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# AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

## QUARTERLY TECHNICAL PROGRESS REPORT FOR PERIOD: MARCH 30 - JUNE 28, 1980

Mechanical Technology Incorporated

August 1980

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-32

for
**U.S. DEPARTMENT OF ENERGY**
**Conservation and Solar Applications**
**Office of Transportation Programs**

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# AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM TECHNICAL PROGRESS REPORT FOR PERIOD: MARCH 30 - JUNE 28, 1980

STIRLING ENGINE SYSTEMS DIVISION
Mechanical Technology Incorporated
Latham, New York 12110

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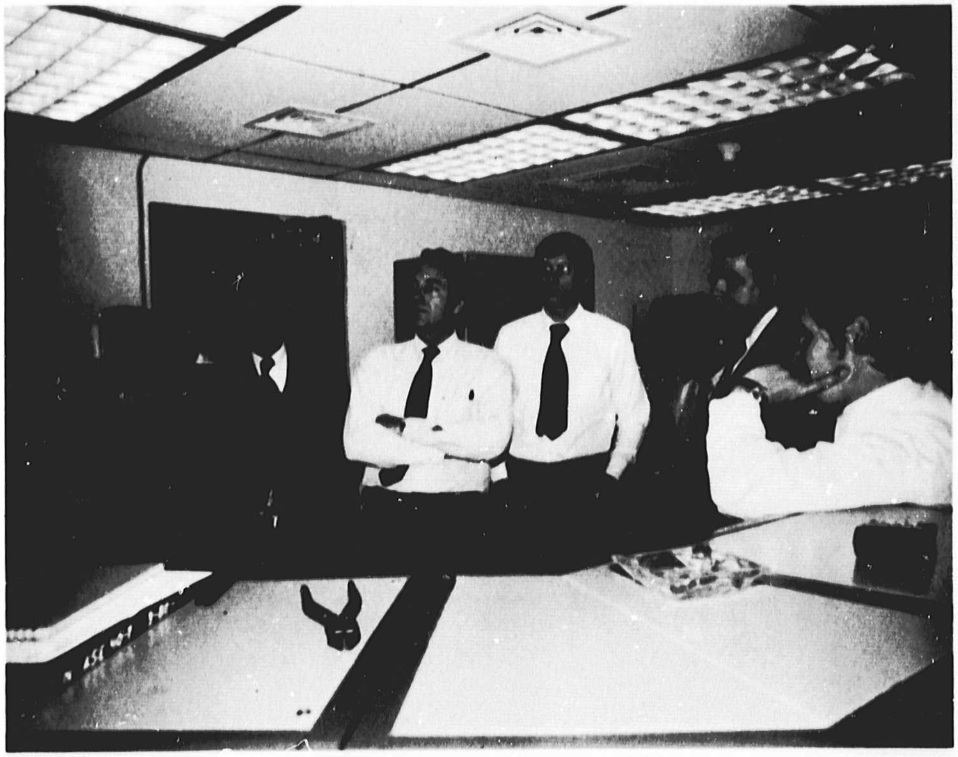
Office of Transportation Programs
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1040

Operating Room of MTI Stirling Engine Test Cell



Visit by Congressman Tom Harkin, Chairman of the House Science and Technology Subcommittee on Transportation, Aviation and Communications (second from left)

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# 1.0 SUMMARY

The DOE/NASA "Automotive Stirling Engine Development Program" has been underway for approximately 27 months. This is the ninth quarterly report to be issued, and it covers the period of March 30 - June 28, 1980.

Prior reports [1, 2, 3, 4, 5, 6]* discussed component and subsystem effort, the Reference Engine System Design and the program's first and second Stirling engine-powered vehicles, the 1977 Opel and the 1979 AMC Spirit containing United Stirling of Sweden (USS) P-40 Stirling engines. The P-40 engine is the program's baseline Stirling engine originally developed as a stationary laboratory engine. It is heavy and underpowered for the vehicles, but was installed in the vehicles in order to obtain engine-vehicle integration experience, experience with Stirling powered vehicles in testing, and to demonstrate the concept of Stirling engines applied to automobile propulusion.

The technology of Stirling engines as applied to automobile propulsion is presented in MTI's report "Assessment of the State of Technology of Automotive Stirling Engines" [7]. This very comprehensive report gives the background and history of the Stirling engine; it discusses the technology, materials, components, controls, and systems; and it presents a technical assessment of automotive Stirling engines.

The previous quarterly report [8] presented information on the Reference Engine design and the design of the ASE Mod I (Automotive Stirling Engine Model No. I) as presented to NASA in January 1980. The report also reviewed component and subsystem development activities, the testing of the baseline P-40 engines, the progress being made on computer code developments, and it presented data on the screening of potential seals materials.

This quarterly report presents updated information on the Reference Engine and the ASE Mod I as presented to NASA at the Design Review Meeting held in May. NASA has approved the updated Reference Engine and ASE Mod I designs, and manufacturing/procurement has started. The ASE Mod I is the program's first Stirling engine designed specifically for automotive use; it is a steppingstone to the program's final prototype engine, the ASE Mod II. Current information is presented on component and subsystems development activities and engine and vehicle testing. Computer code development progress is also covered.

Program engine operating hours through the end of this quarterly period (through June 28, 1980) reached the following:

| Engine No. | Total Hours |
|---|---|
| ASE 40-4 (High Temperature Endurance Test Engine) | 4,610.3 |
| ASE 40-5 (Opel Engine) | 190.0 |
| ASE 40-7 (MTI Test Engine) | 74.9 |
| ASE 40-8 (Spirit Engine) | 178.8 |
| ASE 40-12 (Engine for the Concord) | 41.0 |
| Total | 5,095.0 |

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*References are listed by number in Section 4.0

# 2.0 INTRODUCTION

The Automotive Stirling Engine Development Program is directed at the development of technology and knowledge related to the application of Stirling engines to automotive use, and the transfer of Stirling engine technology to the United States. The high efficiency and low emissions potential of the Stirling engine makes it a prime candidate for automotive propulsion. This contract is directed towards developing the necessary technology, by 1984, to demonstrate these potentials.

MTI, the prime and systems contractor, is responsible for overall program management, alternative and high risk component and systems development, engine and vehicle testing and evaluation, computer code development, and transfer of Stirling engine technology to the United States.

The engine development program is based upon the extensive technological achievements, capabilities, and background knowledge in Stirling engines of KB United Stirling (Sweden) AB & Co. (USS), acting as a subcontractor to MTI.

AM General Corporation (AMG), a wholly owned subsidiary of American Motors Corporation, is the subcontractor responsible for automotive selection, design, integration, and evaluation of Stirling engines installed in passenger cars.

## 2.1 Final Program Objectives

The final Program objectives will be to develop and demonstrate, by September 1984, an Automotive Stirling Engine System which when installed in a late-model production vehicle will meet the following objectives:

1. Using EPA test procedures, demonstrate at least a 30% improvement in combined metro-highway fuel economy over that of a comparable production vehicle. The comparison production vehicle will be powered by a conventional spark-ignition engine. Both the Automotive Stirling and spark-ignition engine systems will be installed in identical model vehicles and will give substantially the same overall vehicle driveability and performance. The improved fuel economy will be based on unleaded gasoline of the same energy content (Btu/gal).

   It is intended that identical model vehicles be used for the comparison. However, a difference in inertia weight between the two vehicles is acceptable if the difference results from the substitution of the Automotive Stirling engine system for the spark ignition powertrain system. The transmission, torque converter, and drivetrain may also differ in order to take advantage of Stirling engine characteristics.

2. Show the potential of gaseous emissions and particulate levels less than the following: NOx = 0.4, HC = .41, CO = 3.4 gm/mile and a total particulate level of 0.2 gm/mile after 50,000 miles.

   The potential need not be shown by actual 50,000 mile tests, but can be shown by Contractor projections based on available engine, vehicle, and component test data and emissions and particulate measurements taken at EPA using the same fuel as used for the EPA fuel economy measurements.

The emissions and particulate measurements will be based on EPA procedures for the metro cycle and will use the same fuel used for fuel economy measurements.

In addition to the above objectives that are to be demonstrated quantitatively, the following design objectives are considered goals of the program.

1. Ability to use a broad range of liquid fuels from many sources, including coal and shale oil. This objective will be pursued initially in the combustor development effort and later in engine and vehicle testing. The candidate alternative fuels and their characteristics, to be considered in this Program, will be identified based on the DOE Alternative Fuels effort. Until these specific fuels and their characteristics are identified for inclusion in the Program, diesel fuel, gasohol, kerosene, and No. 2 heating oil will be used as a representative range of alternate fuels. Engine tests with the alternate fuels will not be initiated for the ASE Mod I and ASE Mod II engines until satisfactory operation, performance, and emissions have been achieved on the baseline fuel -- gasoline. Testing will then be conducted with the selected alternative fuels to determine the extent of any detrimental effects on engine operation, performance, emissions, or fuel economy and to determine the degree of modifications or adjustments that might be required in switching from one fuel to another.

2. Reliability and life comparable with powertrains currently on the market.

3. A competitive initial cost and a competitive life-cycle cost with a comparable conventionally-powered automotive vehicle.

4. Acceleration suitable for safety and consumer considerations.

5. Noise and safety characteristics that meet the currently legislated or projected Federal Standards for 1984.

## 2.2 Program Major Milestones

Progress toward achieving these Final Program Objectives, which will be demonstrated by dynamometer and vehicle testing, will be assessed at several points in the program. Specific milestones will be:

1. ASE Mod I Basic Engine design freeze prior to March 31, 1980.

2. Dynamometer characterization of the first build of ASE Mod I engine at the Contractor's facility prior to September 30, 1981.

3. Dynamometer characterization of ASE Mod I (updated) engine prior to September 30, 1982.

4. ASE Mod I engine system test in a vehicle at EPA prior to September 30, 1983.

5. Dynamometer characterization of ASE Mod II engine at the Contractor's Facility prior to September 30, 1983.

6. Complete ASE Mod II engine system test in a vehicle at EPA prior to September 30, 1984.

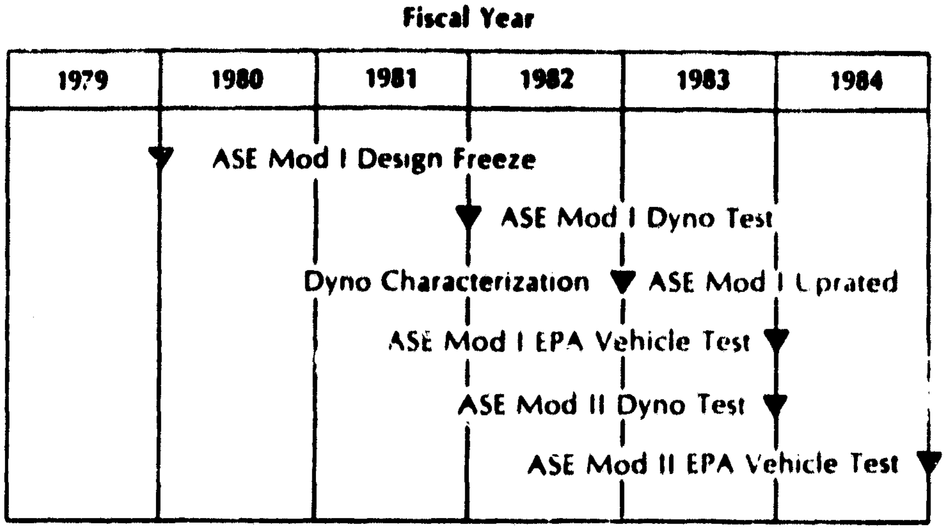

Figure 2.0-1 Program Milestones

## 2.3 Task Description

### MAJOR TASK 1 - REFERENCE ENGINE

This task is intended to guide component, subsystem, and engine system development. A reference engine system design will be generated and continually updated to reflect the best contemplated approaches and the latest technology to meet the final program objectives. The reference engine system will be the focal point to guide development, will be based on approved engine system concepts, and will include anticipated 1990 vehicle power level and size for equivalent spark ignition, diesel, and stratified charge engines.

## Task 1.1 Initial Technology Assessment

A comprehensive technical assessment will be made of the present status and level of technology of Stirling engines as candidates for automotive power plants. This assessment will be directed at, but not limited to, the status of United Stirling of Sweden's engine design and development technology. When completed, the Initial Technology Assessment will be used as a basis for a detail study and reevaluation of the overall technical program plan.

- This task has been completed through the issuance of a final report in September 1979.

## Task 1.2 Reference Engine System Design

A series of conceptual Stirling engine system designs will be produced to meet the final program objectives. Analyses and drawings will be prepared in sufficient detail to be able to assess the potential advantages and disadvantages of the candidate concepts, including material costs. Available transmission technologies, accessory systems, auxiliary systems, and alternate power control systems will be evaluated. Transmission and drive train arrangements and vehicle installation will be assessed. Sufficient design and analyses will be performed to establish performance requirements of the engine and components to meet the required vehicle performance and the final program objectives.

The Reference Engine System Design (RESD) will be the best engine design that can be generated at any given time that will provide the best possible fuel economy and will also meet or exceed all other Final Program objectives. It will be designed to meet the requirements of the projected reference vehicle, which will be representative of the class of vehicles for which the engine might first be produced. It will utilize all new technology that can reasonably be expected to be developed by 1984 and which is judged to provide significant improvement relative to the risk and cost of its development.

In general, all technology advancements that are to be worked on in the Program will be incorporated into the Reference Engine System Design (RESD) and their payoff will be quantified prior to initiation of the technology development. Since there may be more than one attractive technology option for a given component, subsystem, or system which merits development, it may be desirable and necessary to generate one or more alternative designs in addition to the primary design of the RESD. Such alternative designs might range from incorporating high risk, high pay-off alternatives, to providing more conservative reduced risk back-up approaches. As the development program proceeds, actual test experience may eliminate one or more of these back-up approaches, or it may dictate a reduction in performance relative to initial expectations.

- The RESD was generated early in the Program. It will be continually updated to reflect development experience and technology growth.

## MAJOR TASK 2 - COMPONENT AND SUBSYSTEM TECHNOLOGY DEVELOPMENT

Development activities will be conducted on all required component and subsystem development tasks as guided by the Reference Engine System Design (RESD) to support the various Stirling Engine Systems (SES) being developed. The component and subsystem development activities will include conceptual and detail design and analyses, hardware fabrication and assembly, and component and subsystem testing in laboratory test rigs. When an adequate performance level is achieved, the component and/or subsystem design will be configured for in-engine testing and evaluation in appropriate engine dynamometer and vehicle test installations. Design efforts will be carried out with consideration of cost and manufacturing feasibility.

Effort will proceed according to an overall Program Component and Subsystem Development Plan and detailed, individual, Component and Subsystem Test Plans, which will be submitted to the NASA Project Manager for review and approval. At the completion of each significant component or subsystem development effort, a report will be prepared and submitted to the NASA Project Manager. These reports will define the designs, define new fabrication techniques developed, describe the development effort, and present the results.

The following development activities will be carried out to advance the technology in terms of durability, reliability, performance, cost, and fabrication:

Task 2.1 Combustion Technology Development

Task 2.2 Heat Exchanger Technology Development

Task 2.3 Materials Development

Task 2.4 Mechanical Component Development of Seals

Task 2.5 Mechanical Component Development of the Engine Power Chain

Task 2.6 Controls Technology Development

Task 2.7 Auxiliaries Development

Task 2.8 United Stirling Project Support

Task 2.9 United Stirling Component Development (Directed towards ASE Mod I and ASE Mod II)

- Effort on components and subsystems are underway.

## MAJOR TASK 3 - TECHNOLOGY FAMILIARIZATION (BASELINE ENGINE)

The existing USS P-40 Stirling engine will be used as a baseline engine for Stirling engine familiarization and as a test bed for component and subsystem performance improvement. It will also be used to evaluate current engine operating conditions and component characteristics, and to define problems associated with vehicle installation. Four P-40 Stirling engines will be built and delivered to the United States team members, with one installed in a 1979 AMC vehicle. A fifth P-40 Stirling engine will be built and installed in a 1977 Opel sedan.

The baseline P-40 engines will be tested in dynamometer test cells as well as in the automobiles. Test facilities will be planned and constructed at MTI to accomodate the entire program.

### Task 3.1 - Baseline Engine (P-40)

USS will manufacture four P-40 engines, including spare parts. Engine/dynamometer testing will include full and part power operation, transient and cyclic operation, start-stop cycles, and endurance testing. Complete engine performance maps of fuel consumption, emissions, power, and torque versus engine speed over the full range of engine operating pressure levels will be obtained over the entire anticipated range of operating heater head temperatures, combustor flows, inlet temperatures, coolant temperatures, coolant flows, and coolant inlet temperatures.

Tests will be run with the complete Stirling engine system as designed (with all auxiliaries installed and operating off engine power). Where appropriate, selected auxiliaries and/or ducting may be simulated, or compensated for. Tests will also be run with all auxiliaries removed and their functions provided by test facilities, or compensated for.

AMG will modify an AMC vehicle for the P-40 engine, in the first year of the program, thereby gaining experience and knowledge on the integration problems and requirements associated with the installation of a Stirling engine in a passenger car. Limited vehicle testing will be conducted by AMG to establish baseline vehicle-affected engine performance, such as: fuel consumption,.emissions, and under-hood environment. The vehicle installation and test is designed to familiarize AMG and other team members with a Stirling engine equipped vehicle and its performance and operation. It will also establish baseline performance for the total program, including durability.

- P-40 engines have been delivered by USS, installed in vehicles and dynamometer test stands, and testing is well underway.

### Task 3.2 - Facilities

The test facilities and equipment necessary to completely evaluate engines and components will be designed, built, and procured at MTI. It is anticipated that this will include installation at MTI of two engine test cells with appropriate data acquisition equipment and five component test cells to be used for component development purposes.

- Facilities progress is on schedule.

### Task 3.3 - P-40/Opel Test Vehicle

One P-40 engine will be manufactured and installed in a 19[illegible] Opel Rekord 2100D diesel engine-powered automobile to establish baselines for comparison with other program generated Stirling engine-powered automobiles. Vehicle tests will be conducted on a chassis dynamometer and by road testing, in order to measure parameters such as fuel economy, emissions, driveability, and noise.

- This task was completed, and reported in January, 1979. [6,7]

## MAJOR TASK 4 - ASE MOD I ENGINE SYSTEM

A first generation Automotive Stirling Engine (ASE) will be developed. ASE Mod I will use the United Stirling P-40 and P-75 engines as a basis for improvement. The prime objective will be to improve power density and overall engine performance. The ASE Mod I engine will be an experimental version of the RESD. It will be limited by the technology which can be confirmed in the time available. It need not achieve any specific fuel economy improvement, but will be utilized to verify the basic RESD and to serve as a stepping stone toward the ASE Mod II engine. It will provide an early indication of the potential to meet the Final Program Objectives. A preliminary design and analysis will be made of the engine and its installation in an automobile which will include the preparation of detailed layout drawings defining critical features, dimensions, materials, and fabrication techniques. Appropriate analyses will be performed to predict engine system and component performance, in-vehicle performance of the engine system, and appropriate stress and thermal loads. Potential problem areas will be identified.

A Design Review Meeting will be held with NASA to review the results of the engine preliminary design. Information to be presented at the design review will include layout drawings, materials, fabrication techniques, and the results of performance, stress, and thermal analyses.

Seven engines and adequate spares will be manufactured by USS and the engines will be tested in dynamometer test cells to establish performance, durability, and reliability. Continued testing and development may be necessary in order to meet the preliminary design performance predictions. One additional ASE Mod I engine will be manufactured in the United States; USS drawings will be used, but United States vendors will be used to manufacture the engine.

Engine/dynamometer testing will include full and part power operation, transient and cyclic operation, start-stop cycles, and endurance testing. Complete engine performance maps of fuel consumption, emissions, power, and torque, versus engine speed over the full range of engine operating pressure levels, will be obtained over the entire anticipated range of operating heater head temperatures, combustor flow, inlet temperatures, coolant temperatures, coolant flows, and coolant inlet temperatures.

Tests will be run with the complete Stirling engine system as designed (with all auxiliaries installed and operating off engine power). When appropriate, selected auxiliaries and/or ducting may be simulated or compensated for. Tests will also be run with all auxiliaries removed and their functions provided by test facilities or compensated for. The full range of engine transient characteristics will be determined, including startup, shutdown, and typical power and speed transients. Tests will be run both with and without the selected vehicle transmission system, as appropriate.

Four production vehicles will be procured and modified to accept the manufactured engines and the engines will be installed in the vehicles. One of the four vehicles will be an engineering-evaluation front-wheel drive vehicle. Tests will be conducted on the engine-powered automobiles to establish engine-related driveability, fuel economy, noise, emissions, and durability/reliability. Tests will be performed under various steady state, transient, and environmental conditions. One vehicle will be delivered to EPA prior to March 31, 1983, for vehicle assessment by EPA.

- Design effort is underway in preparation for a basic engine design review with NASA-LeRC in January 1980.

## MAJOR TASK 5 - ASE MOD II ENGINE SYSTEM

The second generation engine will be designed, fabricated and tested. It will be power rated according to the reference engine system studies, using the first generation engine system as the basis for improvement. The prime objective will be to upgrade the first generation engine system to improve efficiency, and to improve durability and reliability.

Only high confidence level component and subsystem developments will be used. The design will reflect the use of automotive engineering design and fabrication techniques to the maximum extent possible. Emphasis will be on performance and durability/reliability. The ASE Mod II engine could differ from the RESD by the use of small quantity fabrication techniques and special provisions for instrumentation, parts replacement, and servicing.

A preliminary design and analysis will be made of the engine and its installation in an automobile which will include the preparation of detailed layout drawings defining critical features, dimensions, materials, and fabrication techniques. Appropriate analyses will be performed to predict engine system and component performance, in-vehicle performance of the engine system, and appropriate stress and thermal analyses. Potential problem areas will be identified.

A Design Review Meeting will be held with NASA to review the results of the engine preliminary design. Information to be presented at the design review will include layout drawings, materials, fabrication techniques, and the results of performance, stress, and thermal analyses.

Five engines and adequate spares will be manufactured and the engines will be tested in dynamometer test cells to establish performance, durability, and reliability. Continued testing and development may be necessary in order to meet the preliminary design performance predictions.

Engine/dynamometer testing will include full and part power operation, transient and cyclic operation, start-stop cycles, and endurance testing. Complete engine performance maps of fuel consumption, emissions, power, and torque, versus engine speed over the full range of engine operating pressure levels, will be obtained over the entire anticipated range of operating heater head temperatures, combustor flows, inlet temperatures, coolant temperatures, coolant flows, and coolant inlet temperatures.

Tests will be run with the complete Stirling engine system as designed (with all auxiliaries installed and operating off engine power). When appropriate, selected auxiliaries and/or ducting may be simulated or compensated for. Tests will also be run with all auxiliaries removed and their functions provided by test facilities or compensated for. The full range of engine transient characteristics will be determined, including startup, shutdown, and typical power and speed transients. Tests will be run both with and without the selected vehicle transmission system, as appropriate.

Three late-model front-wheel drive production vehicles will be procured and modified to accept the manufactured engines and the engines will be installed in the vehicles. Tests will be conducted on the engine-powered automobiles to establish engine-related driveability, fuel economy, noise, emissions and durability/reliability. Tests will be performed under various steady state, transient and environmental conditions. One vehicle will be delivered to EPA prior to April 30, 1984 for EPA assessment of the vehicle to meet the Final Program Objectives of fuel economy and exhaust emissions.

- Design effort will not start until PY 1981.

## MAJOR TASK 6 - PROTOTYPE ASE SYSTEM STUDY

A study will be undertaken to describe the effort required to bring the Automotive Stirling Engine from its expected state of development in September 1984 to the start of production engineering. Engine production cost, life cost, operating condition, in-service maintenance requirements, and vehicle-imposed loads and constraints will be studied. Consideration will be given to mass production fabrication techniques. In addition, the prototype ASE system will incorporate the final levels of technology necessary before going into production.

The results of this study will be incorporated into a plan which will be submitted to the NASA Project Manager by September 30, 1983. The plan will describe the development steps required, the schedule of events, and the estimated cost. In addition, the development risk will be assessed and the plan will include supportive manufacturing and cost information. The plan will form part of the basis for a Government decision regarding the extent of its support, if any, for system development activities beyond the scope of this contract.

- This task will start in 1982.

## MAJOR TASK 7 - COMPUTER PROGRAM DEVELOPMENT

Analytical tools will be developed which are required to simulate and predict engine performance, as well as to aid in the design, development, optimization, and evaluation of engine hardware. This effort will include the development of three comprehensive computer programs specifically tailored to: (1) predict Stirling engine system steady state cyclical performance over the complete range of engine operations; (2) optimize the Stirling engine system to maximize and/or minimize specified physical and/or performance characteristics while satisfying given system constraints; (3) evaluate the effects of Stirling engine control system selection on engine transient response to arbitrary power changes. The computer programs will be structured to be user oriented and to have high portability.

The computer programs will be designed and structured to predict the performance of given engine and component configurations and should not be confused with engine and component design computer programs that are used to design physical hardware (i.e., heater head designs, regenerator designs, bearing load computations, stress analysis, dynamics, etc.).

In addition to delivering the source codes for the library of computer programs developed, complete documentation will be provided to describe the logic structure, detailed theory, assumption, operating procedures, demonstrated validity, ranges of applicability, sample problems, etc. for each program. In addition to delivering the final, fully verified version of each program, interim partially verified versions of each program will also be delivered.

The programs will be improved and verified on a continuing basis throughout the course of the program, using data from component, subsystem, and engine system test activities. The test data so utilized will be identified and provided for each program.

In addition to the engine configurations to be specifically investigated, the performance prediction and optimization programs will be correlated against the three engine configurations and performance data to be supplied by NASA.

It is anticipated that several engine systems will be investigated over the course of the contract. The engine performance prediction program will allow for either separate or simultaneous engine/drive system analysis. In addition to the determination of engine piston dynamics, the drive system modeling will include evaluation of the bearing, slip, windage, and pumping losses associated with each drive system concept.

- Effort is underway and the first programs are expected to be completed in mid-1980.

## MAJOR TASK 8 - TECHNICAL ASSISTANCE

Technical assistance to the Government, as requested, will be provided pursuant to the Technical Direction Clause of the contract. This effort will include: Stirling engine and/or vehicle systems for DOE/NASA demonstration purposes; models and displays for use at Government and professional society technical meetings; computer program assistance to evaluate various NASA specified engine modifications, parametric engine variations and engine operating modes; training of personnel in the operation, assembly and maintenance of Stirling engine systems and vehicles delivered to NASA; appropriate communication media including brochures, audio-visual materials, other literature, and independent studies after approval from NASA.

- Effort is underway pursuant to specific Technical Directives received from NASA-LeRC.

## MAJOR TASK 9 - PROGRAM MANAGEMENT

This task defines the total program control, administration and management, including reports, schedules, financial activities, test plans, meetings, reviews, seminars, training, and technology transfer.

Task elements include:

- Program management.
- Technical direction.
- Product Assurance.
- Monitoring of technical and financial progress.
- Report preparation, publication and distribution.
- Preparation of test plans, work plans, design reviews, etc.
- Coordination of monthly meetings, review meetings, etc.
- Transfer of technology to the United States.
- Training of personnel.
- Seminars and technical society presentations.
- Attendance and coordination of government meetings and presentations
- Engineering drawings and installation, operation and maintenance manuals.
- Other items related to overall program management and control.

Figure 2.0-2 is the Work Breakdown Structure of the Automotive Stirling Engine Development Program at the level of reporting to NASA.

- Effort will continue throughout the program.

- 1.0 REFERENCE ENGINE
  - 1.1 Initial Technology Assessment
  - 1.2 Reference Engine System
    - 1.2.1 Project Engineering
    - 1.2.2 USS Engineering Assistance
    - 1.2.3 AMG Engineering Assistance
    - 1.2.4 Reference Engine Analysis
    - 1.2.5 Advanced Concepts Studies
- 2.0 COMPONENT & SUBSYSTEMS DEVELOPMENT
  - 2.1 Combustion Technology Development
  - 2.2 Heat Exchanger Technology Development
  - 2.3 Materials Development
  - 2.4 Mechanical Component Development (Seals)
  - 2.5 Mechanical Component Development (Power Chain)
  - 2.6 Controls Technology Development
  - 2.7 Auxiliaries Development
  - 2.8 USS Projects
  - 2.9 USS Component & Subsystems Development
    - 2.9.1 Baseline Engine
    - 2.9.2 ASE Mod I Engine
      - 2.9.2.1 External Heat System
      - 2.9.2.2 Hot Engine System
      - 2.9.2.3 Cold Engine System
      - 2.9.2.4 Engine Drive System
      - 2.9.2.5 Controls & Auxiliaries
      - 2.9.2.6 Stirling Engine Systems
      - 2.9.2.7 Vehicle Applications
    - 2.9.3 ASE Mod II
      - 2.9.3.1 SES Component/Subsystems Development
        - 2.9.3.1.1 External Heat System
        - 2.9.3.1.2 Hot Engine System
        - 2.9.3.1.3 Cold Engine System
        - 2.9.3.1.4 Engine Drive System
        - 2.9.3.1.5 Controls & Auxiliaries
      - 2.9.3.2 Materials Development
      - 2.9.3.3 P-40 Annular Regenerator
      - 2.9.3.4 Full-Scale Mod II Involute Heater
      - 2.9.3.5 BSE Mod I Components Testing

Figure 2.0-2 Work Breakdown Structure

- 3.0 TECHNOLOGY FAMILIARIZATION

  - 3.1 P-40 Program

    - 3.1.1 Project Engineering
    - 3.1.2 Mfg. and Assemble Engines
    - 3.1.3 Evaluate Engines
    - 3.1.4 Evaluate Engine/1979 Spirit

  - 3.2 Test Facility at MTI

    - 3.2.1 Project Engineering
    - 3.2.2 Design of Integrated Facility
    - 3.2.3 Equip Engine Test Cell
    - 3.2.5 Construct Integrated Facility
    - 3.2.7 Maintenance & Repair

  - 3.3 P-40 Opel

- 4.0 ASE Mod I

  - 4.1 Project Engineering
  - 4.2 Analysis & Design
  - 4.3 Manufacture Engines

    - 4.3.1 External Heat System
    - 4.3.2 Hot Engine System
    - 4.3.3 Cold Engine System
    - 4.3.4 Engine Drive System
    - 4.3.5 Controls & Auxiliaries
    - 4.3.6 Stirling Engine Systems

  - 4.4 Assembly & Acceptance Test
  - 4.5 Engine Test Program

    - 4.5.1 Engine #1
    - 4.5.2 Engine #2
    - 4.5.3 Engine #6

  - 4.6 Vehicle Test Program

    - 4.6.1 Engine #3/1979 Spirit
    - 4.6.2 Engine #5/Vehicle Evaluation (AMG)
    - 4.6.3 Engine #4/Vehicle Evaluation (MTI)
    - 4.6.4 1981 FWD Vehicle/Engine #7 Evaluation

  - 4.7 USA Engine

    - 4.7.1 Manufacture/Procurement
    - 4.7.2 Assembly & Test

Figure 2.0-2 Work Breakdown Structue (Cont'd)

5.0 ASE Mod II

- 5.1 Project Engineering
- 5.2 Analysis & Design
- 5.3 Manufacture Engines
    - 5.3.1 External Heat System
    - 5.3.2 Hot Engine System
    - 5.3.3 Cold Engine System
    - 5.3.4 Engine Drive System
    - 5.3.5 Controls/Auxiliaries
    - 5.3.6 Stirling Engine System
- 5.4 Assemble & Acceptance Test
- 5.5 Engine Test Program
    - 5.5.1 Engine #1 Evaluation (USS)
    - 5.5.2 Engine #4 Evaluation (MTI)
- 5.6 Vehicle Test Program
    - 5.6.1 Vehicle/Engine #3 Test (USS)
    - 5.6.2 Vehicle/Engine #2 Test (AMG)
    - 5.6.3 Vehicle/Engine #5 Test (MTI)

6.0 MANUFACTURING & MARKET STUDIES

7.0 COMPUTER PROGRAM DEVELOPMENT

8.0 TECHNICAL ASSISTANCE

9.0 PROGRAM MANAGEMENT

- 9.1 MTI Program Management
- 9.2 AMG Program Management
- 9.3 USS Program Management

Figure 2.0-2 Work Breakdown Structure (Concluded)

# 3.0 PROGRESS SUMMARIES

The description of the work to be performed under the contract was presented in section 2.0. This section of the report presents the details of the work accomplished on each task during the period of March 30 - June 28, 1980.

## 3.1 MAJOR TASK 1 - REFERENCE ENGINE

The first Engine Design Task Team Meeting was held in Sweden on April 16-17 to discuss stress analysis approaches which need experimental verification. Task Team members are preparing plans for management review and consideration for this experimental verification.

A Material/Design/Structure meeting was held at MTI in June to establish the design criteria for Stirling engine components. Among the topics discussed were: stress analysis techniques, strength criteria requirements, and material selection.

The first RESD Design Review update was held at NASA-LeRC on May 21, 1980 in order to update the January 1980 RESD. The RESD projections show a metro-highway mileage of 42.13 mpg with unleaded gasoline and a cold start penalty (CSP), and 48.45 mpg with diesel fuel and CSP. The following are the major updated revisions:

- Engine Drive Friction

  Bearing friction losses were reduced by reducing the connecting rod and main bearing dimensions. Further friction reduction was achieved by reducing the axial thrust of the helical synchronizing gear, (Ricardo's research had previously shown that a reduction of the helix angle and the tooth module could reduce the noise level) to increase the gear efficiency from 98 to 98.5%. All of these changes resulted in a friction loss reduction of 1.4 kW at the full load point.

  The oil viscosity used in the bearing friction calculation was high (22 cp.); the viscosity used by Vandervell for bearing dimensioning was 7 cp. The previously used oil (SAE20W40) was replaced by a thinner oil (MOBIL No. 1) whose viscosity reduced the full load friction by 2.2 kW.

  The resulting engine-drive friction reduction was 3.6 kW at the full load point for a warmed-up engine. (Since the acceleration test from 0 to 60 mph is supposed to be performed with hot oil, the entire friction reduction was used to establish the full load power criterion.)

- External Heat System

  The CGR bypass valve was removed and the air excess ratio was maintained at a fixed value of 1.1 over the whole range. Some temperatures were corrected in the calculation of the external heat system efficiency, and this resulted in an improved efficiency. For 0.8 g/s of fuel flow, the overall improvement was about 1.5%.

- **Auxiliaries**

  The power consumption characteristics of the burner blower and the alternator were changed. Together, their power consumption was decreased by 0.20 kW at the part load point. Power consumption was increased by 0.35 kW at the full load point because of the increased blower power requirement due to the removal of the CGR bypass valve.

- **Cylinder and Piston Dome**

  The piston dome height was increased in order to reduce heat conduction losses. Stress analyses indicated the need for an increase in the cylinder and piston dome wall thicknesses; however, the net effect of these changes was a decrease in the conduction loss.

- **Redefinition of the Full-Load Power Requirement**

  The full-load power requirement, defined at 4000 rpm engine speed and 15 MPa cycle mean pressure, was changed from 65 kW to 67 kW. For the calculation previously reported, the power steering pump was included as an engine auxiliary.

  The classification of the power steering pump as an auxiliary is not consistent with the definition, so from now on, the power steering pump will be deleted from the auxiliary group and will be considered to be an accessory. If the power steering pump is rated 1 hp (0.75 kW) at 4000 rpm engine speed, the full load requirement should then be 65 + 0.75 = 65.75 kW. However, because the previously calculated acceleration time from 0 to 60 mph was very close to 15.0 seconds, the power requirement was rounded upwards by 1.25 kW to 67 kW (90 hp) in order to ensure the required acceleration. This increase in required power could be made without increasing the indicated engine power because of the reduction of friction losses previously discussed.

  After the updated conditions, the engine was reoptimized. The part-load (13 kW at 2000 rpm) efficiency was improved by 12% relative to the engine specifications presented in January 1980.

- **Drive Chain**

  The 1984 vehicle specification was reviewed and tailored towards an alternate RESD. A 4-speed gearbox was selected for review and its advantages will be assessed. An investigation was initiated to determine the potential of using Chrysler's wide ratio transmission.

Vehicle simulation and optimization studies were performed on various RESD systems. The basic tool used was the MTI vehicle simulation program, which is a growth version of the University of Wisconsin program. MTI has tailored this program to the specific needs of Stirling-powered vehicles, while retaining its utility as a general heat engine vehicle simulation. In addition, the program's ability to handle more sophisticated and advanced vehicle subsystems has been greatly expanded:

- The torque converter can now be locked up in third gear, various accessory loads can be cut off at specified vehicle speeds, and the program can now simulate a continuously variable transmission. The program was validated for spark ignition vehicles by the University of Wisconsin and MTI has performed further validation comparisons on the P-40 spirit vehicle.

- The Reference Engine cold start penalty (CSP) is now believed to be somewhat less than the fuel equivalent value of the stored heat in the hot engine system. The P-40 experience indicates that the cold start for the Spirit is about 6% of the urban mileage. This translates to 86.5 grams of fuel. The Mod I CSP was obtained by multiplying the P-40 Spirit CSP by the ratio of the stored heat within the engines, which calculates to 116 grams of fuel. The Reference Engine CSP was obtained by multiplying the Mod I CSP by the ratio of the stored heat within the engines, which calculates to 89 grams of fuel.

- Table 3.1-1 shows the general characteristics of the 1984 Pontiac Phoenix Reference Vehicle.

- Figure 3.1-1 shows the 1984 Reference Vehicle acceleration, plotted as mph versus time. It is interesting to note that the 0 to 60 mph acceleration is accomplished in first gear only and that the vehicle can accelerate to 100 mph in second gear. Figure 3.1-2 shows the acceleration of the vehicle as a function of the vehicle speed. Figure 3.1-3 shows engine speed and torque as a function of time during acceleration. The cumulative fuel consumed for the urban and highway cycle conditions relative to distance traveled is presented in Figures 3.1-4 and 3.1-5. The four-second time delay shown in Figures 3.1-1 and 3.1-4 is due to computer program stabilization.

- Table 3.1-2 summarizes the predicted mileages and performance values for the 1984 Reference Engine vehicle.

A meeting was held at MTI on June 17 to establish more appropriate design criteria for the heater head components. This was the second in a series of meetings which integrated design, material, and structural requirements into a common standard. Particular attention was paid to those heater components which failed during high temperature testing in order to understand failure mechanisms and to try and avoid them in the future by the proper design/analysis of the RESD. Pressure, temperature, and cycle information was reviewed for each of the failed components. This review was followed by a discussion of conclusions which could be drawn from this analysis.

## 1984 PONTIAC PHOENIX

| | |
|---|---|
| TEST WEIGHT | 3170 lb |
| INERTIA WEIGHT | 3125 lb |
| TOTAL ROAD LOAD | 11.22 hp @ 50 mph |
| DYNO POWER SETTING | 7.3 hp (with A/C) |
| FUEL | Unleaded regular (113,525 Btu/gal) |
| TRANSAXLE | GM THM 125 with lockup |
| TORQUE CONVERTER | Optimized Design for Stirling Power |
| GEARBOX | 3 Speed Automatic |
| GEAR RATIOS | 1.84, 1.60, 1.00 |
| FRONT PUMP | Variable Capacity Gear Pump |
| SHIFT SCHEDULE | Optimized for Stirling Power |
| FINAL DRIVE | Planetary Gear Set |
| RATIO | Optimized for Stirling Power |
| EFFICIENCIES | All Efficiencies Calculating Using Ricardo Polynomial |
| ACCESSORIES | Power Steering/Brakes, A/C |
| COOLING FAN | No Impact on Mileage |

Table 3.1-1 1984 RESD Vehicle Characteristics

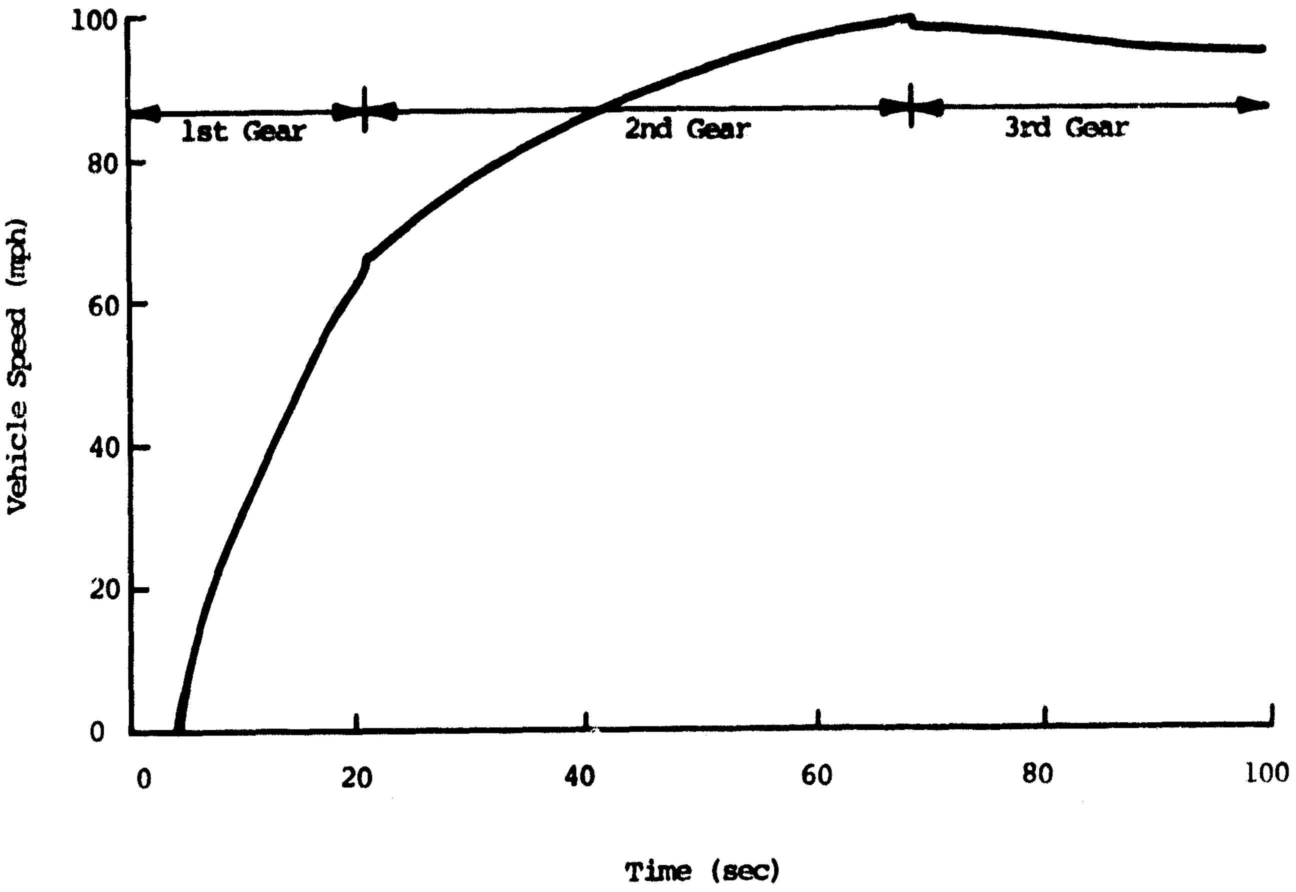

Figure 3.1-1 1984 Reference Engine Vehicle Speed *versus* Time; Transmission Gear Number *versus* Time

802711

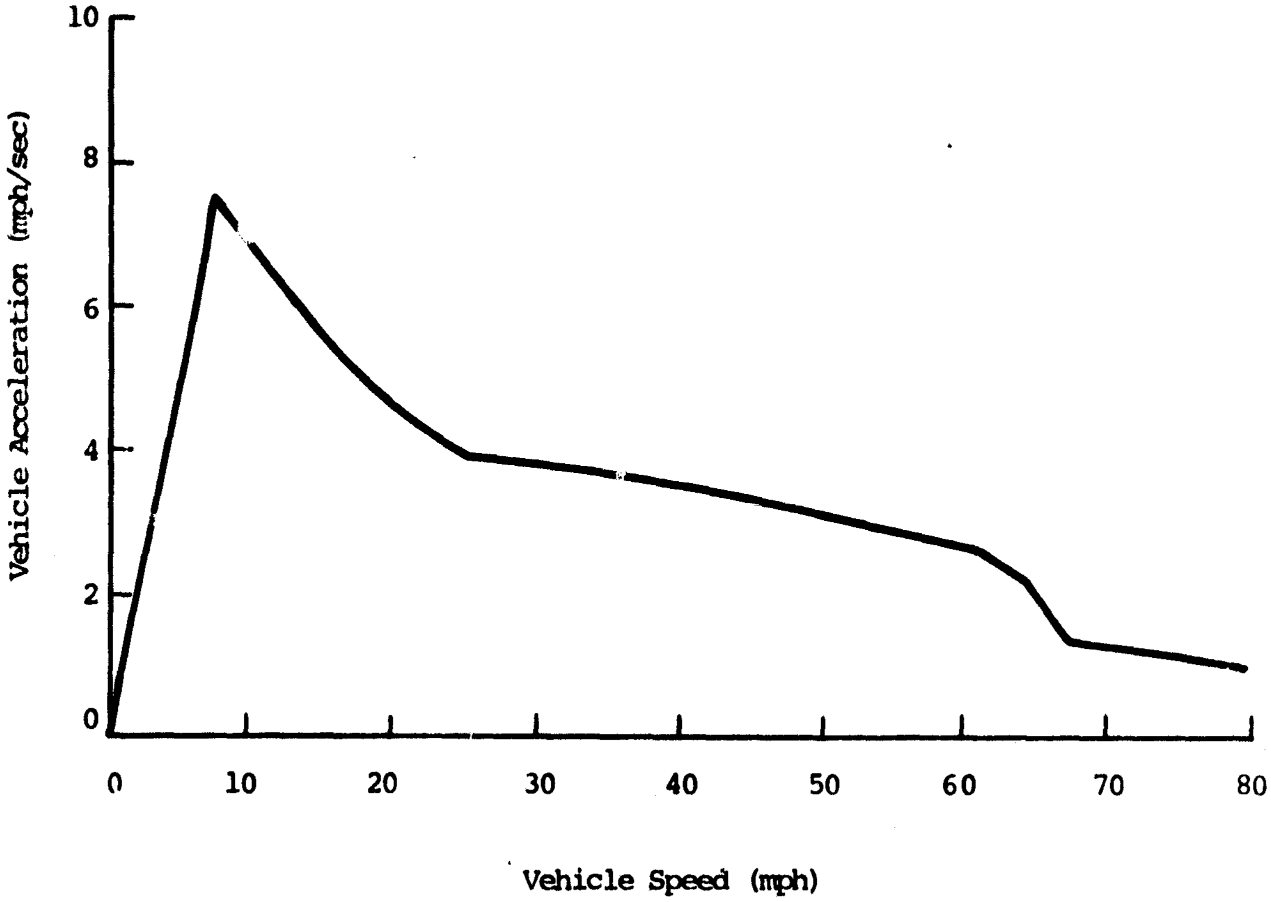

Figure 3.1-2 1984 Reference Engine Vehicle Acceleration *versus* Vehicle Speed

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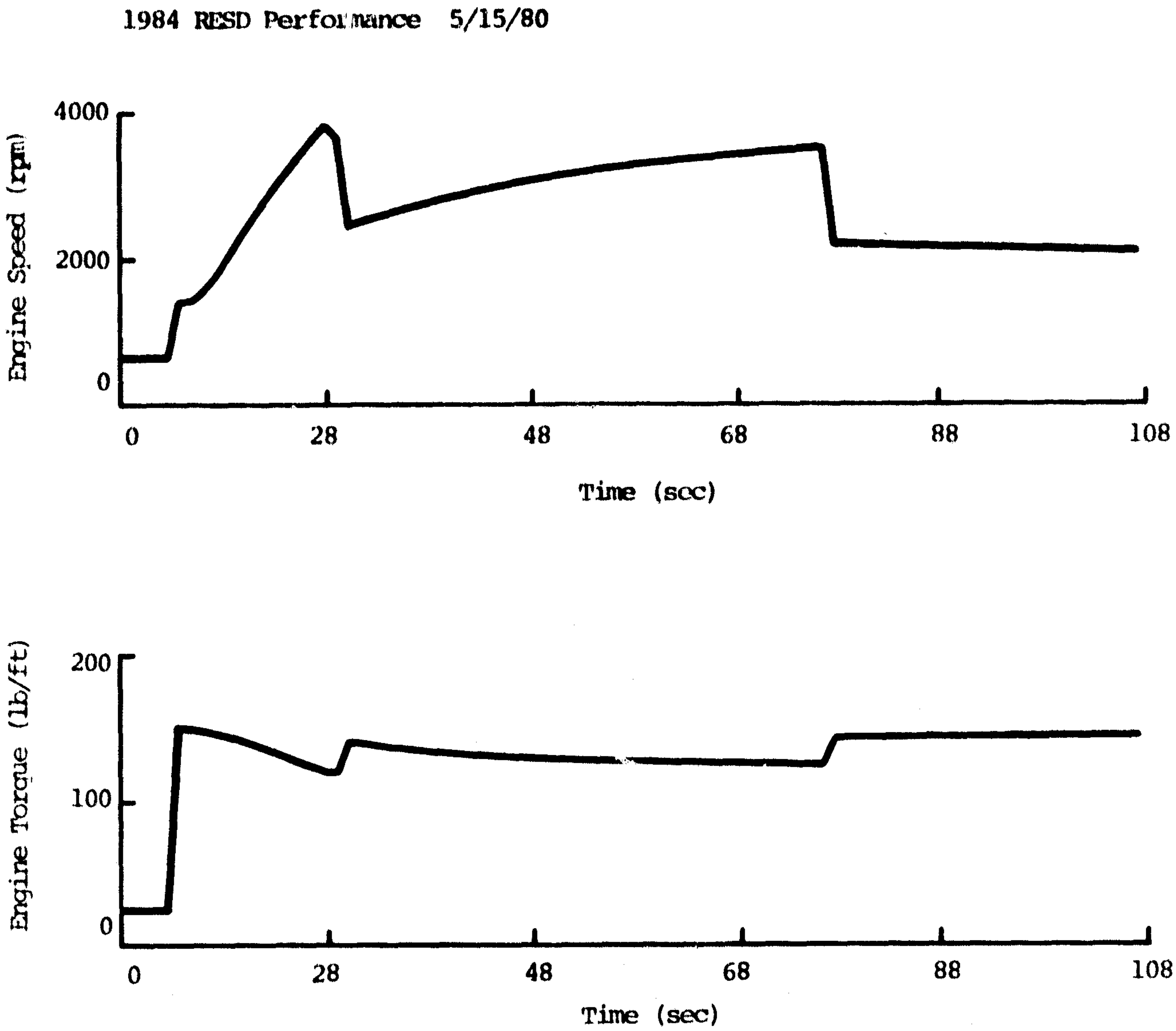

Figure 3.1-3 1984 Reference Engine Speed *versus* Time; Engine Torque *versus* Time

802614

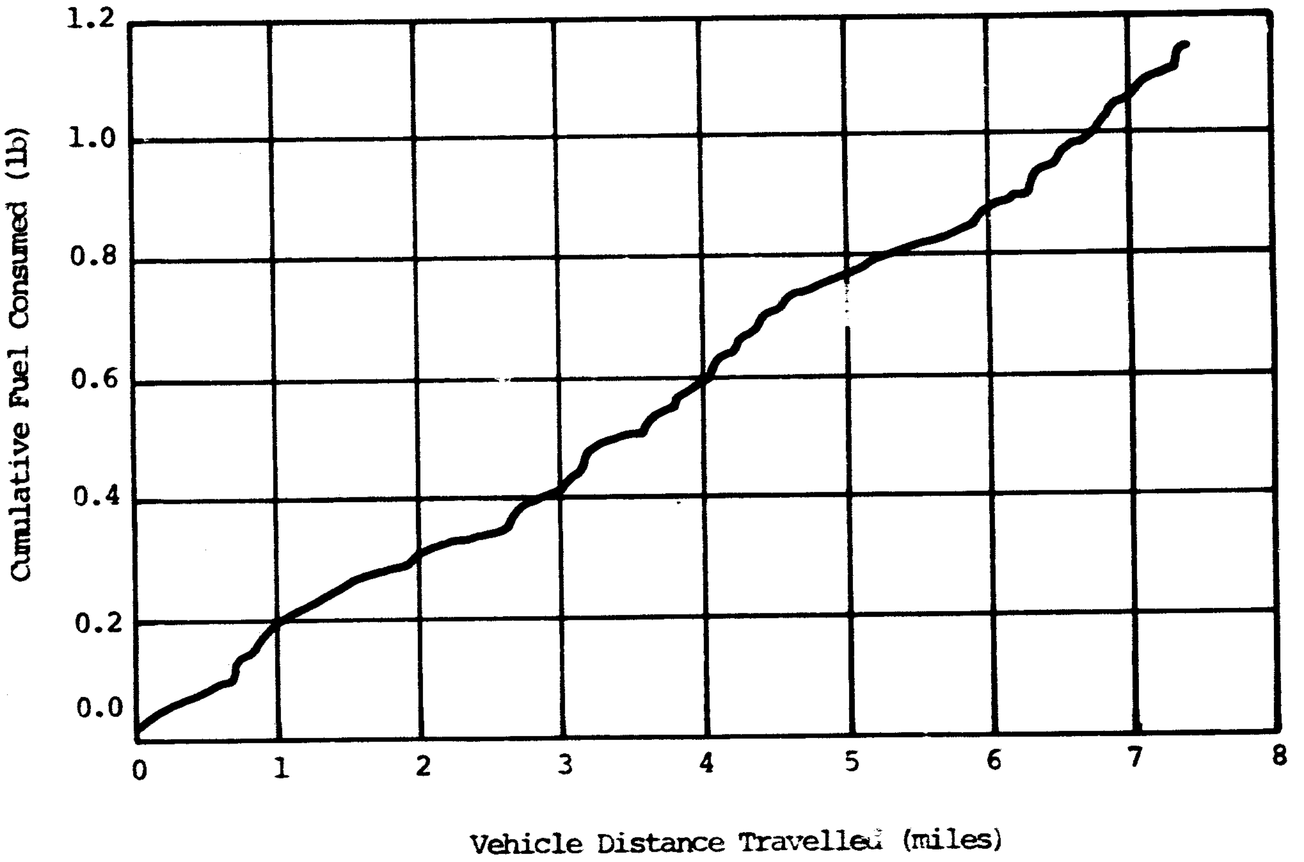

Figure 3.1-4 1984 Reference Engine Vehicle Cumulative Fuel Consumed *versus* Vehicle Distance Travelled for the Urban Cycle

882689

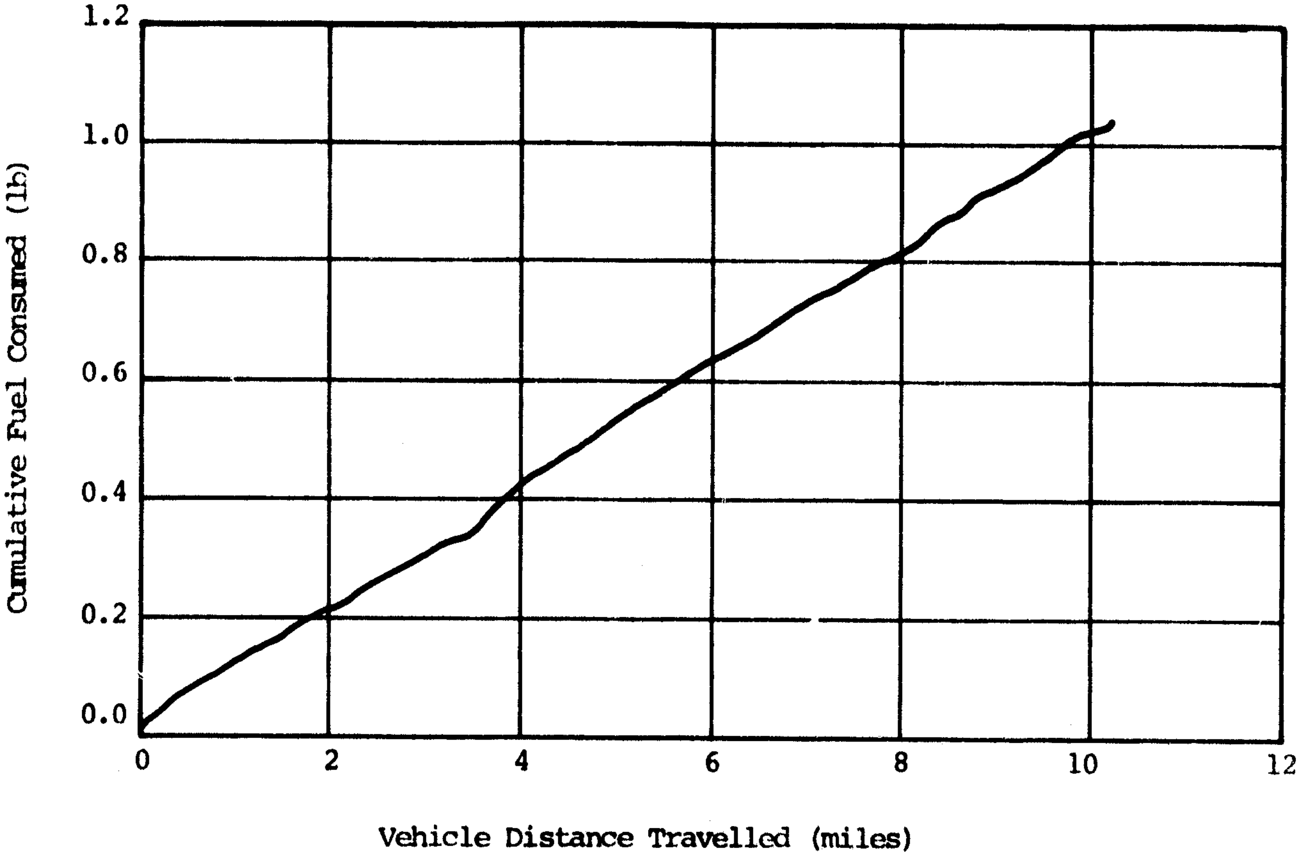

Figure 3.1-5 1984 Reference Engine Vehicle Cumulative Fuel Consumed *versus* Vehicle Distance Travelled for the Highway Cycle

802610

- **FUEL ECONOMY**

| | |
|---|---|
| URBAN MILEAGE | 39.35 mpg |
| URBAN MILEAGE WITH CSP | 33.68 mpg |
| HIGHWAY MILEAGE | 60.78 mpg |
| COMBINED MILEAGE WITH CSP | 42.13 mpg |
| COMBINED MILEAGE WITH DIESEL | 48.45 mpg |

| CRUISE MILEAGE | GAS | DIESEL |
|---|---|---|
| 50 mph | 68.1 mpg | 78.3 mpg |
| 55 mph | 62.5 mpg | 71.9 mpg |
| 60 mph | 57.7 mpg | 66.3 mpg |

- **ACCELERATION AND SPEED**

| | |
|---|---|
| Time from 0 to 60 mph | 15.0 sec |
| Time from 50 to 70 mph | 8.2 sec |
| Acceleration from 5 to 10 mph | 11 ft/sec$^2$ |
| Top Speed | 98 mph |

Table 3.1-2 1984 RESD Projections

The differences between the 1984 Reference Engine and the current P-40 Stirling baseline engine are shown in Table 3.1-3. The definition of the RESD and a schematic of the engine are shown in Figure 3.1-6.

| | P-40 | RESD | Comment |
|---|---|---|---|
| **Basic Engine System** | | | |
| Basic Engine | Research | Automotive | • Part power optimization<br>• Lighter weight<br>• Smaller package<br>• Cheaper<br>• Weight to power ratio improved from 13.4 to 4.7 |
| **External Heat System** | | | |
| Preheater | Plate Fin | Folded Fin | • Lower cost |
| Insulation | Fiber Wool | Air Gap & Fiber Wool | • Reduced radiation loss |
| Fuel Injection | Air Atomization | Prevaporization | • Eliminate air atomizing pump |
| Emission Control | EGR | CGR | • Improved mileage |
| **Hot Engine System** | | | |
| Heater Head | Cobalt based material<br>720°C | Iron based material<br>820°C | • Lower cost<br>• Higher efficiency<br>• Reduced Weight |
| Coolers | Stainless steel | Aluminum | • Reduced weight |
| **Cold Engine System** | | | |
| Piston and Rod Assembly | 2 Piece | 1 Piece | • Eliminate tolerance stack-up |
| | Dome Screwed to rod | Separate Piston Seal carrier | • Ease in Disassembly |
| Rod Seal | Leningrader | Pumping Leningrader | • Reliability<br>• Simplification |
| Piston Dome | Multimet Material | Inconel 718 Material<br>Increased Thickness | • Reliability |
| Cylinder Block | 1 piece Cast Iron | 5 piece Aluminum and Cast Iron | • New concept<br>• Weight reduction |
| **Engine Drive System** | | | |
| Housing | Cast Iron | Aluminum casting | • Reduced weight |
| Water Pump | External | Integral with housing | • Packaging |
| Oil Pump | External | Integral with housing | • Packaging |
| Electronic Controls System | Analog | Digital | • Reduced cost<br>• Reliability |

Table 3.1-3 Comparions of RESD to P-40 Engine

In order to guide component, subsystem, and engine developments on the program, a Reference Engine System Design (RESD) has been generated. The RESD is an engine which exists only on paper in the form of design drawings. Its purpose is to continually reflect the best-contemplated approach and the latest technology that will provide the best possible fuel economy while meeting all of the other program objectives.

The RESD will incorporate all the new technology that (1) can reasonably be expected to be developed within the time frame of the program, and (2) is judged to provide significant improvement relative to the risk and cost of development. Because there may be more than one attractive option available, it may be desirable and necessary to generate one or more alternate designs in addition to the primary RESD.

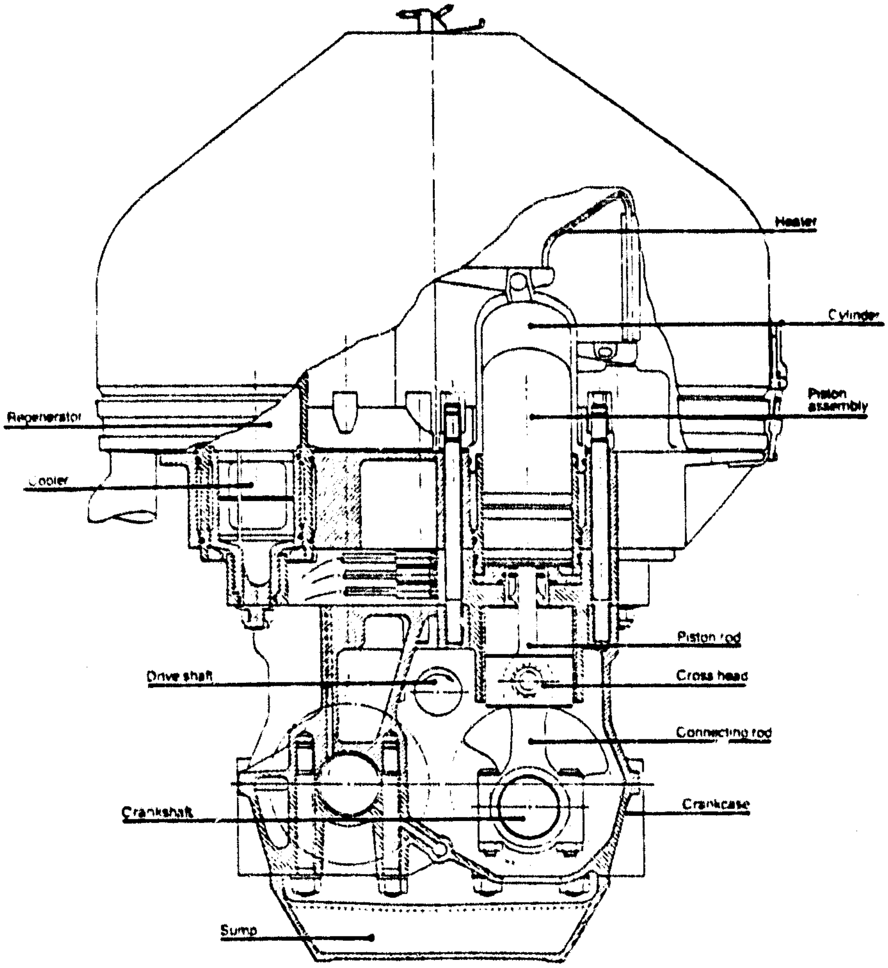

Figure 3.1-6 Current Reference Engine Design

## 3.2 MAJOR TASK 2 - COMPONENT AND SUBSYSTEM DEVELOPMENT

### 3.2.1 Combustion Technology Development

An investigation of alternative fuel nozzles continued. Information was received from vendors (Parker Hanafin, De Lavan) on alternative fuel nozzles which do not use atomizing air. Quotations were received from vendors (Parker Hanafin, Avco Lycoming, Spectron Development Labs) for fuel nozzle spray pattern testing, and these quotations are being evaluated.

A design was initiated for a Free Burning Rig Test Section, which will incorporate United Stirling of Sweden's (USS) CGR involute configuration hardware. A detailed list of questions on the geometry and the operation of the rig was prepared for discussion with USS in order to ensure the ability to compare MTI test results with USS data.

An External Heating System Task Team Meeting was held at USS on June 25-26. Discussions included:

- P-40 Opel combustion test results and design recommendations to reduce the vehicle drive-away time.
- The influence of air/fuel delay time on the emissions. In order to reduce starting emissions, a maximum delay of 0.15 sec at the combustor was suggested.
- Work plans and schedules for the ASE Mod II.

### 3.2.2 Heat Exchanger Technology Development

The Regenerator Heat Transfer Test Rig was received from Sunpower and the installation is underway. This test rig will be used to evaluate candidate regenerator matrices. The data acquisition system needed for this rig has been specified and the order was placed with Hewlett Packard. Work on the data reduction program for these heat transfer tests was started.

The Regenerator Heat Transfer Test Rig was assembled and electric power was connected. The vent system and pneumatic controls were assembled and the blower and gate valve actuation system was checked-out. As a result of the blower tests, the need for an air filter and sound insulation became apparent. Calibration of one of the two temperature measuring grids was done and it showed a satisfactory and very quick linear response to the imposed temperature transients.

A review of the drawings for the manufactured parts of the Regenerator Pressure Drop Test Rig was completed and procurement was started. A review of the test rig control system was performed in order to modify it to accommodate remote operation. The procurement of instrumentation was initiated. Quotes for the manufactured parts of the rig were received and an order was placed with Lipton steel for deliver of parts by mid-August.

### 3.2.3 Materials Development

A tentative program plan was completed for the development of a hybrid concept for cylinder heads and regenerator housings. The hybrid concept was prompted by the desire to improve the endurance of these components through the application of more fatigue resistant materials, particularly in the manifold region.

A Materials Task Force meeting was held at NASA-LeRC, on April 22-24, 1980. Discussion of coordinated activity between USS, MTI, and NASA included:

- Review of all materials changes in the RESD and the Mod 1 since the Design Review in January.
- Development of strength criteria for heater tubes, cylinder heads, regenerator housings, piston domes, and hydrogen coolers.
- Fabrication of Mod I pistons by MTI.
- Testing of Climax Molybdenum samples at the Industrial Research Institute in Oslo.
- Fabrication of quadrants for high temperature P-40 testing.
- Laboratory mechanical testing of candidate alloys for the cylinder heads, regenerator housings, and heater tubes.
- Discussion of existing materials problems and suggested activities to solve these problems.
- Review of work plans and planned activities.

On May 22-23, 1980, MTI attended a meeting at Cornell University on "Hydrogen in Stirling Engines." This meeting was sponsored by the Division of Materials Sciences (DMS) of the Office of Basic Energy Sciences and the Automotive Technology Development Division (ATDD) of DOE. The purpose of the meeting was to:

- Review the current status of the research and development of low cost materials for the containment of high temprature, high-pressure hydrogen in Stirling engines.
- Identify problem areas in materials that may present an obstacle in developing the Stirling engine.
- Initiate an atmosphere of interaction and information exchange between the DMS and ATDD and any other agencies or industries which may work to solve these materials problems.

Oxidation testing of the experimental Climax Molybdenum wrought nickel-base heater tube material has started at the Central Insititute for Industrial Research in Oslo. Oxidation testing is taking place in a combustion rig which burns #2 diesel fuel with 0.5% sulfur. This represents a typical level of sulfur for diesel fuels and a level which is higher than that normally found in gasoline.

Arrangements were completed for the consultation with Dr. Erhard Krempl of RPI. Dr. Krempl will provide support to the program in the design of engine heater components that are resistent to creep and fatigue failure. MTI met with Dr. Krempl to discuss the high temperature P-40 testing experience and what could be learned from the mode and mechanism of cylinder head failures. There was also some discussion about the materials testing required for the Mod II design, based on the previous modes of failure in the high temperature P-40 cylinder heads, regenerator housings, and tubes.

### 3.2.4 Seals Development

The first phase of the materials screening testing was completed. The test results are shown in Table 3.2.4-1. Repeated test results for Dixon 7035 material resulted in good correlation with the initial test data. Repeated wear tests of Rulon LD and 4340 on Rc46 steel were also completed and tests were carried out to assess the influence of surface roughness on the wear rate of seal materials, covering surface roughness of 1 μin. to 32 μin. CLA with both axial and transverse roughness.

Wear tests were also carried out with hot water (130°F) circulating through the test coupon mounting plate. It was found that an increase in temperature resulted in an increase in the wear rate by a factor of up to 4.

Quotations were received for most of the manufactured parts for the Exploratory Test Rig and purchase orders have been placed for all hardware and manufactured parts to complete the Exploratory Test Rig, Cap Seal Test Head, and Piston Ring Test Head. The design of the control station and instrumentation was completed and all orders were placed. The specifications for the lubricant supply unit and scavenge pump unit were completed and procurement has been started. Finish machining of the crankshaft was completed and the base, the motor, the crankshaft, and the crankcase were assembled and turned over successfully. The calibration of the leak detector with helium/nitrogen mixtures was completed.

### 3.2.5 Engine Power Chain Development

The thrust bearing losses and crosshead losses were calculated during a P-40 power loss analysis. Information on the oil flow rate to each of the two meshes will be factored into the gear mesh loss estimate. The following significant items emerged from this study:

- The losses are quite sensitive to oil feed temperatures. For example, at 4000 rpm and 7 MPa mean pressure, the losses (excluding the gear mesh loss) are roughly 1.3 hp at 180°F, 2.7 hp at 140°F, and 6 hp at 100°F. Because of thermodynamic requirements, the current oil feed temperature is estimated to be 140° to 150°F. Reducing the amount of cooling of the lube oil so that the oil

Average Sliding Speed = 1.6 m·s$^{-1}$ (Speed Range 0 to 2.5 m·s$^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate - Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** μm(μin.) | | Transverse Surface Roughness of Plate, CLA*** μm(μin.) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear μm(mil)/hr | Specific mm$^3$ x 10$^{-6}$ N-m | Before | After | Before | After | | |
| 1 | 1-1, -6 | PTFE with glass fibers and other fillers - radial (Rulon LD) | Nitrided SAE 7140 steel ($R_c$ 62) | 0.31 | 0.30 | 10<br>(18) | 1.6<br>(0.064) | 0.40 | 0.05<br>(2) | 0.05<br>(2) | 0.05<br>(2) | 0.05<br>(2) | Transfer film on plate, smooth all over; pin quite smooth | Base-line test |
| 2 | 2-1, -2 | PTFE, polyimide powder filled (Rulon J) | " | - | 0.23 | 9<br>(17) | 0.64<br>(0.025) | 0.16 | 0.05<br>(2) | 0.08<br>(3) | 0.05<br>(2) | 0.25<br>(10) | Transfer film non-uniform, longitudinal grooves; corresponding grooves on pin | |
| 3 | 2-3, -4 | PTFE with glass fibers and other fillers (Rulon E) | " | 0.29 | 0.29 | 7<br>(12) | 0.51<br>(0.02) | 0.13 | 0.05<br>(2) | 0.03<br>(1) | 0.05<br>(2) | 0.05<br>(2) | Coating very smooth and shiny; pin smooth. | |
| 4 | 2-5, -6 | Thermoplastic (polyimide) with powder fillers (Rulon II) | " | - | 0.33 | 9<br>(17) | 3.3<br>(0.135) | 0.83 | 0.05<br>(2) | 0.10<br>(4) | 0.05<br>(2) | 0.30<br>(12) | Coating very spotty and non-uniform; longitudinal grooves on pin. | |
| 5 | 3-1, -2 | Polyamide imide, 3% PTFE and 20% graphite powder filled (Torlon 4275) | " | 0.34 | 0.34 | 11<br>(20) | 1.65<br>(0.065) | 0.42 | 0.05<br>(2) | 0.05<br>(2) | 0.05<br>(2) | 0.05<br>(2) | Ultra thin (can see substrate topography) but uniform film; many grooves on pin. | Squealed |
| 6 | 3-3, -4 | Polyamide-imide, 3% PTFE and 12% graphite powder filled (Torlon 4301) | " | 0.39 | 0.39 | 12<br>(22) | 101.6<br>(4) | 25.6 | 0.05<br>(2) | 0.1<br>(4) | 0.05<br>(2) | 0.30<br>(12) | Pieces of black powder stuck on the plate; no evidence of film; some grooves on pin. | Wear: black powder came off; squealed badly; high wear rate; test stopped after 9 hr.<br>Friction:<br>Violent stick slip; test stopped after 1 hr. |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: Load, 0.69 MPa; surface speed, 1.2 m·s$^{-1}$

** Operative length of traverse used in the measuring instrument was 1.8 mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 Friction and Wear Test Results from Reciprocating Sliding Tester

Average Sliding Speed = 1.6 $m \cdot s^{-1}$ (Speed Range 0 to 2.5 $m \cdot s^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate - Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** μm(μin.) | | Transverse Surface Roughness of Plate, CLA*** μm(μin.) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear μm(mil)/hr | Specific $\frac{mm^3}{N \cdot m} \times 10^{-6}$ | Before | After | Before | After | | |
| 7 | 3-5, -6 | Polyimide, 15% graphite powder filled (SP-21) | Nitrided SAE 7140 Steel ($R_c$62) | 0.47 | erratic | 20 (36) | 1.52 (0.06) | 0.38 | 0.05 (2) | 0.3 (12) | 0.05 (2) | 0.20 (8) | Heavy coating in patches; pin generally smooth; some film transferred back to the pin. | **Wear:** Squealed<br>**Friction:** Pin vibrated violently after 5 min., test stopped after 1 hr. |
| 8 | 4-1, -2 | Linear aromatic polyester, 20% graphite powder filled (Ekkcel CL-1340) | " | 0.54 | erratic | 19 (35) | 102 (4) | 25.7 | 0.05 (2) | 0.30 (12) | 0.08 (3) | 0.48 (19) | Heavy coating in patches; no apparent polishing of plates; longitudinal grooves on pin. | **Wear:** Heavy deposit of black powder on metal plate immediately after starting; test stopped after 3 hr.<br>**Friction:** Pin vibrated; test stopped after 1 hr. |
| 9 | 4-5, -6 | Polyphenylene sulfide, 15% TFE and 30% carbon fibers filled (Thermocomp OCL-4036) | " | 0.39 | erratic | 19 (35) | 0.64 (0.025) | 0.16 | 0.05 (2) | 0.05 (2) | 0.05 (2) | 0.05 (2) | Ultra-thin coating (can see substrate topography on plate, fine grooves on pin. | |

---

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa; surface speed, 1.2 $m \cdot s^{-1}$

** Operative length of traverse used in the measuring instrument was 3.8 mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 (Cont'd)

Average Sliding Speed = 1.6 $m \cdot s^{-1}$ (Speed Range 0 to 2.5 $m \cdot s^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials* | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** $\mu m$($\mu in$) | | Transverse Surface Roughness of Plate, CLA*** $\mu m$($\mu in$) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear $\mu m$(mil)/hr | Specific $mm^3 \times 10^{-6}$ / N·m | Before | After | Before | After | | |
| 10 | 5-1, -2 | PTFE, 15% graphite powder filled (Dixon) | Nitrided SAE 7140 Steel ($R_c$ 62) | | | 7 (12) | 119 (4.7) | 29.9 | 0.05 (2) | 0.30 (12) | 0.05 (2) | 0.50 (20) | Center of plate (high sliding speed) covered with nonuniform, patchy coating; other areas untouched; pin smooth. | Center of plate covered with black powder immediately after starting; high wear; test stopped after 3 hr. |
| 11 | 5-3, -4 | PTFE, carbon powder filled (Dixon 7035) | " | 0.36 | 0.41 | 8 (14) | 0.28 (0.011) | 0.070 | 0.05 (2) | 0.08 (3) | 0.05 (2) | 0.10 (4) | Ultra thin coating; plate essentially unchanged; pin smooth. | |
| 12 | 5-5, -6 | PTFE, 10% glass fibers and 15% C40 graphite-Ag filled (Dixon TFE GL BL 800-2) | " | 0.25 | 0.28 | 7 (13) | 0.51 (0.02) | 0.13 | 0.05 (2) | 0.04 (1.5) | 0.05 (2) | 0.05 (2) | Ultra-thin coating on plate, slightly thicker in the center; pin smooth. | |
| 13 | 6-1, -2 | PTFE, 10% glass fibers and 15% C30 Graphite-Ag filled (Tribol-TFE-GL BL-800-2) | " | 0.30 | 0.31 | 9 (16) | 0.76 (0.03) | 0.19 | 0.051 (2) | 0.025 (1) | 0.051 (2) | 0.051 (2) | Ultra-thin coating; no apparent polishing of plate; pin smooth. | |
| 14 | 6-3, -4 | PTFE, 10% graphite fibers and 10% C40-Graphite-Ag Filled (Dixon TFE CF BL-800-2) | " | 0.15 | 0.22 | 8 (14) | 0.61 (0.024) | 0.15 | 0.051 (2) | 0.025 (1) | 0.051 (2) | 0.051 (2) | Heavy and quite uniform coating on plate; fine grooves on pin. | |
| 15 | 6-5, -6 | PTFE, 10% Graphite fibers and 10% C40-Graphite-Ag Filled (Tribol TFE CF BL-800-2) | " | 0.15 | 0.19 | 7 (13) | 0.71 (0.028) | 0.18 | 0.051 (2) | 0.025 (1) | 0.051 (2) | 0.025 (1) | Thin, nonuniform coating on plate, pin smooth. | |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa, surface speed, 1.2 $m \cdot s^{-1}$

** Operative length of traverse used in the measuring instrument ca. 3.8 mm

***Operative length of traverse used in the measuring instrument ca. 1.8 mm

Table 3.2.4-1 (Cont'd)

Average Sliding Speed = 1.6 m·s$^{-1}$ (Speed Range 0 to 2.5 m·s$^{-1}$) or 1200 strokes/min
Stroke Length - 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate - Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** μm(μin.) | | Transverse Surface Roughness of Plate, CLA*** μm(μin.) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear μm(mil)/hr | Specific mm$^3$ x 10$^{-6}$/N·m | Before | After | Before | After | | |
| 16 | 7-1, -2 | Polyimide, 15% CdO-Graphite-Ag filled (Dixon-PI-ML-800-2) | Nitrided SAE 7140 Steel ($R_c$62) | 0.37 | 0.38 | 9<br>(16) | 0.84<br>(0.033) | 0.21 | 0.051<br>(2) | 0.089<br>(3.5) | 0.051<br>(2) | 0.152<br>(6) | Heavy coating in longitudinal patches; plate topography unchanged; longitudinal grooves on pin. | |
| 17 | 7-3, -4 | Polyimide (PI500), 15% CdO Graphite-Ag filled (Tribol-PI-ML-800-2) | " | 0.38 | 0.39 | 8<br>(15) | 1.19<br>(0.047) | 0.30 | 0.051<br>(2) | 0.102<br>(4) | 0.051<br>(2) | 0.23<br>(9) | Heavy plastic transfer in patches on plate; plate surface worn in center; longitudinal grooves on pin. | |
| 18 | 7-5, -6 | Phenolic, 15% graphite powder filled | " | 0.69 | 0.61 | >13<br>(>25) | 56<br>(2.2) | 14.1 | 0.051<br>(2) | 0.20<br>(8) | 0.051<br>(2) | 0.23<br>(9) | Wear:<br>Heavy and spotty coating on plate, longitudinal grooves on pin<br>Friction:<br>Pin vibrated violently, test stopped after 1 hr | Wear very high; test stopped after 25 hr. |
| 19 | 8-2 | PTFE, 55% bronze powder and 5% MoS$_2$ filled (Crane) | " | 0.24 | 0.30 | 8<br>(15) | 0.66<br>(0.026) | 0.17 | 0.025<br>(1) | 0.025<br>(1) | 0.051<br>(2) | 0.051<br>(2) | Thin and uniform coating on plate; pin smooth; bronze particles clearly visible. | |
| 20 | 8-3, -4 | PTFE, 25% glass fiber filled (Crane) | " | 0.29 | 0.29 | 9<br>(16) | 1.40<br>(0.055) | 0.35 | 0.051<br>(2) | 0.051<br>(2) | 0.051<br>(2) | 0.051<br>(2) | Very thin coating on plate; pin smooth. | |
| 21 | 8-5, -6 | Graphite with 50% (volume) 2D graphite weave (FMI) | " | 0.21 | 0.22 | 16<br>(29) | 1.30<br>(0.051) | 0.33 | 0.025<br>(1) | 0.102<br>(4) | 0.025<br>(1) | 0.102<br>(4) | Streaked black coating on plate; numerous cracks on pin | |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa; surface speed, 1.2 m·s$^{-1}$

** Operative length of traverse used in the measuring instrument was 3.8 mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 (Cont'd)

Average Sliding Speed = 1.6 m·s$^{-1}$ (Speed Range 0 to 2.5 m·s$^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate - Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** µm(µin.) | | Transverse Surface Roughness of Plate, CLA*** µm(µin.) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear µm(mil)/hr | Specific $\frac{mm^3 \times 10^{-6}}{N \cdot m}$ | Before | After | Before | After | | |
| 22 | 9-1, -2 | Phenolic with 50% (volume) 3D-graphite weave (FMI) | Nitrided SAE 7140 Steel ($R_c$62) | 0.46 | 0.39 erratic | - | 2.97 (0.117) | 0.75 | 0.025 (1) | 0.025 (1) | 0.051 (2) | 0.203 (8) | Numerous longitudinal scratches on plate; no plastic transfer; visible weave in plastic pin. | Wear test stopped after 2 hr; no temperature measured because of difficulty in drilling.<br>**Friction:** Pin vibrated; test stopped after 0.7 hr. |
| 23 | 9-3, -4 | Polyimide with 50% (volume) 3D-graphite weave (FMI) | " | 0.54 | 0.49 erratic | 14 (25) | 1.96 (0.077) | 0.49 | 0.051 (2) | 0.051 (2) | 0.051 (2) | 0.051 (2) | Plate has some longitudinal scratches, no plastic transfer. Can see weave in plastic pin, has rough appearance. | Wear test stopped after 2 hr<br>**Friction:** Pin vibrated; test stopped after 0.6 hr. |
| 24 | 9-5, -6 | PTFE, 15% graphite fiber filled (Dixon) | " | 0.23 | 0.33 | 12 (21) | 3.23 (0.127) | 0.81 | 0.025 (1) | 0.025 (1) | 0.025 (1) | 0.051 (2) | Very thin and uniform coating on plate; pin deformed during test - oval shaped in cross section and ridges present | |
| 25 | 10-1, -2 | PTFE, 10% graphite fibers and 10% CdO-graphite-Ag filled (MTI) | " | 0.24 | 0.31 | 3 (5) | 104.1 (4.1) | 26.23 | 0.051 (2) | 0.051 (2) | 0.051 (2) | 0.051 (2) | Very thin and uniform coating on plate; pin smooth. | Test stopped after 2 hr. |
| 26 | 10-3, -4 | PTFE, 15% CdO graphite-Ag filled (MTI) | " | 0.17 | 0.23 | 11 (19) | 342.9 (13.5) | 86.41 | 0.051 (2) | 0.152 (6) | 0.051 (2) | 0.279 (11) | Patches of pin material on the plate. | Test stopped after 2 hr. |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa; surface speed, 1.2 m·s$^{-1}$

** Operative length of traverse used in the measuring instrument was [illegible] mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 (Cont'd)

Average Sliding Speed = 1.6 $m \cdot s^{-1}$ (Speed Range 0 to 2.5 $m \cdot s^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate - Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials | | Coefficient of Friction* | | Temp. Rise During Test °C(°F) | Wear Rate | | Longitudinal Surface Roughness of Plate, CLA** μm(μin.) | | Transverse Surface Roughness of Plate, CLA*** μm(μin.) | | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pin | Plate | Static | Kinetic | | Linear μm(mil)/hr | Specific $mm^3 \times 10^{-6}$ / N·m | Before | After | Before | After | | |
| 27 | 10-1', -2' | Tantalum based alloy, $MoS_2$ filled (Molalloy PM 107) | Nitrided SAE 7140 Steel ($R_c$62) | 0.45 | Erratic | - | 457.2 (18) | 115.21 | 0.051 (2) | 0.051 (2) | 0.051 (2) | 0.457 (18) | Graphite patches on plate. | Pin fractured in middle after 2 hr; no temperature measurement made because of difficulty in drilling.<br>__Friction__: Pin - hard, could cut radius; pin vibrated badly; test stopped after 0.25 hr. |
| 28 | 11-1, -2 | Impregnated carbon graphite (P5N) | " | 0.27 | 0.26 | 7 (13) | 0.48 (0.019) | 0.122 | 0.051 (2) | 0.025 (1) | 0.051 (2) | 0.051 (2) | Plate unchanged; grainy appearance of pin. | One of the pins fractured in middle after 20 hr. |
| 29 | 10-1", -2" | Polyimide 152 graphite powder filled (Envex 1315) | " | 0.49 | 0.53 - erratic | 17 (30) | 419.1 (16.5) | 105.61 | 0.051 (2) | - | 0.051 (2) | - | - | Pin broke after 2 hr; wear test stopped.<br>__Friction__: Pin vibrated badly; test stopped after 0.25 hr. |
| 30 | 11-3, -4 | PTFE, glass fiber filled (GI-15) | " | 0.34 | 0.35 | 7 (12) | 1.17 (0.046) | 0.30 | 0.051 (2) | 0.025 (1) | 0.051 (2) | 0.076 (3) | Thick and uniform plastic coating and scratches filled on plate; glass fibers and powdered glass visible on the surface (same as Rulon LD). | |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa; surface speed, 1.2 $m \cdot s^{-1}$

** Operative length of traverse used in the measuring instrument was 3.8 mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 (Cont'd)

Average Sliding Speed = 1.6 $m \cdot s^{-1}$ (Speed Range 0 to 2.5 $m \cdot s^{-1}$) or 1200 strokes/min
Stroke Length = 40 mm
Normal Stress = 0.69 MPa (100 psi)

Test Duration = 100 hours
Ambient = Nitrogen Atmosphere at Room Temperature
Steel Plate Water Cooled (15°C ± 1°C)

| Item No. | Test No. and Specimen Designation | Test Materials |  | Coefficient of Friction* |  | Temp. Rise During Test °C(°F) | Wear Rate |  | Longitudinal Surface Roughness of Plate, CLA** µm(µin.) |  | Transverse Surface Roughness of Plate, CLA*** µm(µin.) |  | Surface Examination After Tests | General Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Pin | Plate | Static | Kinetic |  | Linear µm(mil)/hr | Specific $mm^3 \times 10^{-6}$ N·m | Before | After | Before | After |  |  |
| 31 | 11 5, 6 | PTFE with 25% (volume) containing glass fibers and additions of complex salts (Fluon VX1) | Nitrided SAE 7140 Steel ($R_c$ 62) | 0.29 | 0.31 | 8<br>(14) | 2.11<br>(0.083) | 0.54 | 0.051<br>(2) | 0.025<br>(1) | 0.051<br>(2) | 0.102<br>(4) | Thin coating and some scratches on plate; glass fibers and powdered glass visible on pin surface. |  |
| 32 | 12 1, -2 | PTFE with glass fibers and other fillers- axial (Rulon LD) | " | 0.28 | 0.31 | 9<br>(16) | 2.01<br>(0.080) | 0.518 | 0.051<br>(2) | 0.051<br>(2) | 0.051<br>(2) | 0.076<br>(3) | Thick coating with patchy appearance on plate glass fibers and powdered glass visible on pin surface. |  |
| 33 | 12 3, -4 | Polyimide with 50% graphite powder (Fillimide) | " |  | - | 7<br>(13) | 0.76<br>(0.030) | 0.194 | 0.051<br>(2) | 0.152<br>(6) | 0.051<br>(2) | 0.254<br>(10) | Thick coating with patchy appearance on plate, metal worn in spots; pin smooth, graphite powder visible. | Edges of pin chipped off during test. |
| 34 | 12 5, -6 | PTFE, (MFI) |  | 0.16 | 0.29 | - | 1346<br>(53) | 343 | 0.051<br>(2) | 0.051<br>(2) | 0.051<br>(2) | 0.051<br>(2) | Very thin coating on plate; pin polished. |  |

* The data were obtained in unidirectional sliding mode (Pin against cylinder; no water cooling employed). Test conditions were: load, 0.69 MPa; surface speed, 1.2 $m \cdot s^{-1}$

** Operative length of traverse used in the measuring instrument was 3.8 mm

***Operative length of traverse used in the measuring instrument was 1.8 mm

Table 3.2.4-1 (Concluded)

feed could be 180°F or higher could substantially reduce the power chain losses.

- All of the minimum film thicknesses at a temperature of 180°F are adequate; the minimum thickness is 48 in. in the main bearings at 2000 rpm and 50 MPa mean pressure.
- The crosshead losses are rather high; they represent about 1/6 of the total bearing losses. Correspondingly, the minimum film thicknesses on the crosshead appear to be more than adequate, ranging upwards from 7/10 of a mil (700 μ in.). Losses could be reduced by redesigning the crosshead to carry the load with less projected area at a smaller film thickness.

The following are the main conclusions of this study:

- The level of power losses are mainly affected by clearance, speed, and inlet oil temperature.
- The design of the main bearings is correct as far as minimum film thickness is concerned.
- The connecting rod bearing is larger than necessary based on the minimum film thickness.
- The drive shaft bearing is larger than necessary.
- The crossheads are over-designed, running at an estimated minimum film thicknesses of 1 mil.
- The level of power loss for 140°F (SAE 20) oil inlet temperature at 4000 rpm is 2.4 hp (1.8 kW).

### 3.2.6 Controls Technology Development

The development of a computer subroutine to handle the power control hydrogen transfer processes for the vehicle performance code (charge, dump, short-circuit) was completed and validation has been started. The subroutine will calculate the impact of these power control transients on fuel consumption.

The detailed design of the electrical activation mechanism for the hydrogen control valve is continuing.

Quotations on low cost pressure and position transducers were received from several vendors. The design of the pressure and position transducer text fixtures were completed and parts were ordered. Two different types of pressure and position transducers were selected for testing based on performance and cost criteria. The selected vendors are:

| | |
|---|---|
| Position Transducers: | Trans-Tek Incorporated, Ellington, Connecticut |
| | Waters Mfg. Inc., Wayland, Massachusetts |
| Pressure Transducers: | BLH Electronics, Wealtham, Mass. |
| | Foxboro/I.C.T. Inc., San Jose, California |

A generalized software flowchart for the engine simulator was started. The flow chart will show, in detail, the interaction of the various system models. Work was started to specify the analog circuit design associated with the mechanical transducer and actuator interfaces, and the output monitoring system.

The Texas Instruments FS990 Microprocessor Development System was received, inspected, and installed. The equipment is now being run through a rigorous inspection to ensure that hardware and software are fully operational and productive. Several components needed to complete the system, including the printer expansion memory, have still not arrived. The lack of these components do not impair the initial usage of the system. The load (dynamometer) analytical model provided to MTI by General Electric Company, and a general P-40 engine torque versus speed map, were coded in Texas Instrument TMS-990 assembly language. Work was started to specify the analog circuit design associated with the mechanical transducer, actuator interfaces, and the output monitoring system.

A two-cylinder diesel engine was delivered to MTI to become the basis for designing a new cylinder head to provide the oscillating flow geometry required to test check valves.

The specification for the integrated electronic air/fuel control system was completed with the assistance of USS. Several prospective air flow and fuel metering transducer vendors were contacted. These vendors included Eaton, Chrysler, Ford, and J-Tec. Eaton and J-Tec appear to be willing to work with MTI in the development effort; however, formal discussions will be necessary before this is ensured. Chrysler and Ford are still undecided.

The MTI Blower Test Rig shown in Figure 3.2.6-1 was moved from its location and installed at the MTI Automotive Stirling Engine Test Facility. The rig was operated and data were collected. This data validated the results obtained for the rig and the blower in its previous test location. The rig was prepared for the testing of air flowmeters.

The Controls Task Team met in Malmo, Sweden on May 6-8, 1980. The meeting concentrated on the preparations for the Mod I Design Review.

# MODI Combustion Air Blower Experimental Test Rig

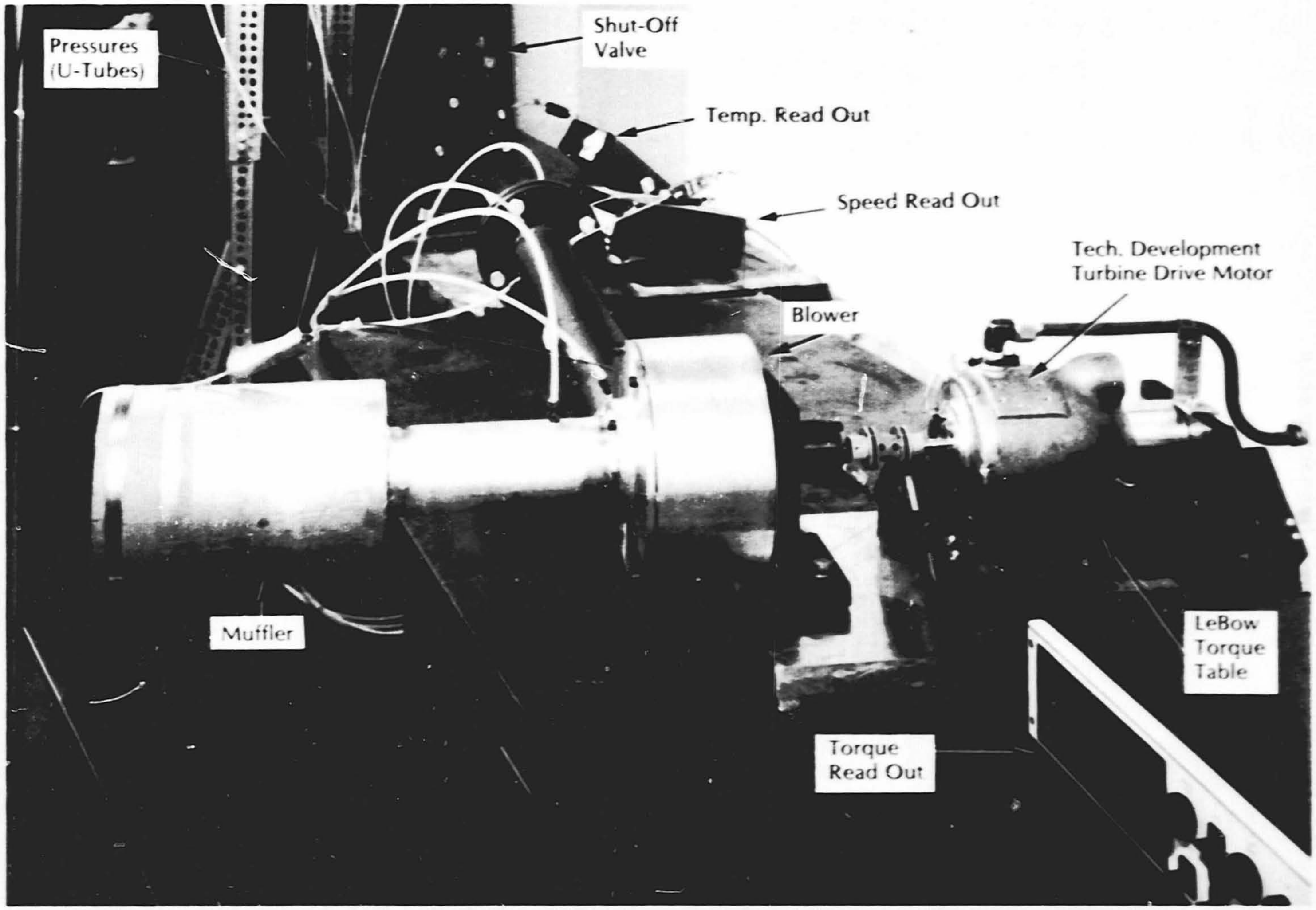

Figure 3._6-1 Mod I Combustion Air Blower Experimental Test Rig

### 3.2.7 Auxiliaries Development

An Auxiliaries Task Team Meeting was held April 15-17, 1980 at USS to prepare for the ASE Mod I Design Review presentation.

MTI shipped several belts to USS for use on their Combustion Air Blower Drive Test Rig. These belts were manufactured by Butler Precision Belting Inc. USS and MTI have agreed that a plastic gear drive for the combustion air blower should be further explored and the combustion air blower system clutch was deleted from the design in favor of a different drive pulley ratio.

### 3.2.8 ASE Mod I Combustion Air Blower Development

The drive turbine air supply hook-up was modified and the torque instrumentation system readings were checked out over the speed range. The test program was completed and the goals were realized for the various diffusers and the volute modifications. Over 200 different test points were run and the performance was evaluated. The final configuration efficiency reached 66%. Noise tests were conducted over the entire blower speed range and the data are currently being analyzed. MTI received favorable feedback from USS for the MTI-designed combustion air blower. This new blower is much quieter than originally anticipated and USS is very satisfied. Work continued on the manufacturing costs and schedules for producing 12 combustion air blowers for USS. MTI is currently awaiting approval from USS to procure hardware for these production combustion air blowers.

### 3.2.9 USS Component Development

#### 3.2.9.1 ASE Mod I

- Heat Generating System

  During testing with different jet-nozzles in the Mod I scale test rig, it was found that at higher loads the combustor pressure drop could be reduced considerably without any significant increase in $NO_x$ emissions. The emissions at lower loads, however, were strongly influenced by the jet-nozzle size. At present, the influence of heater tube temperature and preheated air temperature on emissions is being studied. CO emissions seem to be very sensitive to the heater tube temperature; decreased tube temperature results in increased emissions of CO. This effect is caused by the reduced gas temperature in the space between the two heater tube rows which decrease the reaction rate of the CO-reducing reactions.

CGR combustor tests in the Mod I-scale test rig were continued to study the influence of $\lambda$ on emissions. Data gathered from testing was used in a recently developed computer program which calculates the CVS cycle emissions as a function of air/fuel control time lag. According to calculations, the maximum tolerable time difference between the air and fuel responses in the combustor is about 0.15 seconds.

The comparative tests between the straight guide vane-type CGR combustor and the EGR combustor on the P-40/Opel engine (on the engine dynamometer) are almost completed. Engine performance with the CGR system seems to be higher than with the EGR system; however, the CGR system combustion efficiency is low during the start up sequence and has a high hydrocarbon emission. The poor combustion during the heating-up sequence also results in a longer start up time than with the conventional combustor. Cold starts will be studied on one of the Mod I combustor rigs.

During the testing of CGR combustors on the P-40/Opel, long heat-up times (time from key-on until the heater tube temperature reached 600°C) were experienced. This is partly due to the higher pressure drop of the CGR combustors which causes reduced fuel flow, and partly due to the low flame temperature caused by a high percentage of CGR.

- Heat Engine System

The driving unit of the Mod I engine was tested separately by using dummy heater heads. The dummy regenerator housing was made of SS2225-03 (type AISI 4130) steel; the following material property data were used in an analysis of fatigue:

| | |
|---|---|
| Yield strength | $\sigma_y = 490$ MPa. |
| Ultimate tensile strength | $\sigma_u = 690$ MPa. |
| Fatigue limit | $\sigma_f = \pm 350$ MPa. |
| | $i_{r} = (290 \pm 290)$ MPa. |

The dummy regenerator housing operates at room temperature and it will be exposed to a cyclic pressure. In the analysis, the cyclic pressure at maximum mean pressure was used ($p = 15 \pm 5$ MPa).

The dummy regenerator housing was analyzed using the finite element method. An axisymmetric finite element model, consisting of 8-nodes isoparametric elements was used. The most critical fatigue point is located at the radius of the flange.

An approximate Haigh diagram was drawn, based on the fatigue limit and the ultimate tensile strength of the material. Volume dependence and surface influence were considered by reducing the stress amplitude in the Haigh diagram by a factor of 0.8 The stress cycle at the critical point was entered in the diagram, and the safety factor was estimated to be 2.0.

The dummy cylinder housing was made of the same material as the dummy regenerator housing. The dummy cylinder housing will be exposed to a maximum cyclic pressure of 15 ± 5 MPa at room temperature. The most critical fatigue of the dummy cylinder housing point is at the radius of the flange. In the critical area at the flange, the dummy housing has the same geometry as the cylinder housing; therefore, the stresses will be the same. Considering notch sensitivity (with a factor of 0.85), the safety factor was estimated to be 2.6.

- Control Systems and Auxiliaries

The gas storage vessel and valve were fatigue tested at the Swedish National Testing Institute. Tests were performed with a cyclic oil pressure (12-40 Hz) at an oil temperature below 35°C. The valve was successfully tested in two steps: 1) $10^7$ cycles, $p = 21.5 \pm 3.5$ MPa, and 2) $10^7$ cycles, $p = 13.0 \pm 9.0$ MPa. The gas storage vessel was successfully tested for $10^7$ cycles with $p = 21.5 \pm 3.5$ MPa. A second test is being prepared.

The piston and the piston rod of the hydrogen compressor is bolted to the cross head with a necked-down tie bolt as shown in Figure 3.2.9.1-1. A stress analysis was performed using the following material properties:

Bolt

M 8 x 1 Umbrako quality 12.9

Yield stress (0.2%) $\sigma_y$ = 1170 MPa

Ultimate tensile strength $\sigma_u$ = 1300 MPa

Young's modulus E = 206,000 MPa

Piston

SIS 2541-03

Yield stress (0.2%) $\sigma_y$ = 700 MPa

Ultimate tensile stress $\sigma_u$ = 900 MPa

Young's modulus E = 205,000 MPa

Brinell hardness HB = 275

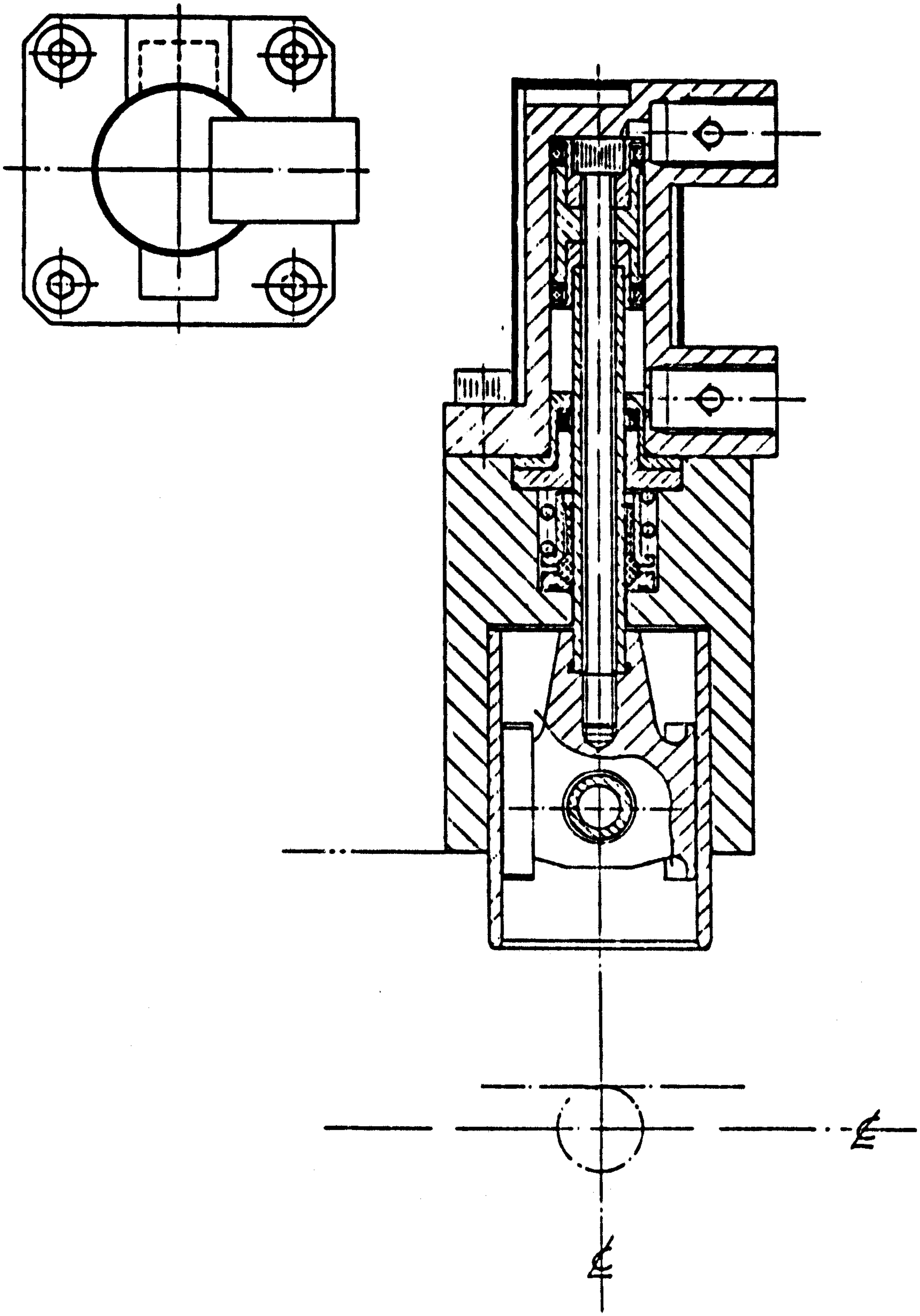

Figure 3.2.9.1-1 Compressor Piston

**Piston rod**

SIS 9940-04

Yield stress (0.2%) $\sigma_y$ = 700 MPa

Ultimate tensile strength $\sigma_u$ = 950 MPa

Young's modulus E = 205,000 MPa

Brinell hardness HB = 290

**Crosshead**

SIS 2225-05

Yield Stress (0.2%) $\sigma_y$ = 700 MPa

Ultimate tensile strength $\sigma_u$ = 900 MPa

Young's modulus E = 206,000 MPa

Brinell hardness HB = 270

The load is cyclic, with a maximum net pressure of 17.5 MPa between the upper and lower side of the piston. Considering the spring constant of the bolt and its environment, the stress amplitude caused by the applied load was 54 MPa, which is below the maximum allowable value of 64 MPa for rolled M8 bolts. Thus, the bolt design fulfilled the VDI 2230 (Verein Deutscher Ingeneure, "Systematische Berechnung hochbeanspruchter Schraubenver-bindungen") requirement. The amplitude force in the bottom crosshead threads gives a nominal amplitude stress equal to 12 MPa, which is below the maximum value of 30 MPa for cut M8 bolts. Assuming a friction coefficient of 0.1, the tie bolts have a good margin against loosening. In combination with the applied load, the preload resulted in a compressive stress safety factor against yielding of 1.6. Thus, the surface pressure of the clamped parts were far below allowable levels.

Stress analyses were also performed for four pressurized power control blocks:

- Power Control Block No. 1 (see Figure 3.2.9.1-2)

  SS2172 steel is assumed in the analysis and the following material property data were applied:

  Yield stress: $\sigma_y$ = 300 MPa

  Ultimate tensile strength: $\sigma_u$ = 490 MPa

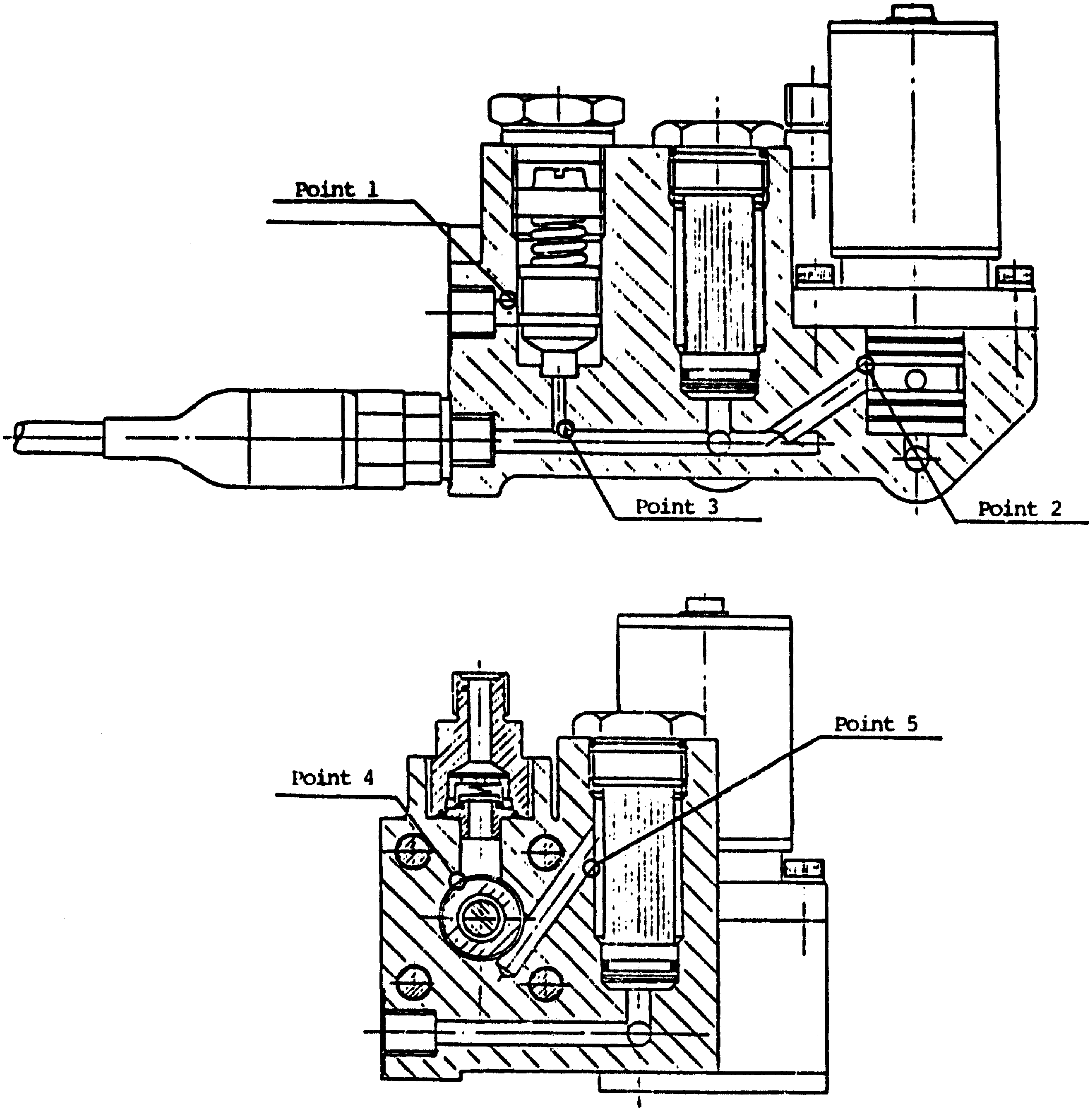

Figure 3.2.9.1-2 Points on Block 1 Used in the Stress Analysis

Fatigue limit $\sigma_f = \pm 210$ MPa

$\sigma_{fp} = 185 \pm 185$ MPa

The maximum temperature is 100°C and the internal parts of the block are exposed to the following pressure loads: $p = 12 \pm 7$ MPa

$p = 7.8 \pm 4.8$ MPa

$p = 21.5 \pm 3.5$ MPa

In the static stress analysis, the maximum internal pressure ($p_{max} = 25$ MPa) was used. In the fatigue analysis, the pressure cycle with the maximum amplitude $p = 12 \pm 7$ MPa was used.

The total number of pressure cycles in the analysis is; $2.5 \times 10^6$; the corresponding stress cycles were compared to the fatigue limit. The gas pressure in the channels of the block resulted in stresses which are estimated by considering the material around each channel as an equivalent, thick-walled cylinder exposed to internal pressure. In most cases, the pressurized thick cylinder has a hole in the cylinder wall and the stress concentration factor was then taken from R. E. Petersson: Stress Concentration Factors. The minimum safety factor against yielding is 6.4, and the minimum safety factor against fatigue is 3.3.

- Power Control Block No. 2 (see Figure 3.2.9.1-2)

SS2 172 steel is assumed in the analysis, and the following material property data were applied:

Yield stress: $\sigma_y = 300$ MPa

Ultimate tensile strength. $\sigma_u = 420$ MPa

Fatigue limit: $\sigma_f = \pm 210$ MPa

$\sigma_{fp} = 185 \pm 185$ MPa

The maximum temperature is 100°C and the internal parts of the block are exposed to a maximum pressure load: $p = (21.5 \pm 3.5)$ MPa. The total number of pressure cycles in the analysis is $2.5 \times 10^6$, the corresponding stress cycles were compared to the fatigue limit.

The analysis procedures are the same as for Block 1. The minimum safety factors against yielding and fatigue is 4.9 and 2.1, respectively.

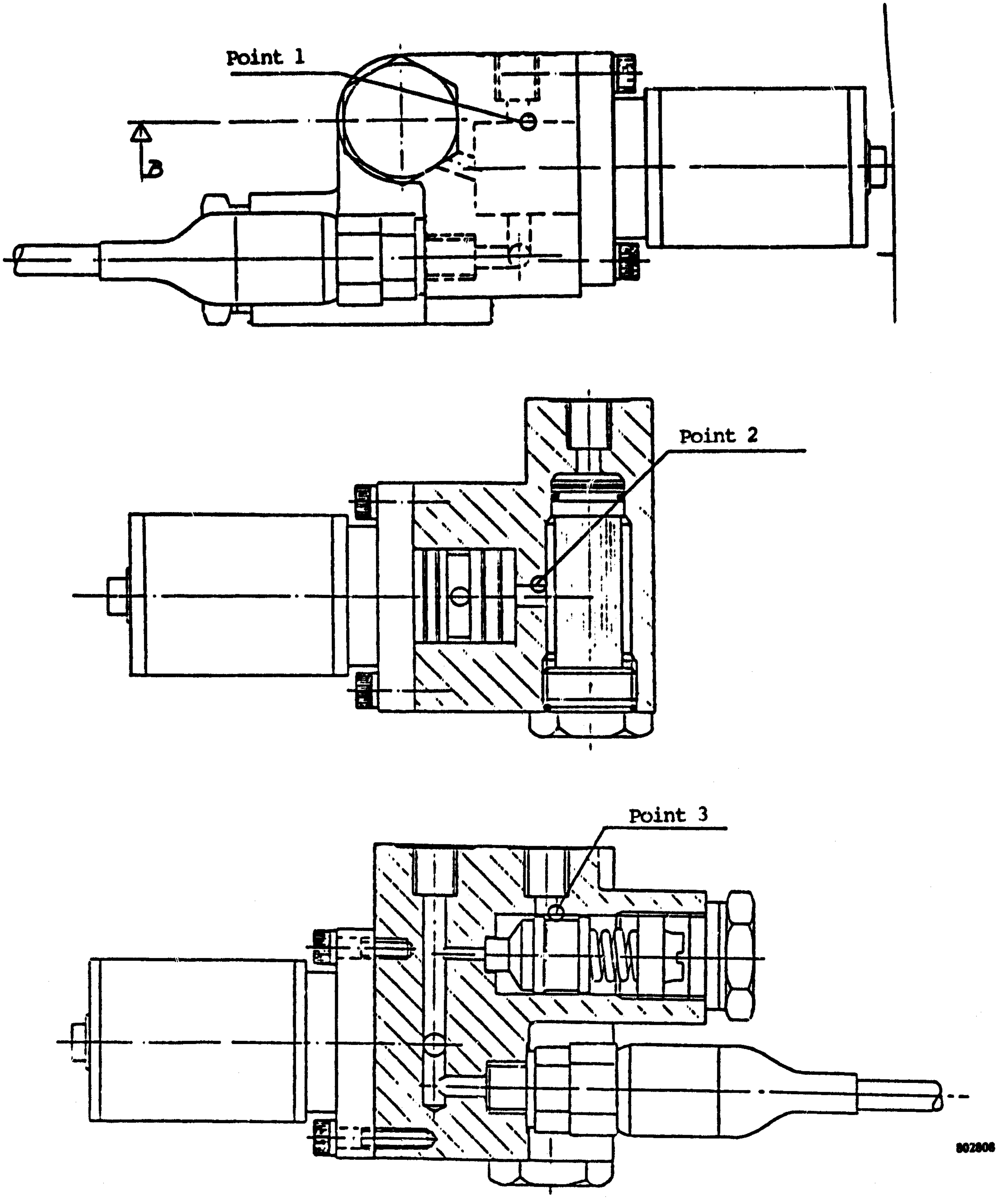

Figure 3.2.9.1-3 Points on Block 2 Used in the Stress Analysis

- <u>Power Control Block No. 3</u> (see Figure 3.2.9.1-4)

  SS2337 (AISI 321) stainless steel is assumed in the analysis, and the following material property data were applied:

  Yield stress: $\sigma_y = 174$ MPa

  Ultimate tensile strength: $\sigma_u = 490$ MPa

  Fatigue limit: $\sigma_f = \pm 270$ MPa

  $\sigma_{fp} = 240 \pm 240$ MPa

  The maximum temperature is 100°C and the internal parts of the block are exposed to a pressure load: $p = 17.5 \pm 7.5$ MPa. The total number of pressure cycles in the analysis is $2.5 \times 10^6$; the corresponding stress cycles were compared to the fatigue limit.

  The analysis procedures are the same as for Block 1. The endplate is considered to be a simple, supported, circular plate exposed to a uniform pressure. The bolts in the endplate are designed to fulfill the requirements of VDI 2230 (Verein Deutscher Ingenieure, "Systematische Berechnung hochbeanspruchter Schraubenverbindungen"). The calculation procedure illustrated that M10 bolts of quality 12.9 will meet the requirements of VDI 2230. The minimum safety factors against yielding and fatigue are 2.0 and 2.8 respectively. The endplate, bolted with four M10 bolts (quality = 12.9) meets the requirements of VDI 2230.

- <u>Power Control Block No. 4</u> (see Figure 3.2.9.1-5)

  SS4212 aluminum is used in the analysis, with a yield stress: $\sigma_y = 250$ MPa.

  The maximum temperature is 100°C and internal parts of the block are exposed to a constant gas pressure, p = 5 MPa; consequently, only a static analysis was done. Due to low pressure, the safety factors against yielding is very high.

The Mod I compressor has been operated to a total of 5422 hours and 731,169 pumping cycles at the end of this quarterly period.

Test unit No. 2 of the power control valve has been operated to a total of 2988 hours and 206,097 pumping cycles at the end of this quarterly period.

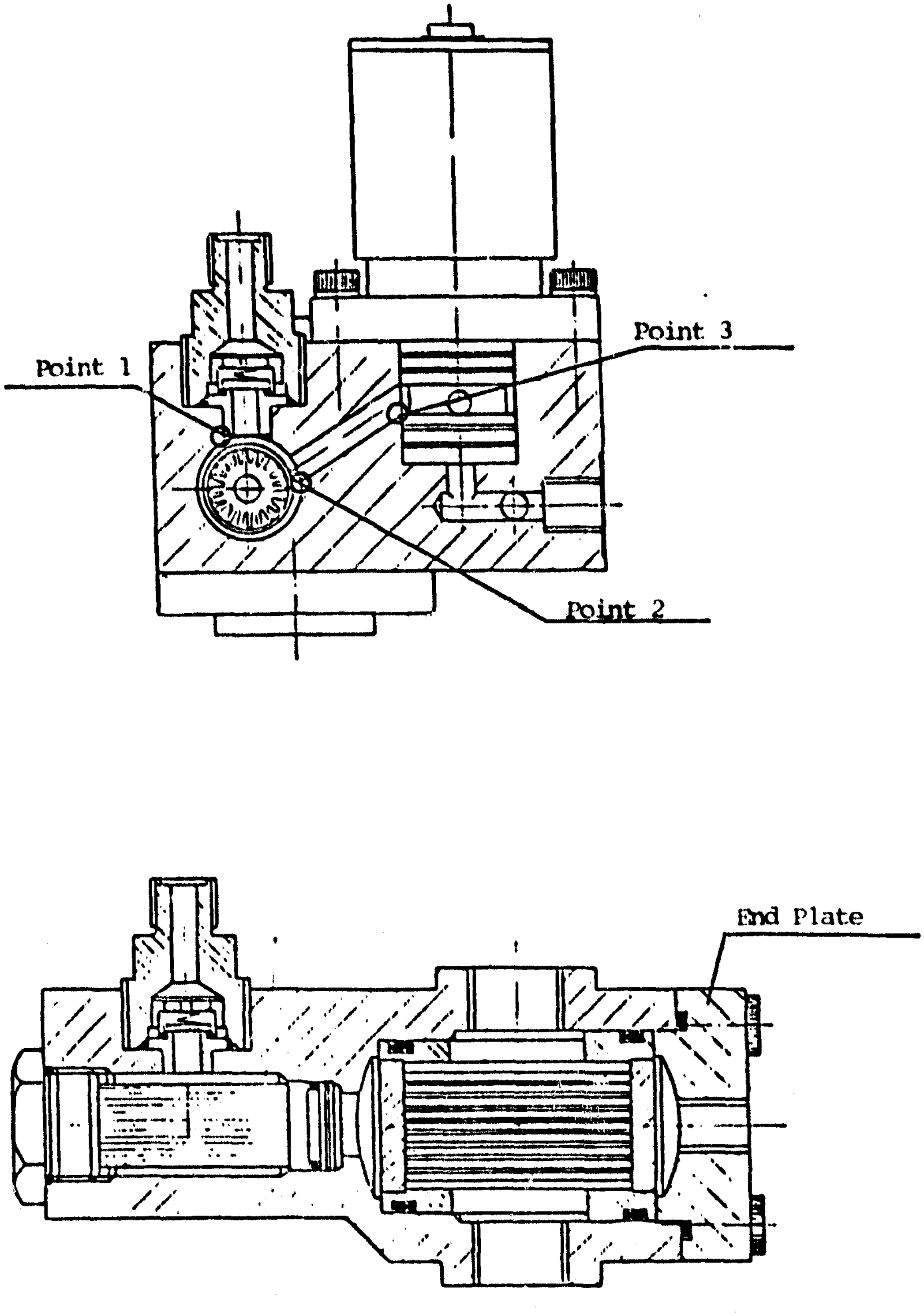

Figure 3.2.9.1-4 Points on Block 3 Used in the Stress Analysis

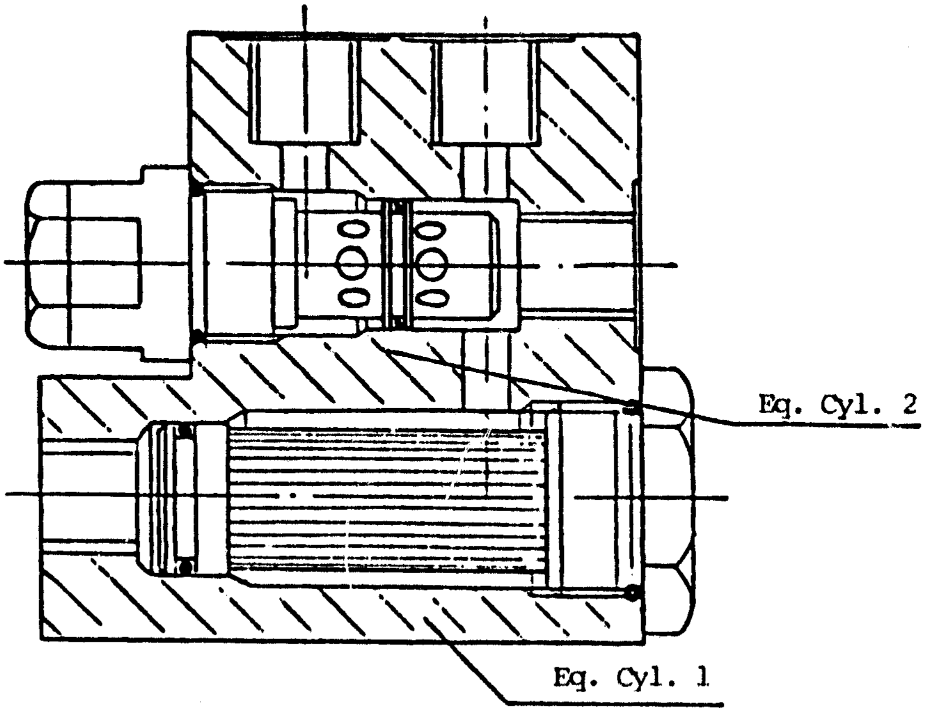

Figure 3.2.9.1-5 Points on Block 4 Used in the Stress Analysis

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The vortex-type air flow transducer from the Ford Motor Company was tested. The response of the flow meter was compared with a hot-wire anemometer; the results are shown in Figure 3.2.9.1-6. The vortex flow meter has a response which is faster than the response of the anemometer and the signal is stable without overshoots. The test was only a comparative test between these two types of flow meters; no absolute response time can be obtained from the curves. One of the disadvantages of the vortex flow meter is its nonlinearity, which is shown in Figure 3.2.9.1-7. The flow meter is a volume flow meter not a mass flow meter, so that it requires compensation for air pressure and air temperature changes.

- **Engine Software**

  The engine control program was run through a series of modules (see Figure 3.9.2.1-8). Each module consisted of its own program. The time to run through all of the modules is 50 ms. All written programs and system layouts are preliminary. Changes and additions may occur later, and may result in longer running time. The debugging of the programs and the study of program/engine compatability cannot be performed until the engine is running.

  - **Input A/D Conversion** The signal was called upon as differential or single ended through a low and high level multiplexer. Correction of offset and cold junction compensation was also done.

  - **Floating-Point**

    This routine makes the floating-point format integrate the format, and vice versa.

  - **Highest/Lowest Thermocouple Temperature**

    In the analog electronics, the highest/lowest thermocouple temperature passes through to the PI(D)-control.

  - **Input Key-Decoder**

    The starting and stopping conditions were defined; this routine has its own guard function against cable disconnection.

  - **Thermocouple Temperature Guard**

    The temperature guard for maximum temperature cuts off the fuel supply. If disconnection occurs in the thermocouples, this will be observed and a lower

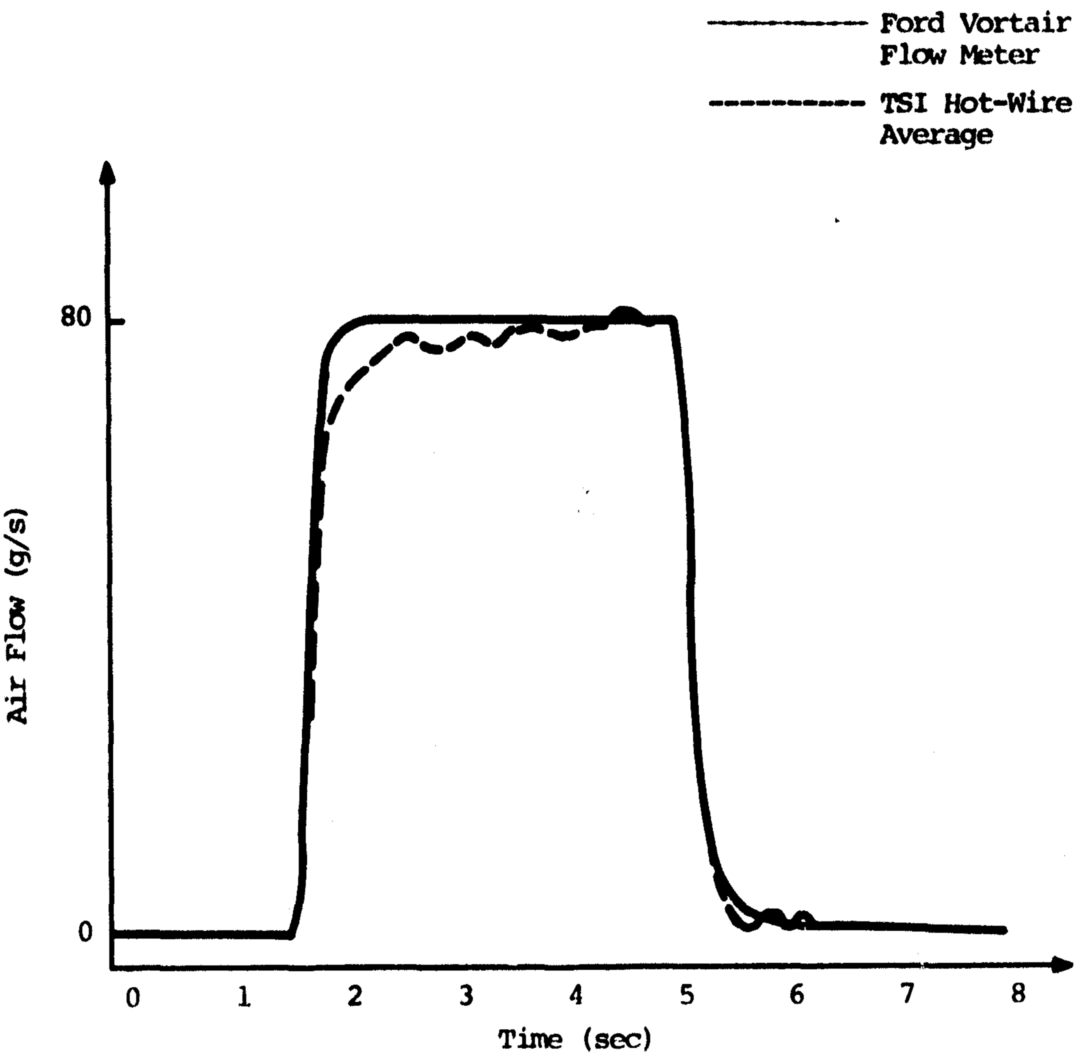

Figure 3.2.9.1-6 Flow Meter Response Test

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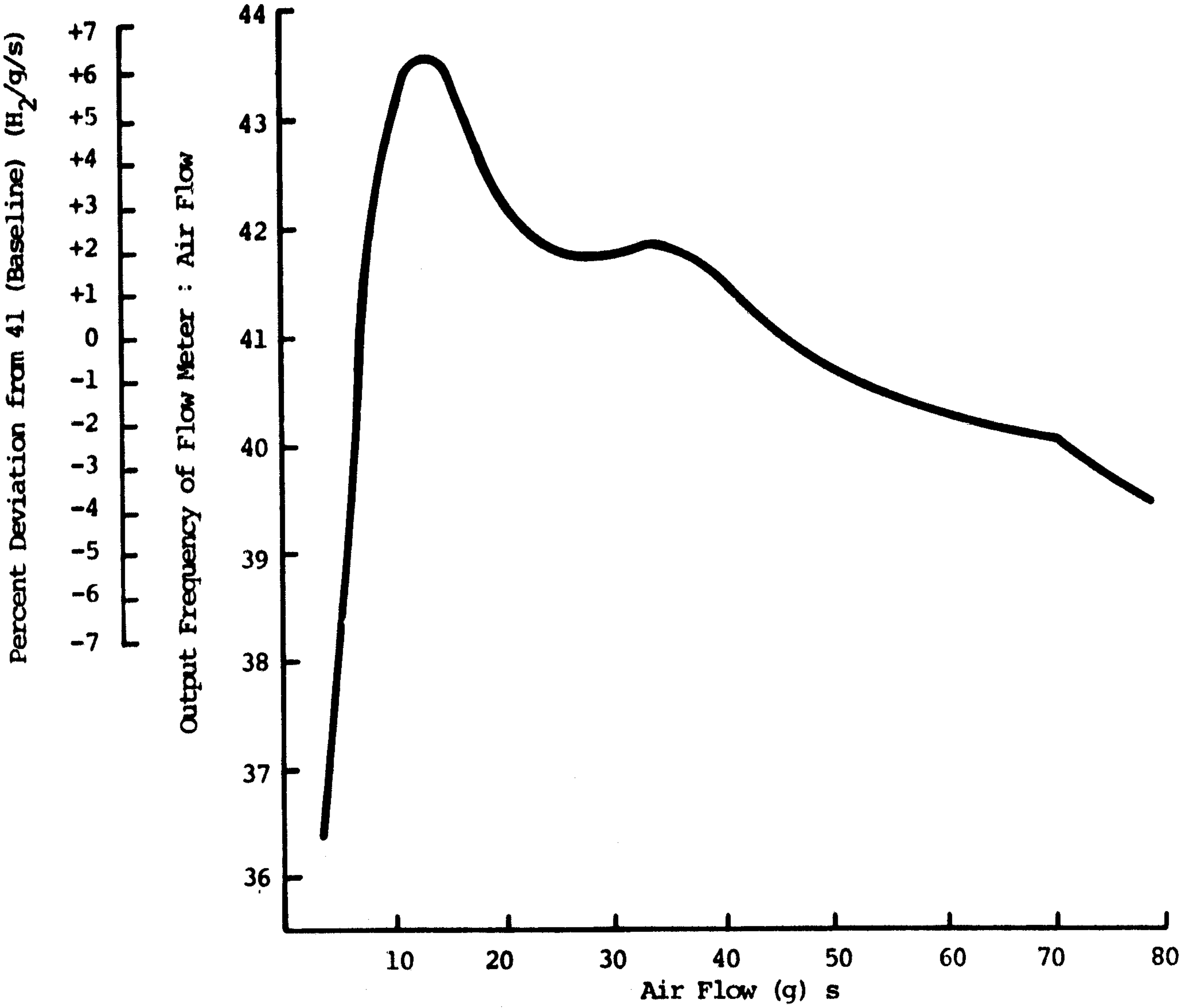

Figure 3.2.9.1-7 Characteristic of the Ford Vortair Flow Meter

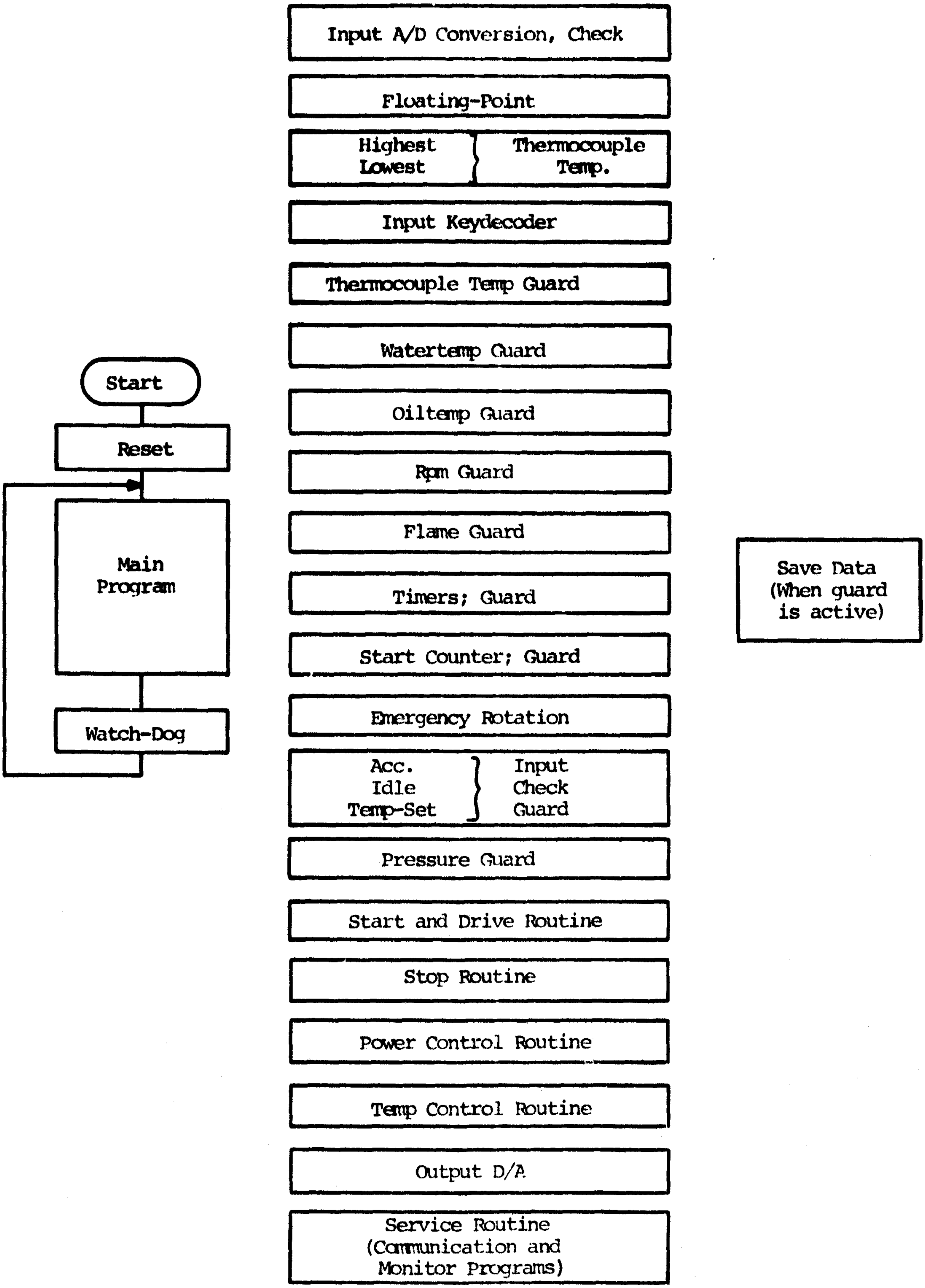

Figure 3.2.9.1-8 Engine Control Program Modules

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set-temperature will be set and displayed. In this case, the engine is not stopped by cutting off the fuel. If all thermocouples are disconnected, the fuel is switched off. If a signal of low temperature is recorded, the fuel is cutoff. When a stop routine is called for, the engine is always "run out" to decrease the temperature.

- Water Temperature Guard

  When the cooling water temperature exceeds 95°C, the fuel is cut off.

- Oil Temperature Guard

  See "Water Temperature Guard" routine.

- RPM Guard

  See "Water Temperature Guard" routine.

- Flame Guard

  The flame is sensed by a positive temperature derivation. A special unit, which works with the flame as a rectifier, is used. The signal from this unit will indicate flame or flame-out.

- Timers Guard

  The timers for the starter, blower motor, and the total time during the cooling down sequence are built up in the same way as in the analog unit. Also, the number of restarting sequences will be programmed to allow the engine to do three starting-up trials before being shut down.

- Emergency Rotation

  If the engine is stopped by accident, there is a risk to the seals and O-rings because of lack of cooling. In this case, the engine will be rotated by the starter.

- Accelerator

  The accelerator is checked for a disconnection. There are idle-set and temperature-set routines in this program.

- **Pressure Guard**

  Pressure transducers are guarded in case of a disconnection. Maximum pressure, start pressure, and leakage are also involved in this routine.

- **Start and Drive Routine**

  Uses the same routines as in the analog unit.

- **Stop Routine**

  All stops begin with fuel and ignition cutoff. The gas pressure is lowered, and the cooling-down sequence is performed.

- **Control Stop Routine**

  The PI(D) regulator used in the LM301 amplifier is transformed into a program having the possibility to change constants and variables. This program changes the constant according to load.

- **Output D/A**

  The outputs are analog for the throttle and the power control valve (Moog). The signals are also analog for the instruments and the recorders.

- **Service Routine**

  This program contains communicating routines to the monitor.

The following control programs were coded:

a. AD-routine.

b. Temperature maximum routine.

c. Key (car key) decoding.

d. Scale and control of accelerator, temperature set, and idling.

e. Tube temperature (for working gas), missing speed guard.

f. Accelerator curves.

g. S-curve (Moog-valve "speed up curve").

h. By-pass routine.

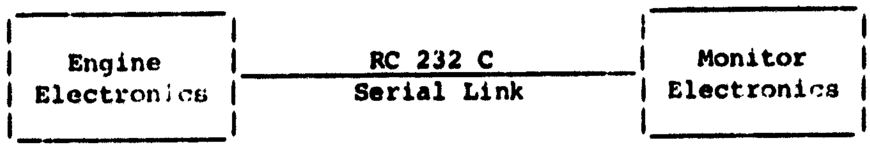
i. Stop routine.

j. Start and drive routines.

k. PID routine.

l. DA routine.

All of these routines are finished but have not been debugged on the computer. Debugging will start in August. All hardware was finished except for a board which con-tains servos and boost-amplifiers In order to converse between the monitor and the Stirling engine, the following electronic circuits are suggested:



- <u>Link</u>: Asynchronous 38,400 baud (opt. 9,600).

- <u>Character format</u>: ASCII for control and 8 bit binary for data message.

- <u>Purpose of communication link</u>: To transfer data (variables) from the engine electronics (EE) to the monitor- The monitor sends an index list to the EE. Each index. corresponds to a variable in the EE program. Data are then sent continously from the EE unit until a new index list is received.

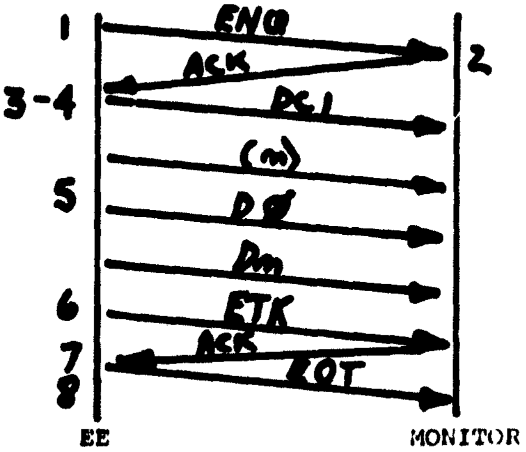
| | | | | | |
|---|---|---|---|---|---|
| ENQ | DC2 | IXO | IX1 | Etc. | EOT |

INDEX LIST (MESSAGE)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ENQ | DC1 | (n) | D | D1 | Etc. | Dn | ETX | EOT |

DATA MESSAGE

**DATA TRANSFER EE MONITOR**



1. Following each computation cycle, the engine electronics issues an ENQ (Enquire) character.

2. If the monitor is connected and active, it sends an acknowledgement character.

3-4. The EE sends a message header, DC1 + (n), which gives the length of the data message to follow.

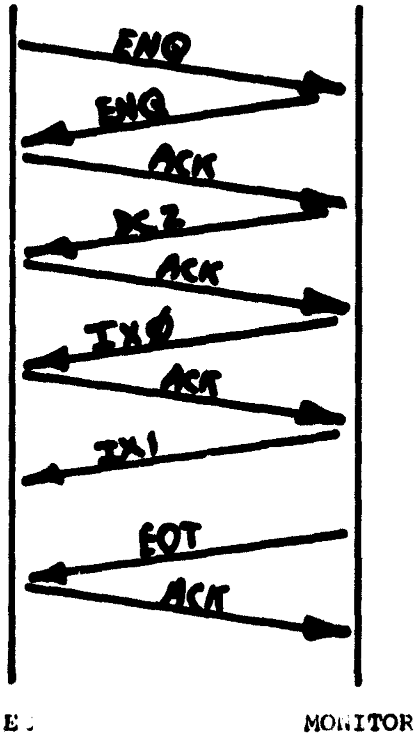
5. Data characters are sent as a stream of 16 bit words, two bytes each with the most significant byte first.

6. ETX (End of Text) indicates end of message.

7. Monitor responds with ACK (Answer).

8. EE terminates transfer.

If a monitor is not connected or is inactive, the EE will send only one ENQ each cycle and suspend communication activity until it is interrupted by a character from the monitor.



Monitor Request to Engine Electronics

### 3.2.9.2 ASE Mod II

- **Seals**

  Effort has started to screen capseal materials. Three different seal designs were run and one was selected for the subsequent rod surface test. Different rod materials and different surface treatments are being run against a Rulon LD seal:

| Designation | Surface | Finish Ra µm |
|---|---|---|
| A | Nitrided steel | 0.06 |
| B | Nitrided steel | 0.25 |
| C | Nitrided steel | 0.21 |
| D | Plasma spray coating Metco 505 (Mo) | 0.22 |
| E | Plasma spray coating Metco 505 (Mo) | 0.28 |
| F | Plasma spray coating Metco 101 ($Al_2O_3$) | 0.35 |
| F | Plasma spray coating Metco 101 ($Al_2O_3$) | 0.55 |
| H | Plasma spray coating Metco 74 F (WC) | 1.10 |

### High Temperature P-40 Endurance Engine

During April, the preheater system was replaced due to high exhaust temperatures, after a total accumulated running time of 1232 hours on the preheater. The removed preheater will be tested in the fluid dynamics laboratory. Five stops were caused by fuel delivery problems to the test rig, and one stop was caused by preheater change.

In May, the engine had trouble starting; this was due to worn piston rings and the leakage of working gas into the engine coolant. The engine was stopped when these failures occurred and new piston rings and gas cooler seals were mounted. This eliminated further starting problems; however, the working gas leak is still there. Further investigation is in progress to find out the reason for this leak. The total operating time for this set of piston rings was 3,063.3 hours.

The operating time of the high temperature P-40 engine reached 4610.3 hours at the end of this quarter. 1320.3 hours were accumulated on heater 2-12739 No. 17, of which 1150.4 hours were run with hydrogen as the working gas.

### Annular Regenerator-Type Heater

The total operating time on the annular regenerator type heater on the P-40 engine reached 105.5 hours at the end of this quarter. During May, when the engine was tested with heater No. 1, it was observed that the gas distribution was so poor that it affected the operation of the regenerators, which lowered the efficiency of the engine. When the new heater is installed for future tests, the gas distribution around the regenerators will be more regular and the dead volume of the heater will be decreased from 17 cm$^3$ to 2.8 cm$^3$ per quadrant. Strain gauge measurements were performed on a modified P-40 cylinder housing in order to validate the new heater head design.

### Simplified Test Cycle

A simplified engine test cycle was established for [illegible] in the high temperature materials test program. The cycle is based on the mean metro cycle and highway cycle pressure variation computed for the Reference Engine installed in an X-body vehicle with front wheel drive. In the establishment of the test cycle, the metro and highway cycles were combined 55% and 45% respectively. The mean pressure variation was analyzed in order to extract relevant peaks from the low cycle fatigue point of view, and linear creep damage theory was used in order to ensure equivalent creep damage. Such a creep analysis is material dependent: 12 RN 72 tube material at 870°C was used. The time of the simplified test cycle is 840 seconds; testing will be repeated 15,000 times, for a total of 3500 hours. The test cycle mean pressure level plot is given in Figure 3.2.9.2-1

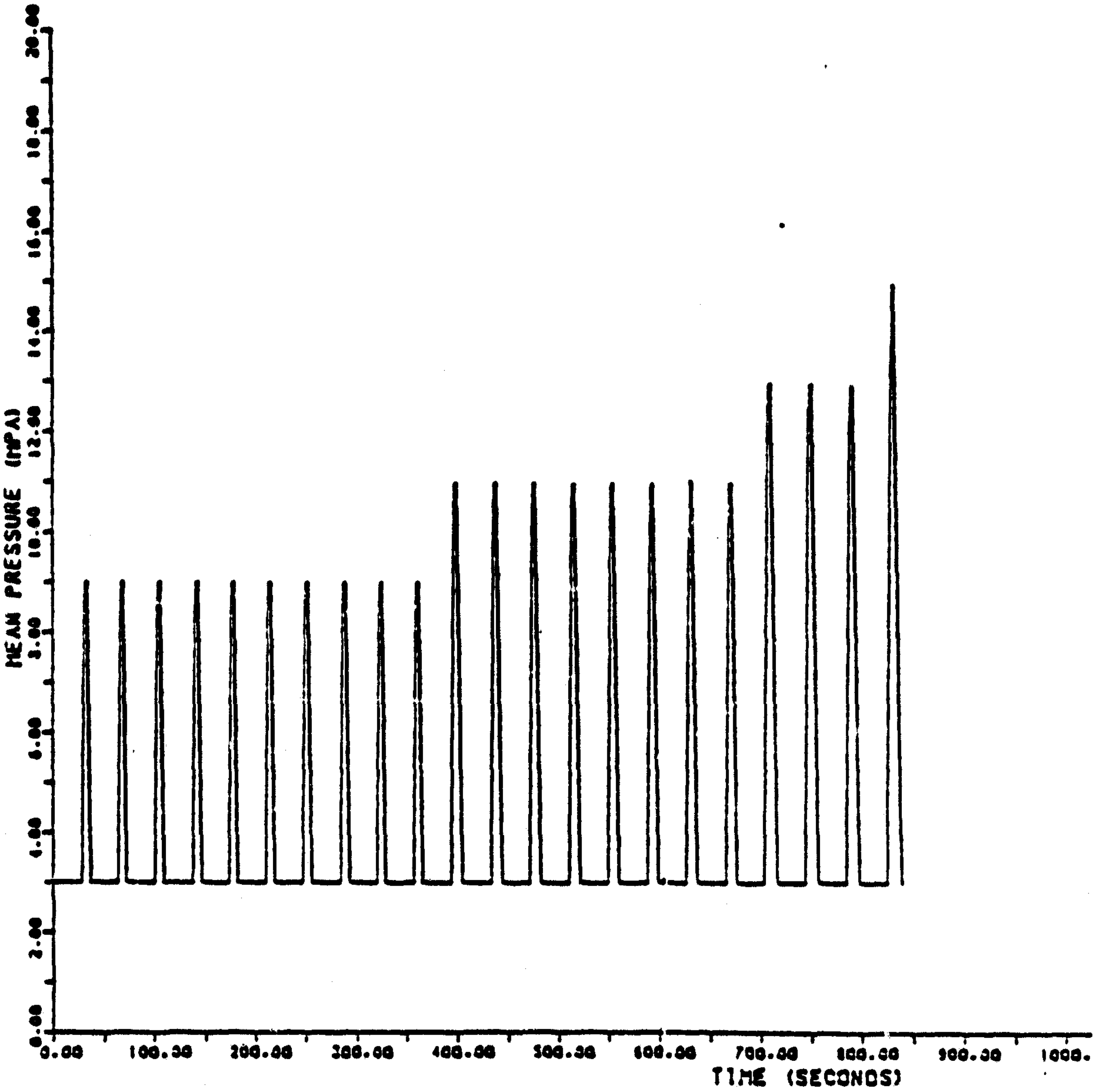


Figure 3.2.9.2-1 Test Cycle Mean Pressure Distribution Plot

## 3.3 MAJOR TASK 3 - TECHNOLOGY TRANSFER (BASELINE ENGINE)

### 3.3.1 Baseline Engine System (P-40)

- **P-40 Spirit Program (ASE 40-8)**

The P-40 Spirit was demonstrated several times during April. During May, it was transported to MTI and overhauled under the supervision of USS personnel. This overhaul served as a training session for MTI and AMG participants. In preparation for the overhaul, ASE40-8 was removed from the vehicle, disassembled, and inspected. In general, the cylinders were very clean and no oil was present. The engine was reported to be very tight with no gas leakage prior to disassembly. The gas filters in the power control system were very dirty and had to be replaced. The slide in the power control valve was corroded and pitted. The valve rod was also pitted but will be reused since it is not a sealing surface. The Spirit engine was rebuilt during June. The major items changed during the rebuild were:

- Regenerators (replaced).
- Hydrogen compressor seals (replaced with new-type seals).
- Power control valve slide (replaced).
- All new O-rings, backup rings, and seals installed.
- Piston domes were updated (plugged).
- New thermocouples.

The engine was reinstalled in the car and vehicle tests were run. During the tests, a transmission flexplate failed and was replaced. Acceleration tests were run before and after the rebuild. Testing after the rebuild indicated 0-60 mph accelerations of 45 seconds without the fan and 53 seconds with the fan continuously running. However, due to the differences in vehicle weights, these figures cannot be directly compared with previously published figures. After rebuild, the engine showed a definite improvement in performance. The engine electronics were also tuned up and a faulty chip was replaced in the air throttle circuit. Surface irregularities in the repaired cylinders were honed out and a high spot in cylinder #1 was reworked using a cylinder bore. The cylinder was inspected and additional work was required to smooth down the high spot before the block was used.

- **MTI Engine Testing (ASE40-7)**

A detailed engine maintenance training session, under the direction of USS personnel, was conducted at MTI from April 9-29, 1980. At the end of this session, ASE40-7 reassembly was essentially complete. In addition, the engine parts list was corrected and updated. In May, the engine was leak-checked and installed in the engine test cell. Initial engine and facility checkout tests were run, during which approximately 2.5 hours of operating time were accumulated. A problem encountered with the power control valve was corrected by the realignment of parts. Some difficulties also arose in the operation of the test facility oil cooling system. In June, work continued on the checkout of the instrumentation and the subsystems in the Phase I engine test cell. During check out testing, the engine accumulated 29.0 hours at various operating conditions. Rated maximum power of 40 kW was measured, which indicates that the engine is performing satisfactorily after the recent overhaul. Approximately 90% of the intended engine and facility instrumentation is currently functional. Some difficulties were encountered with the operation of the water cooling and oil cooling systems; as a result, these systems were revised. Activities also included the verification of the engine data from the Data Acquisition System and the computer output format was updated to be more convenient to use.

- <u>General Engine Support</u>

  A list of spare parts required to support P-40 engine activities was generated. This list contains the minimum quantities needed to be on hand at MTI to support engines in the U.S. The list also provides a reference from which engine parts utilization can be evaluated.

  The previously leaking and replaced P-40 Spirit engine block was sealed at the Loctite Corporation. A test tank was built, and the block was leak-tested to 1800 psi with helium. A special "O" ring transfer sleeve was fabricated for this test. No leakage of gas was observed. The cylinder-bore surfaces will be inspected and honed if necessary so that this repaired block can be used at a later data if necessary.

### 3.3.2 Test Facilities at MTI

During May, work was essentially completed on the Phase I engine test cell with the installation of ASE40-7. The only open activities include the upgrading of the underground fuel pumping system and installation of the gas analyzer.

MTI personnel traveled to Richmond Instruments to inspect the gas analyzer which was completed but had not been calibrated. Some problems were experienced with the $NO_x$ detector amplifier, but these problems were later corrected. The overall quality of the unit appears to be satisfactory.

## 3.4 MAJOR TASK 4 - ASE MOD I

During April, work continued on the detailed design and manufacture of the Mod I engine and the preparation for the engine system Critical Design Review in May. The objectives of the Critical Design Review, which was held at NASA-LeRC on May 22-23, are listed in Table 3.4-1 and a summary of the presentation

## DESIGN REVIEW OBJECTIVES

- To Update Mod I Basic Stirling Engine Design.
- To Review Detail Design of Mod I Stirling Engine System:
    - Control System
    - Auxiliaries
    - Vehicle Integration
- To Seek NASA Approval of Mod I Stirling Engine System Design.
- To Seek NASA Approval to Commence Procurement of Stirling Engine System Hardware for Mod I Program.
- To Update and Evaluate the Risk Assessment of Mod I Engine Design.

Table 3.4-1 Design Review Objectives

topics is contained in Table 3.4-2. The review concentrated on the auxiliary and accessory designs shown in Figure 3.4-1. Figures 3.4-2 and 3.4-3 show the auxiliary power demand at both full load and no load. The auxiliary power requirements are significantly lower than comparable power demands for the P-40 engine.

The major control system elements are shown in Figure 3.4-4. The design for each element was discussed in detail. The prime approach for the air/fuel control is shown in Figure 3.4-5. The Bosch K-Jetronic backup system, which is currently being used in P-40 engines, is shown in Figures 3.4-6. A major improvement over the P-40 engine is in the combination of a number of mean pressure control system components into separate blocks, as shown in Figure 3.4-7. These blocks (or modules) greatly reduce the number of external gas lines. In addition, the control system will be microprocessor-based rather than analog-based as in the P-40.

The engine and vehicle performance predictions are shown in Table 3.4-3 and Figures 3.4-8 and 3.4-9. As shown in Table 3.4-4, the Mod I performance represents a significant improvement over the P-40 engine. Table 3.4-5 shows a comparison between the Mod I and P-40 engine weights; the Mod I engine represents a 40% reduction in the weight to power ratio.

Because of the small clearance between the preheater housing and the vehicle hood, the design of the upper part of the combustion chamber will be revised in the area of the atomizer. In addition, in order to decrease the start-up time, a part of the incoming air will by-pass the combustor. The by-pass function will be obtained by using a throttle with required control equipment.

The position of the blower in relation to the air inlet on the manifold was finalized and the detailed design of the air inlet casing was completed.

The air preheater casting from Carl Schmidt will be delivered by the end of August; machining of the casting will be done by Lerema. The heater quadrant detailed design is finished and the heater will be completed in July; documentation on heater brazing and pressure testing will be finished in August. The detailed design of the gas cooler leak testing tools is finished. Leife AB has started to manufacture the tooling and it will be finished by the end of August. The seal cup and cylinder barrel are being detailed.

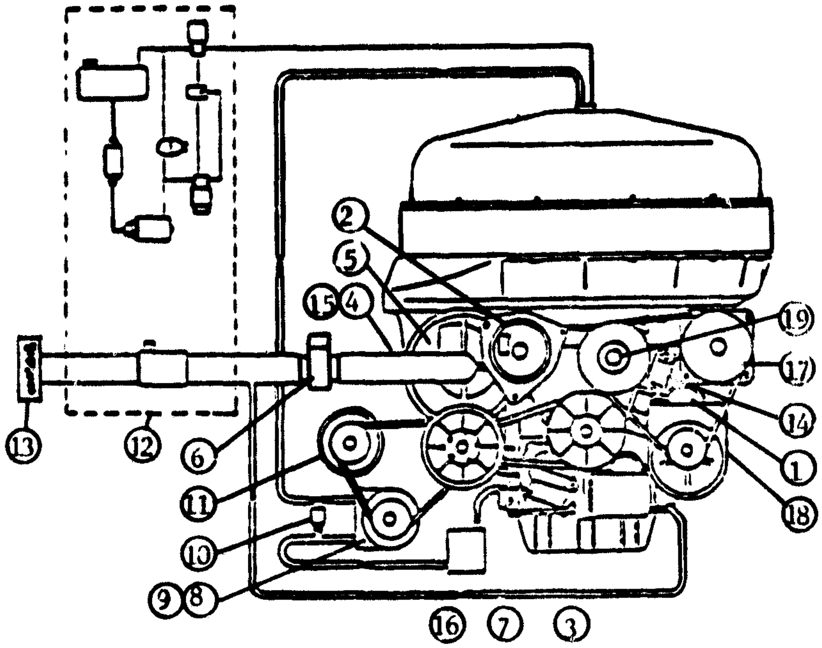
The variable belt drive parts are being manufactured and the drive is expected to be completed in early July*. The first and second drives were delivered to USS by Ricardo and all basic engine parts are being manufactured. The piston rods (from Facid AB in Malmo) were completed and grinding is starting at Sterner Blomqvist AB to be completed in August*. The seal housings were machined and will be mounted in a drive unit and used as fixtures during the build-up phase of the gas system. The cold engine parts are scheduled for delivery in August*; assembly is scheduled for September*. Hot engine parts are scheduled for delivery in October*; assembly is scheduled for November*.

---

*There was a general labor strike in Sweden dururing May which may result in a delay of the reported build dates.

- Updating of <u>Basic Stirling Engine</u> Presented In January 1980:
  - New Piston Dome Design
  - CGR Combustor Without Bypass Valve
  - Assembly Sequence - Tolerance Stack-up
- Concentration on the Other Parts of the <u>Stirling Engine System</u>:
  - Auxiliaries
  - Air/Fuel Control
  - Power Control
  - Electronic Control
- Installation in Vehicle
  - Packaging and Vehicle Modifications
  - Cooling System

Table 3.4-2 Agenda for Mod I Design Review



1. Starter motor
2. Alternator
3. Lubrication oil pump
4. Water pump
5. Combustion air blower
6. Air throttle
7. Variable ratio belt drive
8. Atomizer air compressor
9. Servo oil pump
10. Pressure relief valve
11. Electric blower motor
12. Air-fuel system
13. Air filter
14. Hydrogen compressor
15. After cooling pump
16. Crank case ventilation system
17. Air-conditioning compressor
18. Power steering pump
19. Radiator fan shaft

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Figure 3.4-1 Auxiliaries and Accessories of ASE Mod I

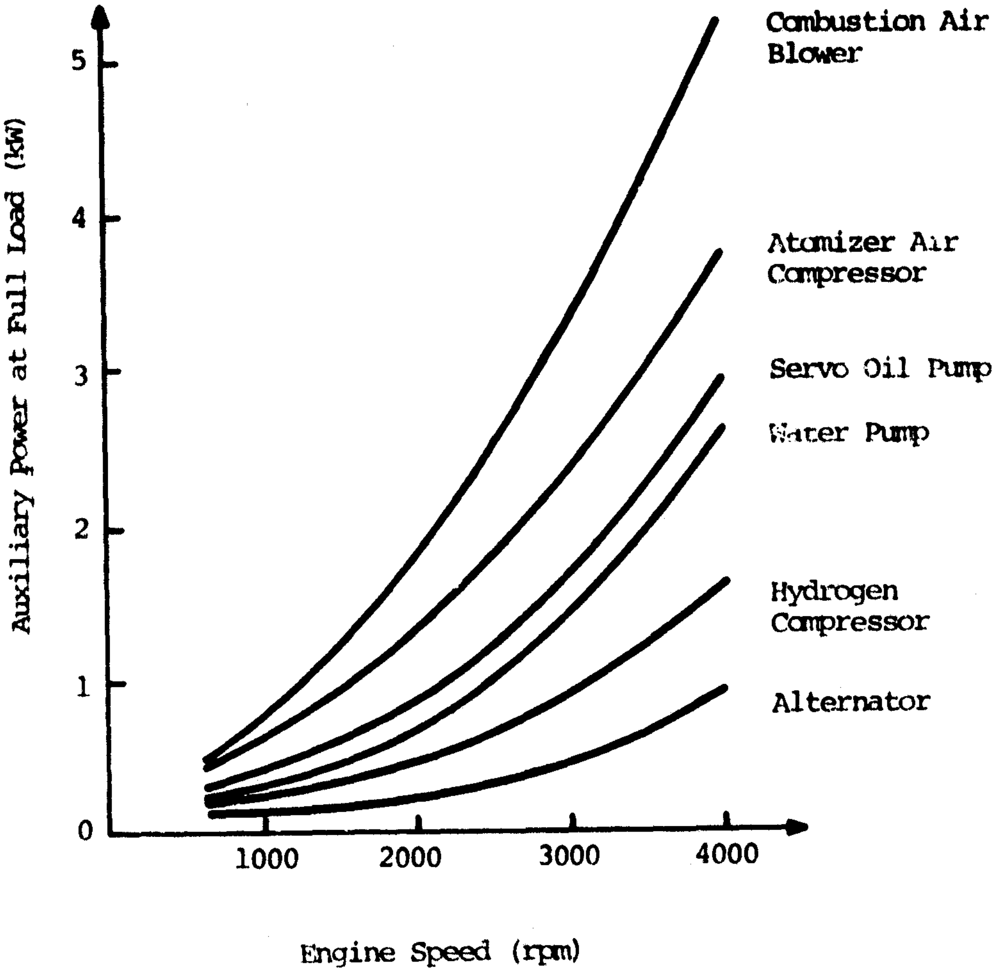

Figure 3.4-2 Total Auxiliary Power Demand at Full Load (No Accessories)

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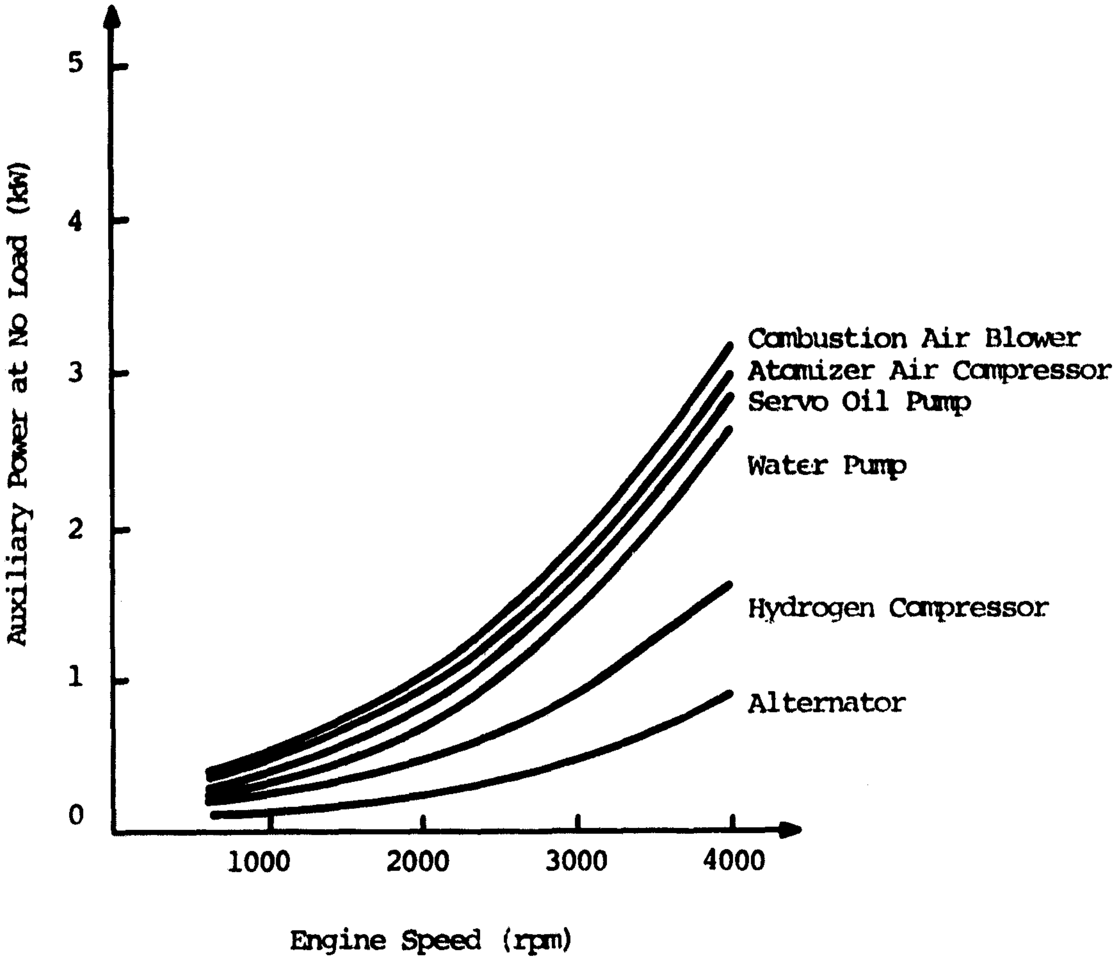

Figure 3.4-3 Total Auxiliary Power Demand at No Load (No Accessories)

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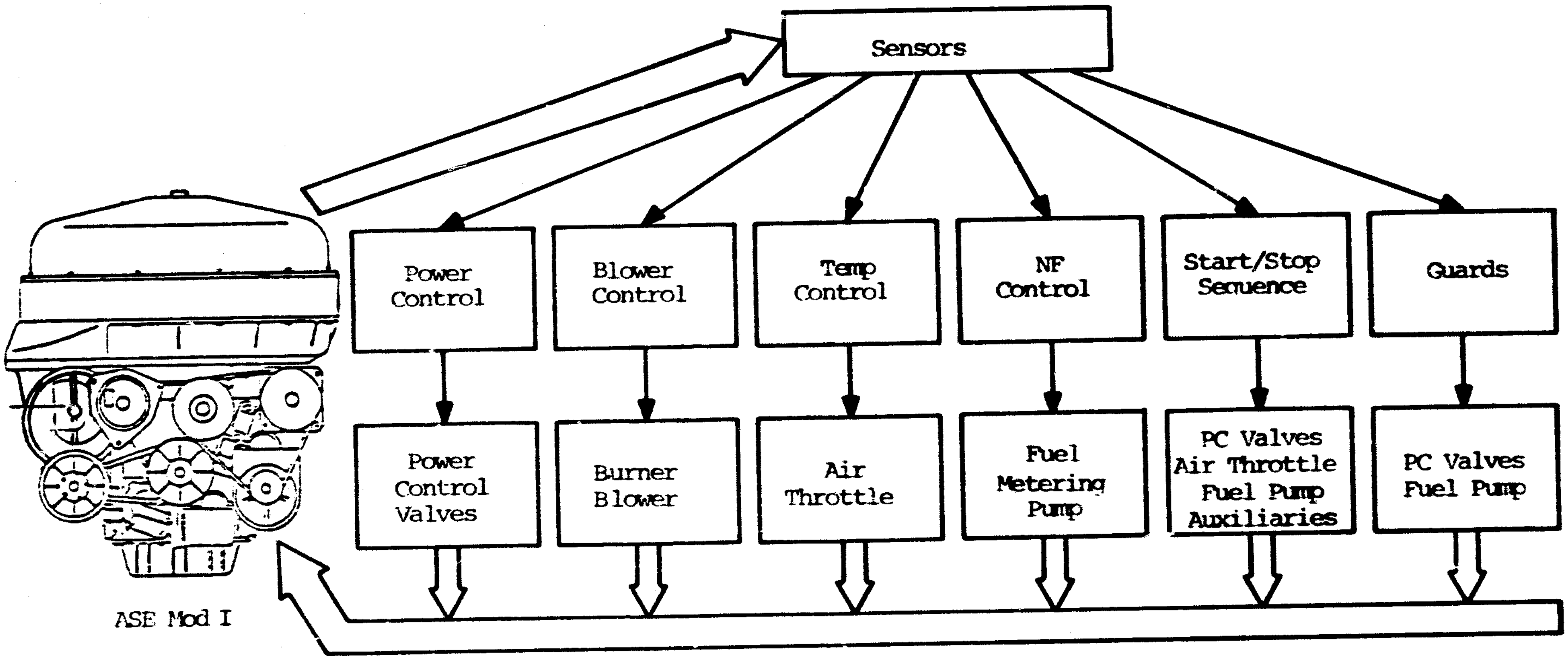

Figure 3-4.4 ASE Mod I Control Blocks

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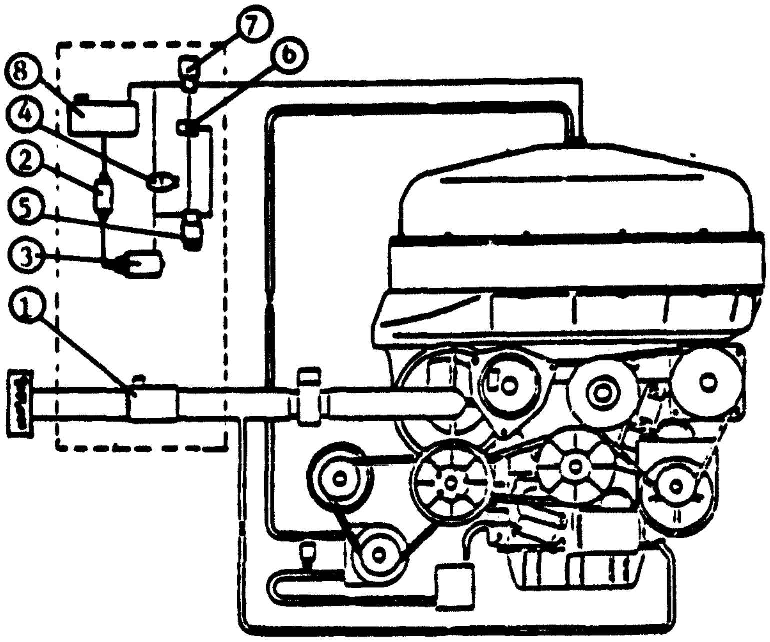

1. Air flow meter
2. Fuel filter
3. Fuel supply pump
4. Fuel pressure regulator
5. Fuel metering pump
6. Fuel equalizer
7. Fuel valve
8. Fuel tank

Figure 3.4-5 Air/Fuel System Diagram

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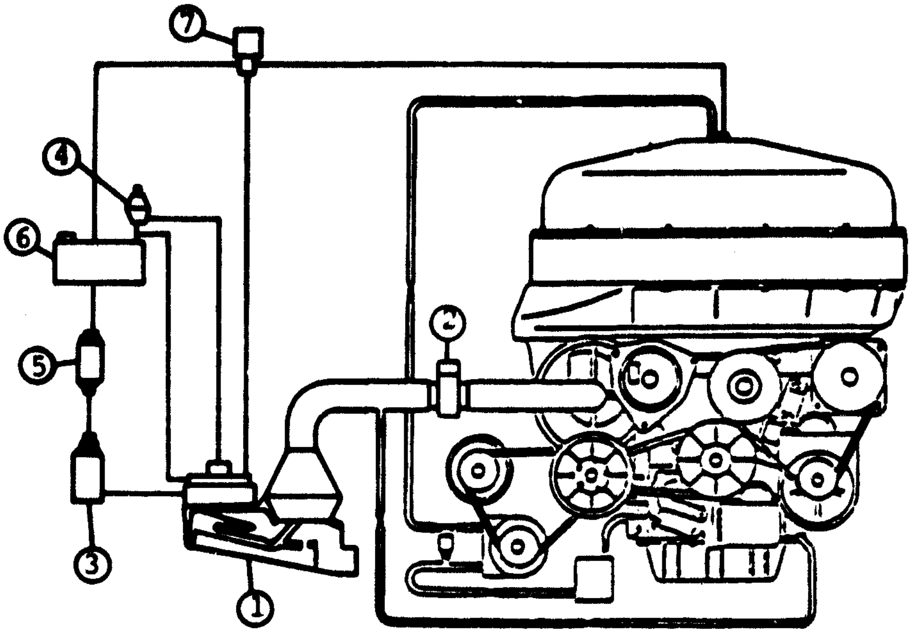

1. Bosch K-jetronic
2. Air Throttle
3. Fuel Pump
4. Pressure Relief Valve
5. Fuel Filter
6. Fuel Tank
7. Fuel Valve

Figure 3.4-6 Bosch K-Jetronic Air/Fuel System Diagram as Backup

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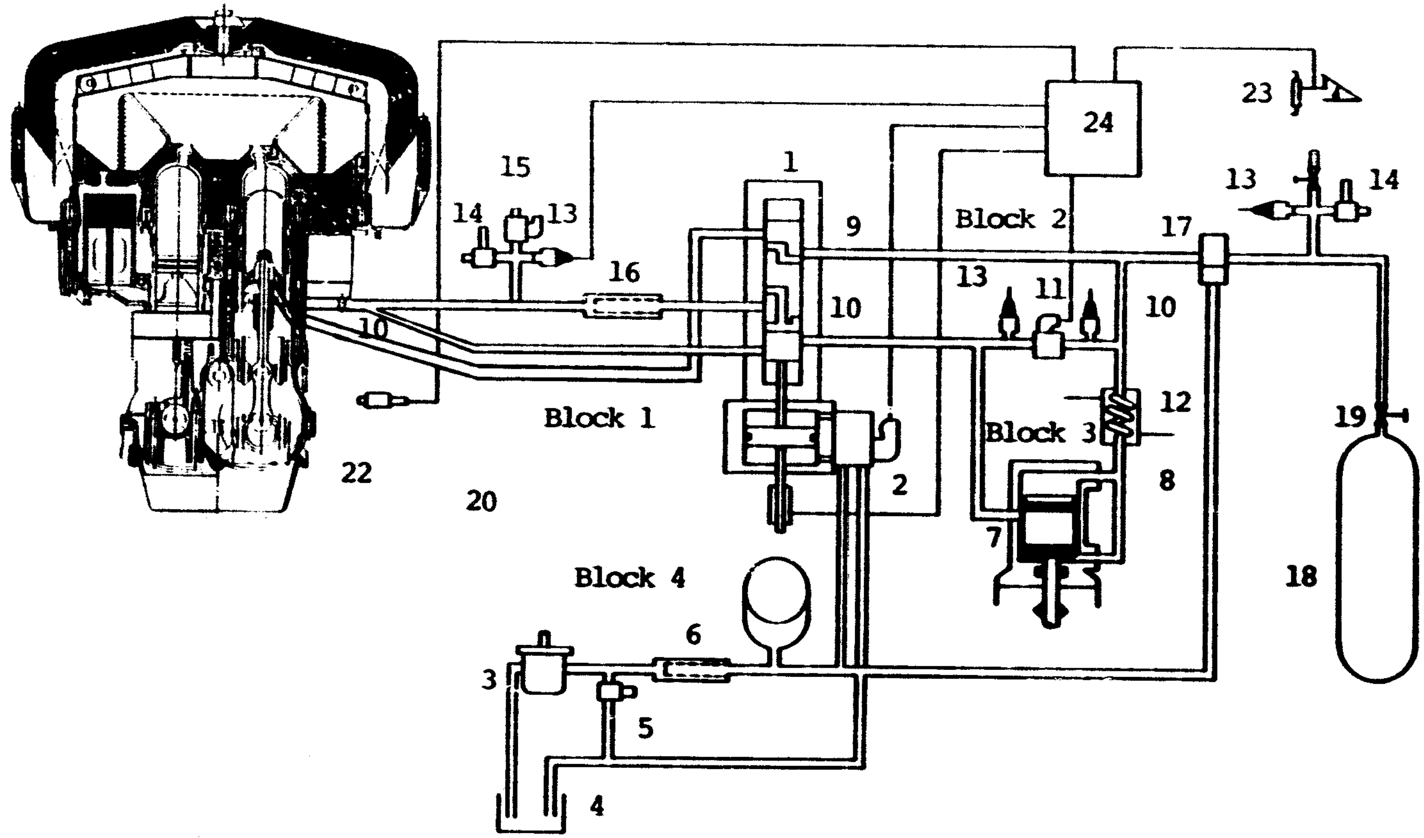

1. Supply, Dump and Short-Circuit Spool Valve
2. Electro-Hydraulic Servo Actuator
3. Oil Pump
4. Oil Tank
5. Constant Pressure Valve
6. Oil Filter
7. Hydrogen Compressor
8. Hydrogen Filter
9. Hydrogen Filter
10. Check Valve
11. Compressor Short-Circuiting Solenoid Valve
12. Hydrogen Cooler
13. Pressure Transducer
14. Safety Valve
15. External Dump Valve
16. Hydrogen Filter
17. Shut-Off Valve
18. Hydrogen Storage Valve
19. Shut-Off Valve
20. Hydrogen Refilling Valve
21. Temperature Melting Disc
22. Speed Transducer
23. Accelerator Potentiometer
24. Electronics

Figure 3.4-7 Block Diagram of ASE Mod I Power Control System

## ENGINE PERFORMANCE PREDICTIONS

| Point/Parameter | Power (kW) | Efficiency (%) | Pressure (MPa) | Speed (rpm) |
|---|---|---|---|---|
| Max Power | 53.6* | 28.1 | 15 | 4000 |
| Max Efficiency | 24.6 | 36.7 | 15 | 1300 |
| Part Load Point<br>(AOP for fuel flow) | 10.7 | 28.8 | 5 | 2000 |

*Difference as compared to January, 1980.

| | |
|---|---|
| January 1980 | 58.0 kW |
| Updating of Auxiliary Power | - 1.7 kW |
| - Increased Alternator Speed | |
| - Increased Combustor Pressure Drop (blower power) | |
| Basic Engine Finalization | - 2.7 kW |
| - Increased Pressure Drop Factor in Heater (after model flow test) | |
| - Increased CCD Dead Volume | |
| - Increased Dead Volume in Regenerator Manifold | |
| May 1980 | 53.6 |

Table 3.4-3 Engine Performance Predictions

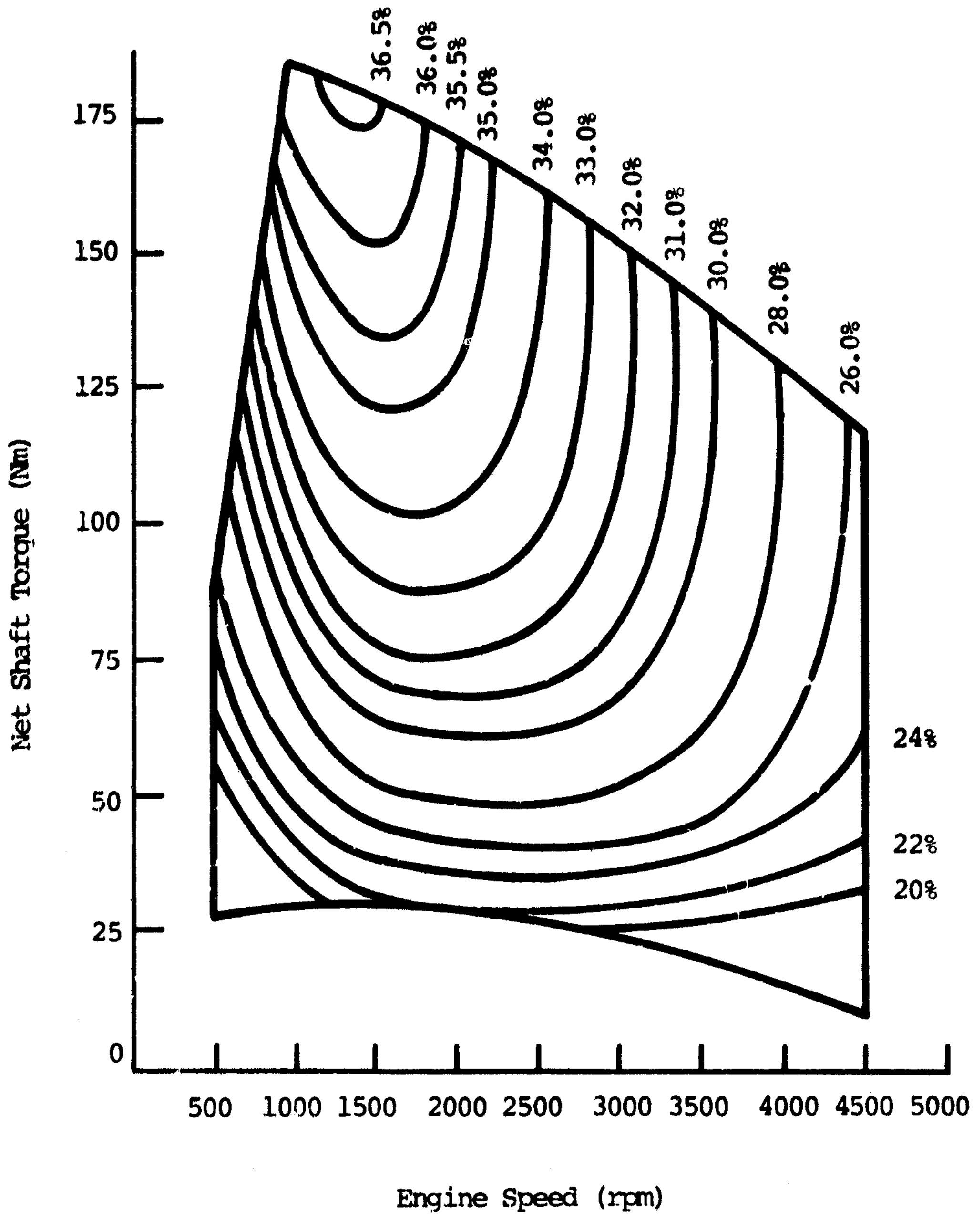

Figure 3.4-8 ASE Mod I Performance Map: Net Shaft Torque *versus* Speed

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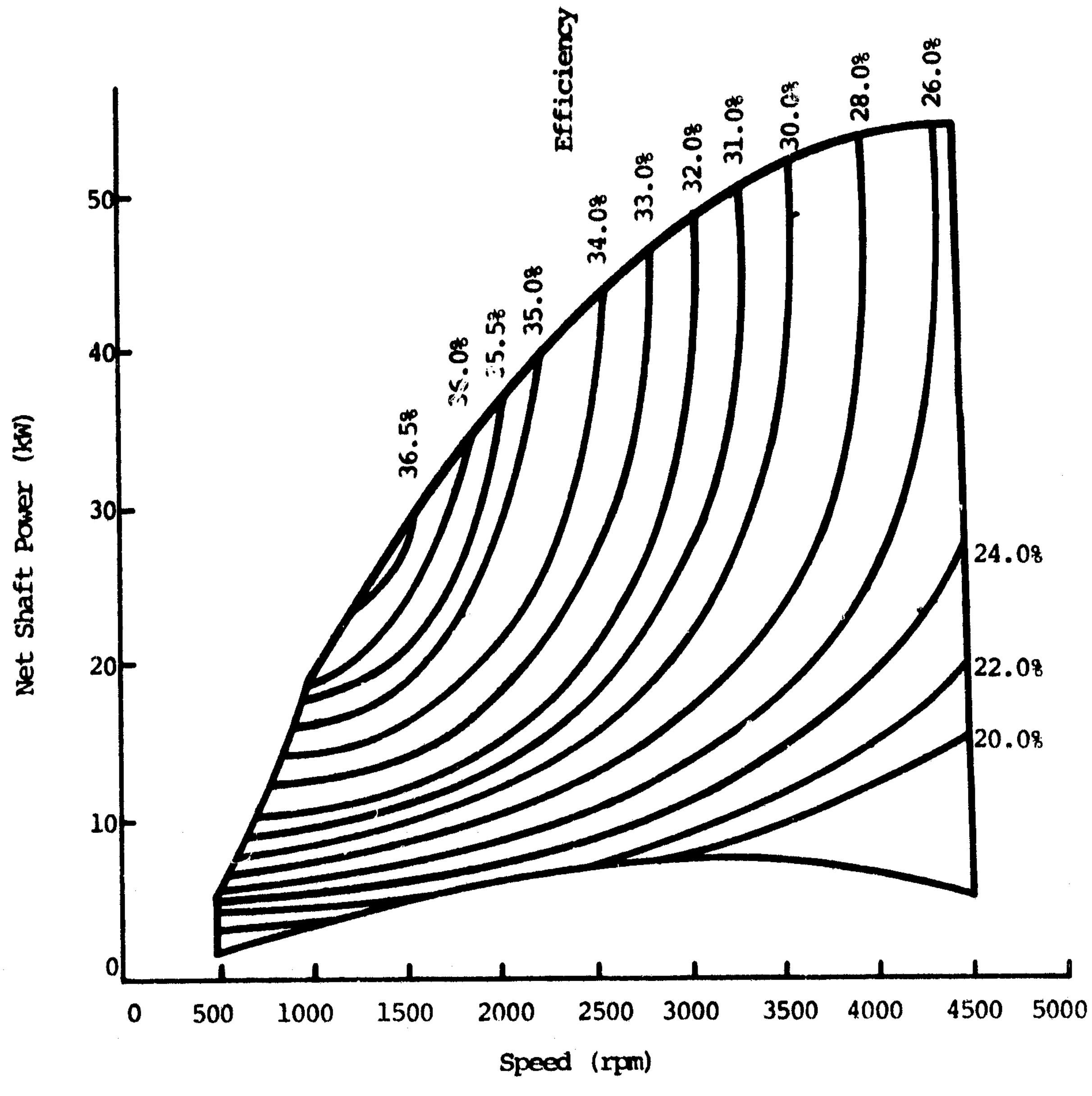

Figure 3.1-9 Performance Map of ASE Mod I: Net Shaft Power *versus* Speed

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# VEHICLE PERFORMANCE PREDICTIONS

| Mileage (mpg) | I.C. Engine | P-40 | Mod I | % Improvement |
|---|---|---|---|---|
| EPA Combined Cycle | | | | |
| (with A/C) | - | 20.8 | 27.1 | 30 |
| (without A/C) | 22.2 | | 27.5 | 24 |

| Acceleration (sec) | | I.C. Engine | P-40 | Mod I |
|---|---|---|---|---|
| 0-60 mph | 1979 Spirit | 19.1 | 38 | - |
| | 1981 Spirit | 15.9* | - | 22 |

## Emissions (g/mile)

Based on Latest CGR Combustor Test Data:

| | |
|---|---|
| $NO_x$ | 0.3 |
| HC | 0.1 |
| CO | 0.7 |

*1981 Spirit has 151 cu in. Engine whereas 1979 Spirit had 121 cu in. Engine.

Table 3.4-4 Vehicle Performance Predictions

## WEIGHT/POWER SUMMARY

| | | P-40 | Mod I |
|---|---|---|---|
| Weight* | KG | 329 | 266 |
| | LB | 724 | 587 |
| Power | kW | 40.0 | 53.6 |
| | hp | 54.0 | 72.4 |
| Weight/Power (lb/hp) | | 13.4 | 8.1 |

*Dry weight including auxiliaries, without accessories.

Table 3.4-5 Weight/Power Summary

Piston domes are being made by Bomco (Gloucestor, Mass.) and are scheduled for delivery by the end of July. Planning has started for the manufacturer of the Mod I drive unit. Quaker Alloy Investment Casting Division will quote on the Mod I cylinder heads and regenerator housings.

All design and detailing work for the Mod I engine drive system was completed. During the assembly of the first Mod I drive unit, various minor alterations were identified; these alterations required the correction of the detail drawings.

Although the design and detailing is essentially complete, and the first drive unit was assembled, tested, and shipped to USS, various minor drawing alterations and changes still were necessary and have been completed. An analysis was performed of the overall balance of the pair of chain-drive crankshafts. The "Build Book", which is a history of the assembly/ inspection of each delivered drive unit, is complete and Ricardo is ready to ship it to USS.

The first ASE MOD I drive unit was assembled with the safety clutch and was shipped to USS in mid-May. The second MOD I unit is now being assembled; its completion will be delayed while waiting for the driving gears from Fleron Kugg. The manufacture of the remaining seven units is proceeding satisfactorily.

The Stirling analysis computer program input was updated to match the final drawings and to reflect the latest predictions concerning auxiliary power consumption. The auxiliary power demand is 1.7 kW greater at the full-load point than what was used in previous calculations. In total, the calculated full-load shaft power has decreased by 4.4 kW; however, the part-load (5MPa, 2,000 rpm) efficiency was not significantly changed and there was a negligible impact on the mileage.

Figure 3.4-10 defines the ASE Mod I and shows a schematic of the engine.

## 3.5 MAJOR TASK 5 - ASE MOD II

Design effort under this task is not scheduled to start until 1981.

## 3.6 MAJOR TASK 6 - PROTOTYPE ASE SYSTEM STUDY

This task will not start until 1982.

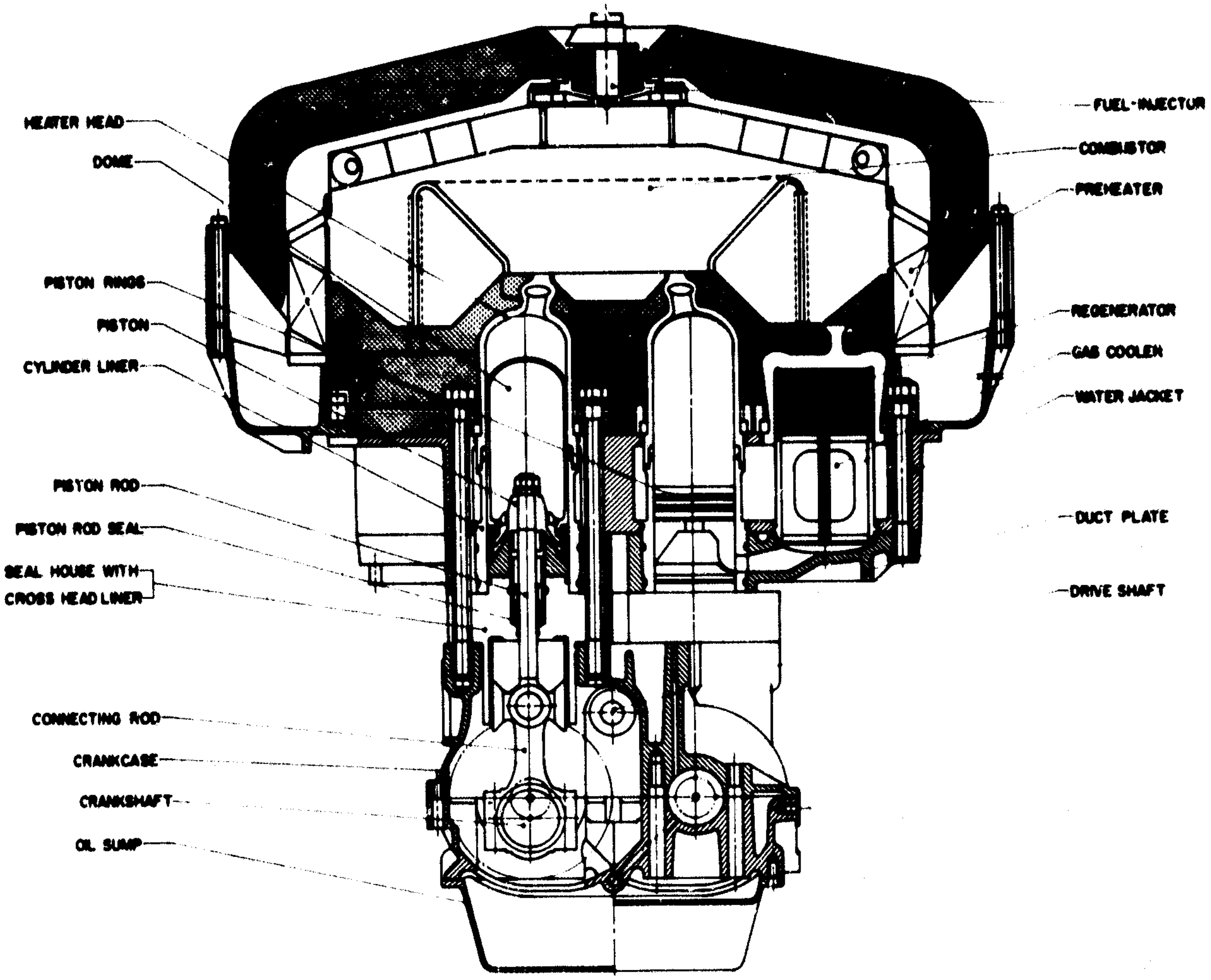

Figure 3.4-10 Schematic of ASE Mod I

## 3.7 MAJOR TASK 7 - COMPUTER PROGRAM DEVELOPMENT

The development of the Stirling engine performance code focused on the thermodynamic cycle analysis and the global thermal network. Initial documentation of the heater system analysis was completed and the revision of the cooling system was rescheduled.

The evaluation of NODAL 7/EPISODE, to identify the mechanism limiting EPISODE's integration time-step to small values, continued at a low level. EPISODE uses a backward-difference formula to predict system parameters at each new time, and then uses Newton's method to iteratively correct these new system parameters. The integration time-step is essentially limited by the effectiveness of Newton's method and it depends on the accuracy of the system's Jacobian matrix; Jacobian matrix errors represent an obvious mechanism which would limit the integration time-step. Two types of Jacobian matrix errors were readily identified:

1. Errors inherent in the matrix formulation.
2. Errors inherent in the generalized Newton or chord method, which uses a Jacobian from a preceeding time-step to approximate the Jacobian at the current time.

While the first type of error has not yet been investigated, the second one was studied and eliminated as the time-step-limiting error source.

Effort was applied to developing and implementing an implicit solution for the continuity and momentum equations. The resulting code, NODAL 8, was applied to a piston-tube-cavity test case. Approximately 2000 time-steps were required by NODAL 7 to traverse the first cycle, but only approximately 50 time-steps were required by NODAL 8 to traverse the first cycle. Because of its large time-steps, NODAL 8 was unable to accurately follow the initial transient ($t < 0.008$ sec.). After the initial transient, however, NODAL 7 and NODAL 8 yielded almost identical results. Simulation costs using NODAL 8 were much less than those currently achieved by NODAL 7. The implicit solution procedure in NODAL 8 was extended to include energy conservation equations for both the working gas and the regenerator material. The resulting code was applied to the piston-tube-cavity test case. Calculations were initiated with a time-step of 1.0E-9 sec. The time-step was allowed to increase to a time-step of 300.0E-6 sec., which corresponds to 50 time-steps/cycle. Inclusion of the energy equations in NODAL 8 did not appear to reduce its numerical stability; however, the number of iterations at each time-step increased dramatically with increasing time-steps. Refinement of the solution procedure is needed to control the number of iterations required at each time-step, and correspondingly, the operating economy of NODAL 8.

A potential cause for the small time-steps experienced by NODAL 7/EPISODE was identified. Since the piston and displacer motions are currently prescribed, their respective displacements, velocities, and accelerations are not explicitly included in the integration process, and the corresponding Jacobian matrix does not include influence coefficients for them. Corrector iterations, using a Jacobian evaluated at a preceeding time, would be very ineffective and would limit the integration time-step. Revision of the simulation and the corresponding Jacobian matrix to explicitly include these parameters is expected to improve the operating economy of NODAL 7/EPISODE.

An analysis was developed to describe the heat transfer in the expansion and compression space resulting from thermal hysteresis in the boundary layer adjacent to the wall. The results of this analysis are being reviewed and validated. Subsequent to validation, the results will be included in the thermodynamic cycle analysis.

The coding for the global thermal network was completed and several simple check cases were successfully executed. The analysis still must be evaluated for a large network which includes several nonlinear heat transfer linkages. The global thermal network was applied to a 21-mode model of an automotive-type heater head (typical two-row, P-40/Mod I geometry). The model included: nonlinear radiation and tube-in-crossflow linkages, axial conduction in the heater tubes, and temperature variations in the combustion gas specific heat. The analysis performed as expected.

During June, activity concentrated on the preparation of an interim code. As previously reported, the thermodynamic cycle analysis and global thermal network codes were checked out with simplified test cases. These two codes have now been combined to form an interim Stirling engine analysis program which will be delivered to NASA. In addition, the required interfaces with the heater system, cooling system, and mechanical analyses were incorporated in the code structure. The interim code is operational and was checked out with a simplified test case. A more comprehensive, representative, Stirling engine test case was prepared and will be used to further evaluate the code.

## 3.8 MAJOR TASK 8 - TECHNICAL ASSISTANCE

The Stirling-powered 1979 AMC Spirit was displayed at the 5th International Symposium on Automotive Propulsion Systems during the week of April 14, 1980, at the Hyatt Regency Hotel in Dearborn, Michigan. The theme of the display was the specifications for the current RESD and the ASE Mod I. A new tape/ slide presentation "The Stirling Engine-Helping to Solve Our Nation's Energy Problem" was also shown for the first time. Figure 3.8-1, shows the Spirit on display.

The P-40 Spirit was displayed at the DOT National Transportation Week Exhibit in Washington, D.C. on May 13-14. The Stirling engine multi-fuel capability was demonstrated during this show as shown.

Congressman Tom Harkin visited MTI on May 19. He was picked up at Albany Airport and driven to MTI in the P-40 Spirit. Congressman Harkin had previously ridden in the P-40 Opel at the CCM in October 1979, and he was very favorably impressed with the Spirit's improvements in performance over that of the Opel.

The Concord with the mockup P-40 engine was displayed at the 1st California Energy and Transportation Fair in Sacramento, California on May 30-31. The fair was sponsored by CALTRANS. A great deal of interest was evident for the Stirling engine's automotive power plant potential, especially the multi-fuel and clean emissions characteristics. Additional Energy Fairs are planned for Los Angeles, San Diego, and San Francisco during the summer months. The Concord and the display were left with CALTRANS for use in these upcoming fairs.

Work activities are well underway for the new, Stirling engine-powered Concord Demonstration vehicle. A detailed schedule of events was prepared. During the week of June 16, the engine was shipped from USS to AMG to be installed in the Concord vehicle. Parts required to install the engine assembly are being ordered and/or fabricated by AMG. The car should be operational by mid-August.

A contract was awarded to MGA Research (of Buffalo, New York) to perform a safety study of Stirling-powered cars. Meetings are scheduled in the near future at both MTI and AMG to provide MGA with the necessary technical information.

## 3.9 MAJOR TASK 9 - PROGRAM MANAGEMENT

The first RESD Design Review update was held at NASA-LeRC on May 21. Information regarding the meeting and the materials presented are included in the Major Task 1 presentation in this report.

The ASE Mod I System Critical Design Review was held at NASA-LeRC on May 22-23. Information regarding the meeting and the materials presented is included in the Major Task 4 presentation in this report. On the basis of verbal approval from NASA, procurement and manufacture of the ASE Mod I has started.

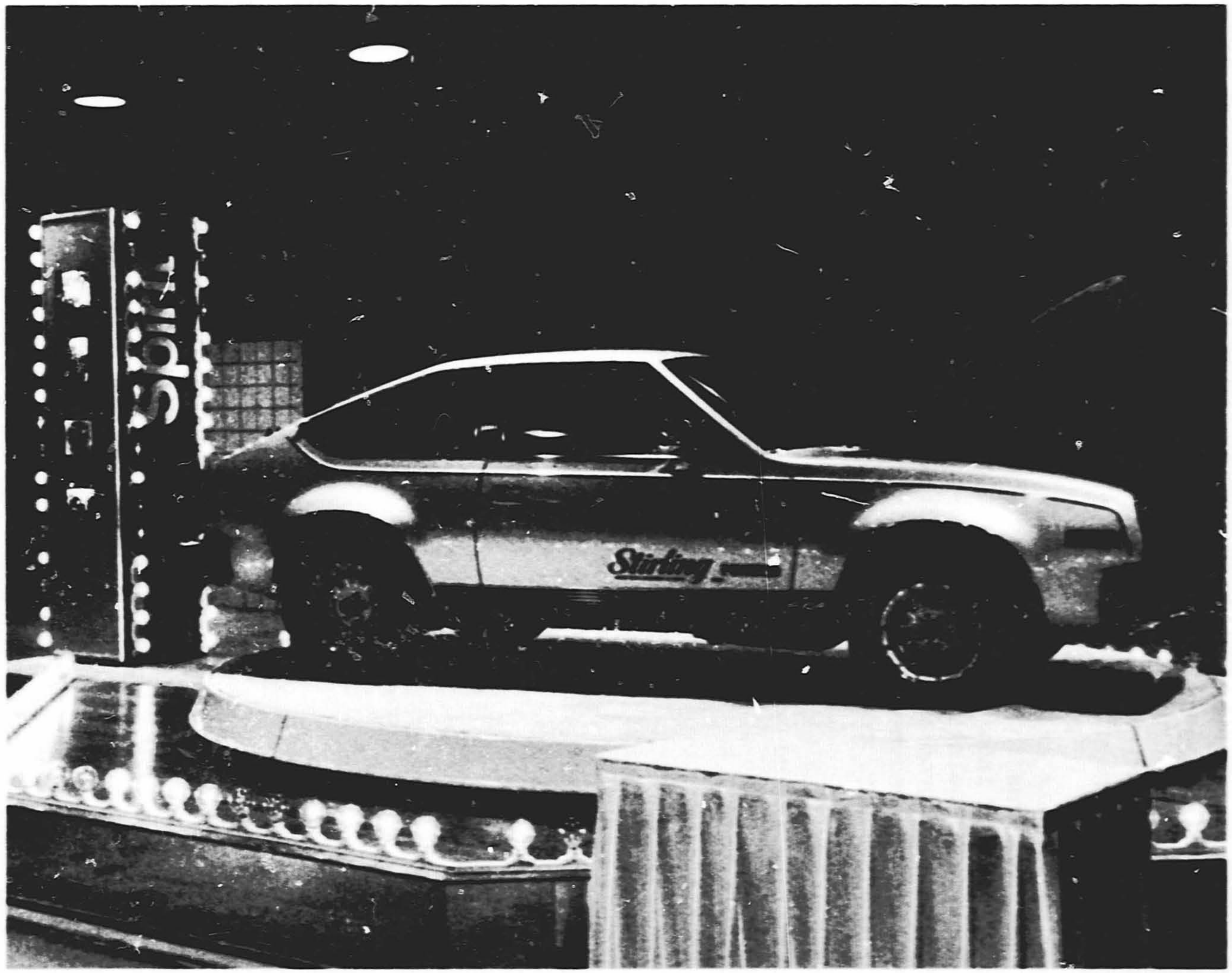

Figure 3.8-1 Stirling-Powered Spirit Vehicle on Display at the Semiannual CCM

An important aspect of program management is product assurance. As an integral part of each engine design, manufacture, and test, complete records are maintained to identify and report defects, discrepancies, failures, and other unsatisfactory conditions.

The Project Manager for Product Assurance has initiated a procedure of Failure Notices (FN) and Discrepancy Notices (DN) reporting. Failure Notices pertain to the failures or unsatisfactory performance of parts, components, systems, and engines; Discrepancy Notices pertain to deviations of parts from the established drawings, specifications, and purchase orders.

The Manager of Reports and Data Management maintains the information contained on the FN and DN forms in the A.B. Dick Shared Logic Word Processor. The information is entered into the system periodically and it is accumulated in the mememory bank. The Select/Search/Sort program allows this random information to be automatically processed for analytical and statistical purposes. The memory bank can be searched to locate all data pertaining to a particular engine part, subassembly, component, control, engine section, vendor, etc.

The parts list for each manufactured/operating engines are also maintained in another data file in the Word Processor. As parts are removed because of wear or failures, or because of routines maintenance or for test purposes, the operating times will be recorded along with the disposition of the removed part and the identification of its replacement. Although this system is new and not functional at present, it is anticipated that a complete history of every important engine part will ultimately be maintained and that the Word Processor will permit cross-referencing and cross-checking between different data files and different engines so as to yield a full and accurate product assurance analyses capability.

## 4.0 REFERENCES

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