, SAE, November, 1974.

98. Platt, Melvin; and Bastress, E. Karl; Northern Research and Engineering Corp.: The Impact of Aircraft Emissions Upon Air Quality. Paper 720610 (P-44), SAE Transactions, Volume 81, May and June, 1972.

99. Pozniak, Donald J.; Res. Labs., General Motors Corp.: Exhuast-Port Fuel Injection for Chemical Reduction of Nitric Oxide. Paper 750173, SAE, February, 1975.

100. Pozniak, Donald J.; Research Labs., General Motors Corp.: A Spark Ignition Lean-Homogeneous Combustion Engine Emission Control System for a Small Vehicle. Paper 760225, SAE, February, 1976.

101. Pozniak, Donald J.; and Siewert, Robert M.; Research Labs., General Motors Corp.: Continuous Secondary Air Modulation - Its Effect on Thermal Manifold Reactor Performance. Paper 730493, SAE, May, 1973.

102. Purins, Egils A.; Ford Motor Company: Pre-Chamber Stratified Charge Engine Combustion Studies. Paper 741159, SAE, May, 1973.

103. Quader, Ather A.; Res. Labs., General Motors Corp.: Effects of Spark Location and Combustion Duration on Nitric Oxide and Hydrocarbon Emissions. Paper 730153, SAE, January, 1973.

104. Quader, Ather A.; Res. Lab. Div., General Motors Corp.: Lean Combustion and the Misfire Limit in Spark-Ignition Engines. Paper 741055, SAE, October, 1974.

105. Rhodes, K. H.; Walker Mfg. Co.: Project Stratofire, Paper 660094, SAE, January, 1966.

106. Ricardo Consulting Engineers: An Evaluation of the Honda CVCC Engined Vehicle and a Comparison with the Conventional 2 Valve Cylinder Head. Report No. DP 76/328, May, 1976.

107. Rivard, J. G.; The Bendix Corp.: Closed-Loop Electronic Fuel Injection Control of the Internal Combustion Engine. Paper 730005, SAE, January, 1973.

108. Rudey, Richard A.; and Kempke, Erwin, E., Jr.; National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio: Technology for Reducing Aircraft Engine Pollution. Paper 750770, SAE, April, 1975.

BIBLIOGRAPHY - Continued

109. Ryan, T. W., III,; Lestz, S. S.; and Meyer, W. E.; The Pennsylvania State University: Extension of the Lean Misfire Limit and Reduction of Exhaust Emissions of an SI Engine by Modification of the Ignition and Intake Systems. Paper 740105, SAE, March, 1974.

110. Sakai, Yasuo; Miyazaki, Hiroaki; and Mukai, Kosaburo; Nissan Motor Co., Ltd.: The Effect of Combustion Chamber Space on Nitrogen Oxides. Paper 730154, SAE, January, 1973.

111. Sakai, Yasuo,; Kunii, Kazuya; Tsutsumi, Saburo; and Nakagawa, Yasuhiko; Nissan Motor Co., Ltd. (Japan): Combustion Characteristics of the Torch Ignited Engine. Paper 741167, SAE, November, 1974.

112. Sallee, G. P.; American Airlines, Inc.: Status Report on Aircraft and Airports as Sources of Pollution. Paper 710318, (P-37), SAE Transactions, Volume 80, 1971.

113. Schiele, Carl A.; Environmental Activities Staff, General Motors Corp.; and DeNagel, Stephen F.; and Bennethum, James E.; Research Labs., General Motors Corp.: Design and Development of a Variable Valve Timing (VVT) Camshaft. Paper 740102, SAE, March, 1974.

114. Schoeppel, R. J.: Design Criteria for Hydrogen Burning Engines. Report Number APTD-0901, Oklahoma State University, October, 1971.

115. Schweikert, John F.; and Johnson, John H.; Michigan Technological University: A Turbocharged Spark Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy. Paper 730633, SAE, June, 1973.

116. Springer, K. J.: An Investigation of Diesel-Powered Vehicle Emissions, Part V. Report No. AR-936, Southwest Research Institute, April, 1974.

117. Springer, K. J.; and Ashby, H. A.: The Low Emission Car for 1975 - Enter the Diesel. Paper No. 739133, Intersociety Energy Conversion Engineering Conference, August, 1973.

118. Springer, Karl J.; Southwest Research Institute; and Stahman, Ralph C.; Environmental Protection Agency: Diesel Emission Control through Retrofits. Paper 750205, SAE, February, 1975.

119. Springer, Karl J.; Southwest Research Institute; and Stahman, Ralph C.; Environmental Protection Agency: Emissions and Economy of Four Diesel Cars. Paper 750332, SAE, February, 1975.

120. Springer, Karl J.; Southwest Research Institute; and White, John T.; and Domke, Charles J; Environmental Protection Agency: Emissions from In-Use 1970-1971 Diesel-Powered Trucks and Buses. Paper 741006, SAE, October, 1974.

BIBLIOGRAPHY - Continuted

121. Stebar, R. F.; and Parks, F. B.; Research Labs., General Motors Corp.: Emission Control with Lean Operation Using Hydrogen-Supplemented Fuel. Paper 740187, SAE, March, 1974.

122. Suzuki, Takashi; and Usami, Kozi; Hino Motors, Ltd. (Japan): A Modification of Combustion Systems for Low Exhaust Emission and Its Effects on Durability of Prechamber Diesel Engine. Paper 760213, SAE, February, 1976.

123. Tabaczynski, Rodney J.; and Klomp, Edward D.; Research Lab., Div., General Motors Corp.: Calculated Nitric Oxide Emissions of an Unthrottled Spark Ignited, Stratified Charge Internal Combustion Engine. Paper 741171, SAE, November, 1974.

124. Tanuma, Takeshi; Sasaki, Kenichi; Kaneko, Touru; and Kawasaki, Hajime; Nissan Motor Co., Ltd.: Ignition, Combustion, and Exhaust Emissions of Lean Mixtures in Automotive Spark Ignition Engines. Paper 710159, SAE Transactions, Volume 80, 1971.

125. Thomas, Stanley R., Jr.; Lawrence Livermore Laboratory: Characteristics of a Four Cylinder Hydrogen-Fueled Internal Combustion Engine. Paper 760100, SAE, February, 1976.

126. Thompson, J. C.: A Report on the Emission Performance of the Ford Stratified Charge Engine Using the 1975 Test Procedure. Report Number APTD-1386, Environmental Protection Agency, August, 1971.

127. Thomson, J. C.: An Evaluation of a Variable Cam Timing Technique as a Control Method for Oxides of Nitrogen. Report Number APTD-1431, National Air Pollution Control Administration, October, 1970.

128. Thomson, J. C.: Exhaust Emissions on an Uncontrolled Passenger Car Using Variable Cam Timing. NTIS Report Number APTD-1437, National Air Pollution Control Administration, August, 1970.

129. Turkish, Michael C.; Eaton Corporation: 3-Valve Stratified Charge Engines: Envolvement, Analysis and Progression. Paper 741163, SAE, November, 1974.

130. Urban, C. M.; Springer, K. J.; and Montalvo, D. A.: Emissions Control Technology Assessment of Heavy Duty Vehicle Engines. Report Number EPA-460/3-74-007, Southwest Research Institute, December, 1973.

131. Uyehara, O. A.; and Myers, P. S.; University of Wisconsin; and Marsh, E. E.; and Cheklich, G. E.; Army Tank Automotive Command: A Classification of Reciprocating Engine Combustion Systems. Paper 741156, SAE, November, 1974.

BIBLIOGRAPHY - Continued

132. Varde, K. S.; University of Michigan; and Lucas, G. G.; University of Michigan; and Lucas, G. G.; University of Technology (United Kingdom): Effects of Pressure Variations and Combustion Duration on the Emission of Hydrocarbons and Nitric Oxide. Paper 760142, SAE, February, 1976.

133. Walder, C. J.; Ricardo & Co. Engineers (1927) Ltd.: Reduction of Emissions from Diesel Engines. Paper 730214, SAE, January, 1973.

134. Warren, Glenn B.; and Bjerklie, J. W.; Mechanical Technology Inc.: Proposed Reciprocating Internal Combustion Engine with Constant Pressure Combustion in a Combustion Chamber Separated from Cylinders (Modified Brayton Cycle). Paper 690045, SAE, January, 1969.

135. Watfa, M., D. E.: The Effects of Charge Stratification on Nitric Oxide Emission from Spark Ignition Engines. Paper 741175, SAE, November, 1974.

136. Weil, K. H.: The Hydrogen I. C. Engine - Its Origins and Future in the Emerging Energy - Transportation - Environment System. Report Number N74-18403, Stevens Institute of Technology, 1974.

137. Wentworth, J. T.; Research Labs., General Motors Corp.: Effects of Combustion Chamber Shape and Spark Location on Exhaust Nitric Oxide and Hydrocarbon Emissions. Paper 750529, SAE, June, 1974.

138. Westfield, William T.; Federal Aviation Administration: The Current and Future Basis for Aircraft Air Pollution Control. Paper 710339 (P-37), SAE Transactions, Volume 80, 1971.

139. Wigg, Eric E.; Esso Research and Engineering Co.: Reactive Exhaust Emissions from Current and Future Emission Control Systems. Paper 730196, SAE, January, 1973.

140. Wimmer, D. B.; and Lee, R. C.; Phillips Petroleum Co.: An Evaluation of the Performance and Emissions of a CFR Engine Equipped with a Prechamber. Paper 730474, SAE, May, 1973.

141. Witzky, J. E.; and Clark, J. M. Jr.; Southwest Res. Institute: A Study of the Swirl Stratified Charge Combustion Principle. Paper 660092, SAE Transactions, Volume 75, 1966.

142. Yagi, Shizuo,; Date, Tasuku; and Inoue, Kazuo; Honda R&D Co., Ltd. (Japan): NO_x Emissions and Fuel Economy of the Honda CVCC Engine. Paper 741158, SAE, November, 1974.

143. Yagi, Shizuo; Fujii, Isao; Narasaka, Mori and Shin: On the Emission-Combustion Temperature Relationship in the CVCC Engine. Paper 760109, SAE, February, 1976.

BIBLIOGRAPHY - Concluded

144. Yun, H. J.; and Lo, R. S.; Ford Motor Company; and Na, T. Y.; The University of Michigan, Dearborn Campus: Theoretical Studies of Fuel Droplet Evaporization and Transportation in a Carburetor Venturi. Paper 760289, SAE, February, 1976.

145. Zechnall, Richard; Baumann, Guenther; and Eisele, Hermann; Robert Bosch, GmbH (Germany): Closed-Loop Exhaust Emission Control System with Electronic Fuel Injection. Paper 730566, SAE, May, 1973.

146. Zegel, W. C.; Souza, A. F.; and Reckner, L. R.; Scott Research Labs: Exhaust Emissions of Light Aircraft. Paper 710370, SAE Transactions, Volume 80, 1971.

147. Zimmerman, Klaus D.; Robert Bosch GmbH (Germany): New Robert Bosch Developments for Diesel Fuel Injection. Paper 760127, SAE, February, 1976.