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NASA CR-167907
MTI 91ASE229QT13

AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

QUARTERLY TECHNICAL PROGRESS REPORT FOR PERIOD: APRIL 1 - JUNE 30, 1981

Mechanical Technology Incorporated

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May 1982

Prepared for:
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN3-32

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Conservation and Solar Applications
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1.0 SUMMARY

The DOE/NASA "Automotive Stirling Engine (ASE) Development Program" has been underway for approximately 31 months. This report covers the period of April 1 to June 30, 1981.

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 comprehensive report gives the background and history of the Stirling engine, discusses the technology, materials, components, controls, and systems, and presents a technical assessment of automotive Stirling engines.

Program engine operating hours for this quarterly period (ending June 30, 1981) are as follows:

Engine No.		Total Hours
ASE 40-4	(High-Temperature Endurance Test Engine)	6,134.46
ASE 40-5	(Opel Engine)	250.0
ASE 40-7	(MTI Test Engine)	206.00
ASE 40-8	(Spirit Engine)	292.44
ASE 40-12	(Engine for the Concord)	140.40
ASE 58-1	(Mod I)	173.00
Total		7,196.30

*References are listed by number in Section 4.0

2.0 INTRODUCTION

The ASE Program is directed at the development of technology and knowledge related to the application of Stirling engines for 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.

Mechanical Technology Incorporated (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 on the extensive technological achievements, capabilities, and background knowledge (in Stirling engines) of KB United Stirling (Sweden) AB & Co. (USSw), 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 are to develop and demonstrate an Automotive Stirling Engine System by September, 1984 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 essentially give the same overall vehicle driveability and performance. The improved fuel economy will be based on unleaded gasoline of the same energy content (Btu/gal).

   The intent of the program is to use identical model vehicles for the comparison; however, a difference in inertia vehicle weight 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: NO_x = 0.4, HC = .41, CO = 3.4 gm/mi, and a total particulate level of 0.2 gm/mi 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/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 metrocycle, and will use the same fuel used for fuel economy measurements.

In addition to the above objectives (to be demonstrated quantitatively), the following design objectives are considered goals of the program:

1. reliability and life comparable with powertrains currently on the market;

2. a competitive initial cost and life-cycle cost comparable to a conventionally powered automotive vehicle;

3. acceleration suitable for safety and consumer considerations;

4. noise and safety characteristics that meet currently legislated or projected Federal Standards for 1984; and,

5. the ability to use a broad range of liquid fuels from many sources, including coal and shale oil.*

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 testing with the alternate fuels will not be initiated for the ASE Mod I/Mod II engines until satisfactory operation, performance, and emissions have been achieved on the baseine fuel -- gasoline. Testing will then be conducted with the selected alternative fuels to determine the extent of detrimental affects on engine operation, performance, emissions, or fuel economy, and to determine the degree of modifications/adjustments that may be required when switching fuels.

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 an ASE Mod I engine at the contractor's facility prior to September 30, 1981;

3. dynamometer characterization of ASE Mod I (upgraded) engine prior to September 30, 1982;

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

---

*This objective will be pursued initially in the combustor development effort, and later in engine/vehicle testing.

5. dynamometer characterization of the Mod II engine at the contractor's facility prior to September 30, 1983; and

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

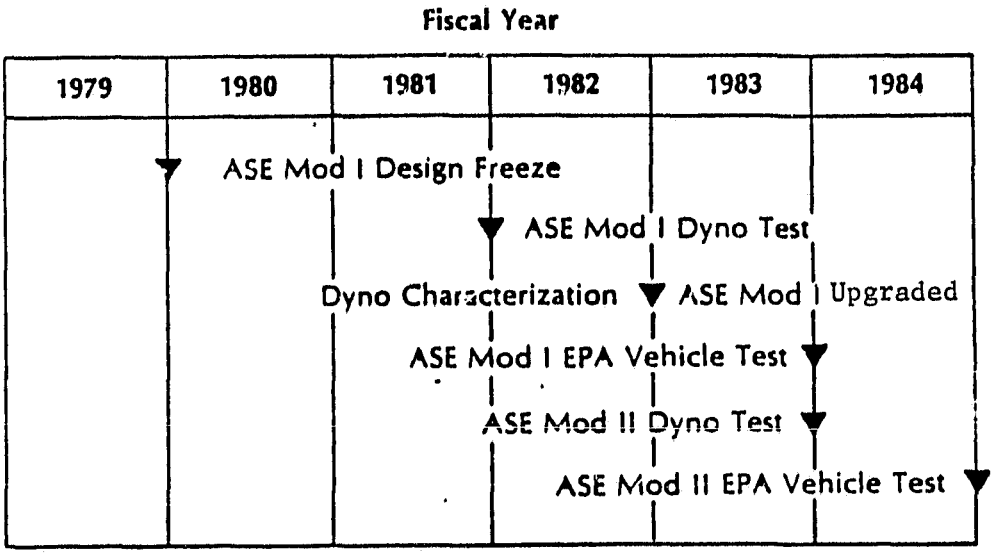

Figure 2.0-1 Program Milestones

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, 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 optimum engine design that can be generated at any given time which will provide the best possible fuel economy and will also meet or exceed all other final program objectives. The RESD 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 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 that 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-payoff alternatives, to providing more conservative, reduced risk backup approaches. As the development program proceeds, actual test experience may eliminate one or more of these backup approaches, or it may dictate a reduction in performance relative to initial expectations.

- The RESD was generated early in the Program and 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 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 and 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)

MAJOR TASK 3 - TECHNOLOGY FAMILIARIZATION (BASELINE ENGINE)

The existing USSw 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 accommodate the entire program.

Task 3.1 - Baseline Engine (P-40)

USSw 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. Tests will also be run with all auxiliaries removed and their functions compensated for or provided by test facilities.

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.

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 the installation of two engine test cells at MTI, with appropriate data acquisition equipment and five component test cells to be used for component development purposes.

Task 3.3 - P-40/Opel Test Vehicle

One P-40 engine will be manufactured and installed in a 1977 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 and will be limited by the technology that 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. The ASE Mod I will also 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, including 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 also 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 USSw, and 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; USSw 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. Tests will also be run with all auxiliaries removed and their functions compensated for or provided by test facilities. The full range of engine transient characteristics will be determined, including start-up, 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.

MAJOR TASK 5 - ASE MOD II ENGINE SYSTEM

The second-generation engine will be designed, fabricated, and tested, and 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, 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 placed 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, including 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 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. Tests will also be run with all auxiliaries removed and their functions compensated for or provided by test facilities. The full range of engine transient characteristics will be determined, including start-up, 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 these 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.

MAJOR TASK 6 - PROTOTYPE ASE SYSTEM STUDY

A study will be undertaken to describe the effort required to bring the Automotive Stirling Engine (ASE) 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 that 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.

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; and (3) evaluate the affects 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, partially verified interim 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.

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; and appropriate communication media including brochures, audiovisual materials, other literature, and independent studies after approval from NASA.

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; and
- 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.

1.0 REFERENCE ENGINE

- 1.1 Initial Technology Assessment
- 1.2 Reference Engine System
  - 1.2.1 Project Engineering
  - 1.2.2 USSw 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 USSw Projects
- 2.9 USSw 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 Structure (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 (USSw)
  - 5.5.2 Engine #4 Evaluation (MTI)
- 5.6 Vehicle Test Program
  - 5.6.1 Vehicle/Engine #3 Test (USSw)
  - 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 USSw 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 is presented in Section 2.0; Section 3.0 of this report presents the details of the work accomplished on each task during the period of April 1 - June 30, 1981.

MAJOR TASK 1 - REFERENCE ENGINE

During April, all activity on this task was stopped while the budget for the remainder of the year was evaluated. After the evaluation was completed, a decision was made to issue the Reference Engine System Design Report and the March, 1981 RESD update as one report*. That report was published in June, and copies are available through the National Technical Information Service in Springfield, Virginia.

A contract for a manufacturing cost study of the Reference Engine was signed with Pioneer Engineering (Warren, Michigan) in May. Pioneer's costing methodology is the same as that employed by the automobile industry. Direct labor rates will be those employed by the automotive companies for 1980. Burden rates, variable and manufacturing, will be typical of those used by the automobile companies, and will reflect 1980 economics. The sum of material, labor, scrap allowance, and manufacturing burden costs will equal the transfer cost (manufacturing cost) of the components. An annual production volume of 300,000 units was selected, representing the optimum point for a sustained, highly productive facility utilizing two eight-hour shift operations.

By June, Pioneer Engineering had established the manufacturing hours for 50% of the Stirling engine hardware they were analyzing.

The following items were analyzed:

- Hot Engine System
  - Gas cooler assembly
  - Heater tube assembly
  - Regenerator
- External Heat System
  - Injector and turbulator assembly
  - Preheater
  - Combustor
- Cold Engine System
  - Piston dome assembly
  - Piston rod
  - Crosshead guide
  - Duct plate
  - Water jacket
  - Seal system
- Engine Drive System
  - Bedplate assembly
  - Crankcase assembly
  - Sump
  - Intercasing
  - Water pump
  - Main drive shaft
  - Crankshafts
  - Oil pump and filter
  - Gears
  - Connecting rod assembly

*Automotive Stirling Engine Design Report; NASA CR-165381

MAJOR TASK 2 - COMPONENT AND SUBSYSTEM DEVELOPMENT

Task 2.1 - Combustion Technology Development

Project Engineering

A decision was made in May to reschedule and rearrange the priorities for testing in MTI's Free-Burning Test Rig. Baseline testing of the AP-80 Straight Guide Vane CGR Combustor was eliminated so that Mod I baseline testing could be performed sooner. The order will now be: Mod I Combustor Ignition; Mod I Baseline; and Alternate Fuel Nozzles (with Mod I Combustor), instead of: AP-80 Baseline; Alternate Fuel Nozzles; and Mod I Baseline and Ignition. The general intent is to evaluate Mod I combustor parameters, relevent to current or future designs, at an earlier date.

A joint MTI/USSw meeting was held at USSw during the week of June 8. Major topics of discussion were:

- Mod I Combustor Rig Sensitivity Tests;
- Mod I Cold Start Testing;
- Mod I Engine External Heat System Experience;
- Alternate Mod I Combustor Rig Tests;
- Alternate Fuel Nozzle and Refractory Surface Combustion;
- MTI/USSw Combustion Development Plans;
- Alternate Low-Emssions Combustors.

A presentation was also made to NASA on the following subjects:

- USSw Mod I Rig versus Engine Emissions;
- USSw Alternate Mod I Combustors;
- MTI Alternate Low-Emission Combustion Approach;
- MTI Alternate Fuel Nozzles;
- MTI Free-Burning Rig Design;
- MTI Free-Burning Rig Involute Combustor Tests;
- MTI Surface Combustion Tests.

The Mod I Combustor Rig sensitivty tests were completed at USSw in June, and the results were issued by USSw. Measurements were made of NO_x, CO, HC, and smoke over a range of lambdas, fuel flows, and tube set temperatures. NO_x and HC emissions were low, while CO showed a tendency to increase rapidly as lambda was reduced to the nominal design value of 1.15. Thus, CO represents a potential problem for the Mod I combustor. This may be overcome by increasing lambda to 1.25 or utilizing one of the alternate combustor designs. The use of the Bacharach smoke system to determine exhaust visibility and particulates is not adequate and, at best, can only give qualitative results. Based on these steady state results, the following CVS cycle emissions are predicted (22.4 mpg):

$$NO_x = 0.26 \text{ g/mi}$$
$$CO = 0.81 \text{ g/mi}$$

To obtain these numbers, the steady state rig data for 12 points were used and the results weighed according to the amount of time at each fuel flow during the CVS cycle. It was assumed that set temperature (725°C) and λ (1.15) were constant. The thermal storage capacity of the engine was accounted for by varying the heat input ($\dot{m}_f$). Since both λ and the set temperature vary over the CVS cycle, and both have affects on emissions, these predictions must be verified by experiment.

Testing of the four alternate Mod I combustors in the Mod I Test Rig was completed at USSw in May. The four designs are as follows:

Combustor	Guide Vane Number	Guide Vane Height (mm)	Guide Vane Angle (°)
1	10	28	30
2	10	20	30
3	18	20	30
4	18	20	45

This progression represents decreased height and increasing swirl intensity. All tests were run at 725°C tube temperature using 48 mm long ejectors, sized to have the same flow area, and at fuel flows of 0.5, 1, 2, 3, and 4 g/s. Basically, Configurations 1 and 3 look best from the NO_x/CO standpoint. Hydrocarbon levels were relatively low for all four, while Configuration 4 had high smoke numbers. Based on these results, it was agreed that a fifth configuration would be made combining the features of Configurations 1 and 3 (i.e., 18 guide vanes, 28 mm high and a 30° guide vane angle). This will then be rig-evaluated and the best of the five configurations will be made into a Mod I engine combustor as a backup to the existing design.

Design and Analysis

A brief study of the Mod I soot formation and the potential impact on particulate emissions was made in April. United Stirling rig data indicates Bacharach Smoke Numbers between 0 and 6 over a range of fuel flows from 1 to 4 g/s and from 1.1 to 1.5. In general, smoke increases with fuel flow and inversely with λ. An approximate estimate of the amount of particulates generated from carbonaceous soot is shown in Figure 2.1-1. If one assumes the Mod I CVS urban mileage of 22.4 mpg and a λ = 1.15, then the program particulate goal of 0.2 g/s converts to 89 ppm (by weight). Looking at the worst measured case, a Bacharach number of 6 would be approximately 21 ppm, or well below the required limit. It must be pointed out that the relationship between the Bacharach Smoke Number and particulates is extremely approximate, and that other sources of particulates, other than carbon, also exist.

An analysis of possible alternate Mod I combustor concepts was also completed in April. Two approaches were considered: water injection and altered CGR ejector location. Possible designs are shown in Figures 2.1-2 and 2.1-3. Water injection seeks to reduce NO_x using water instead of gas recirculation to reduce flame temperature. The altered CGR injector concepts attempt to improve combustion by using the ejectors to increase turbulent mixing of air and recirculating products and fuel, prior to combustion, in addition to inducing recirculation.

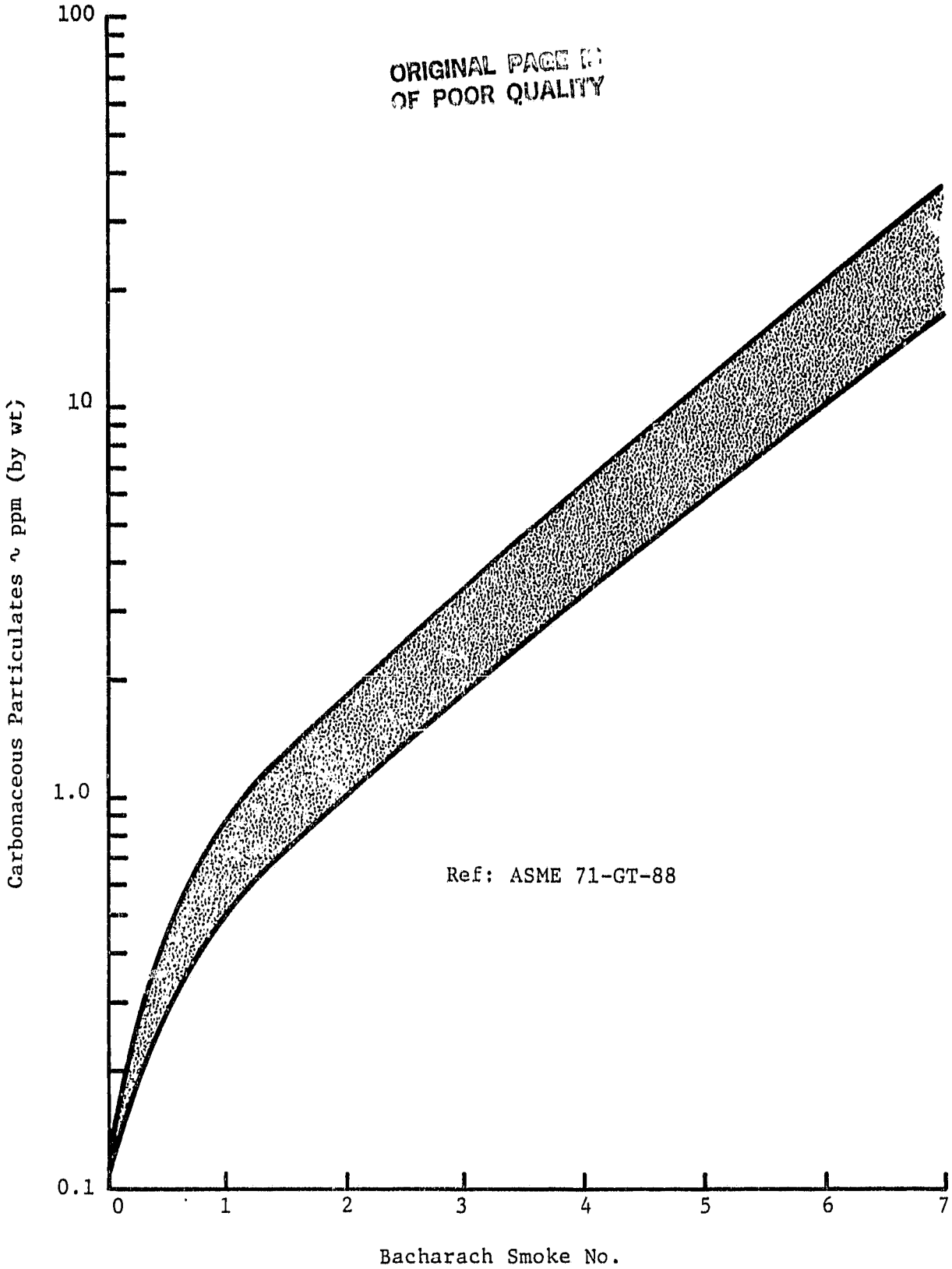

Figure 2.1-1 Conversion from Von Brand to Bacharach Scale

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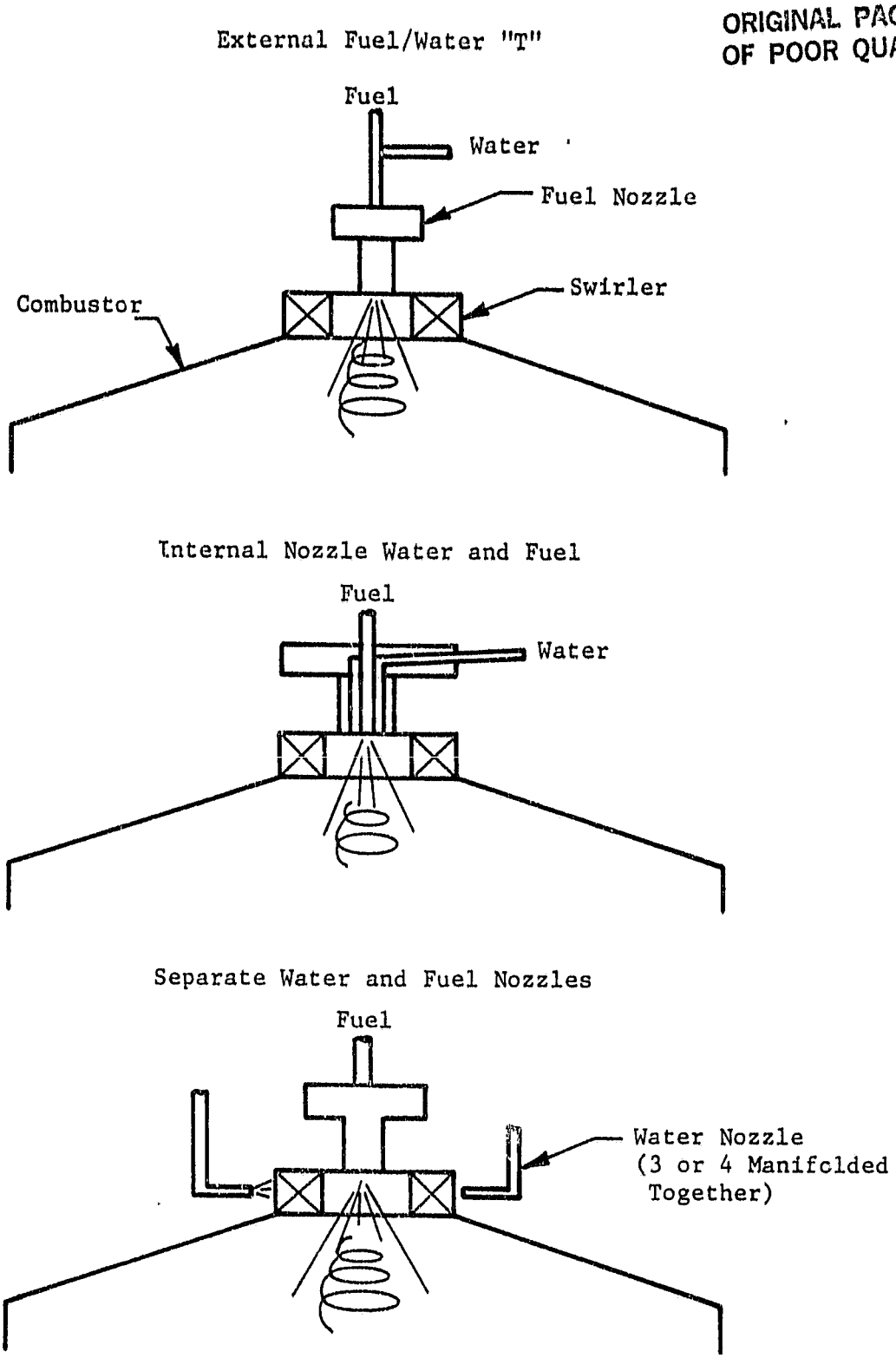

Figure 2.1-2 Possible Water Injection Methods

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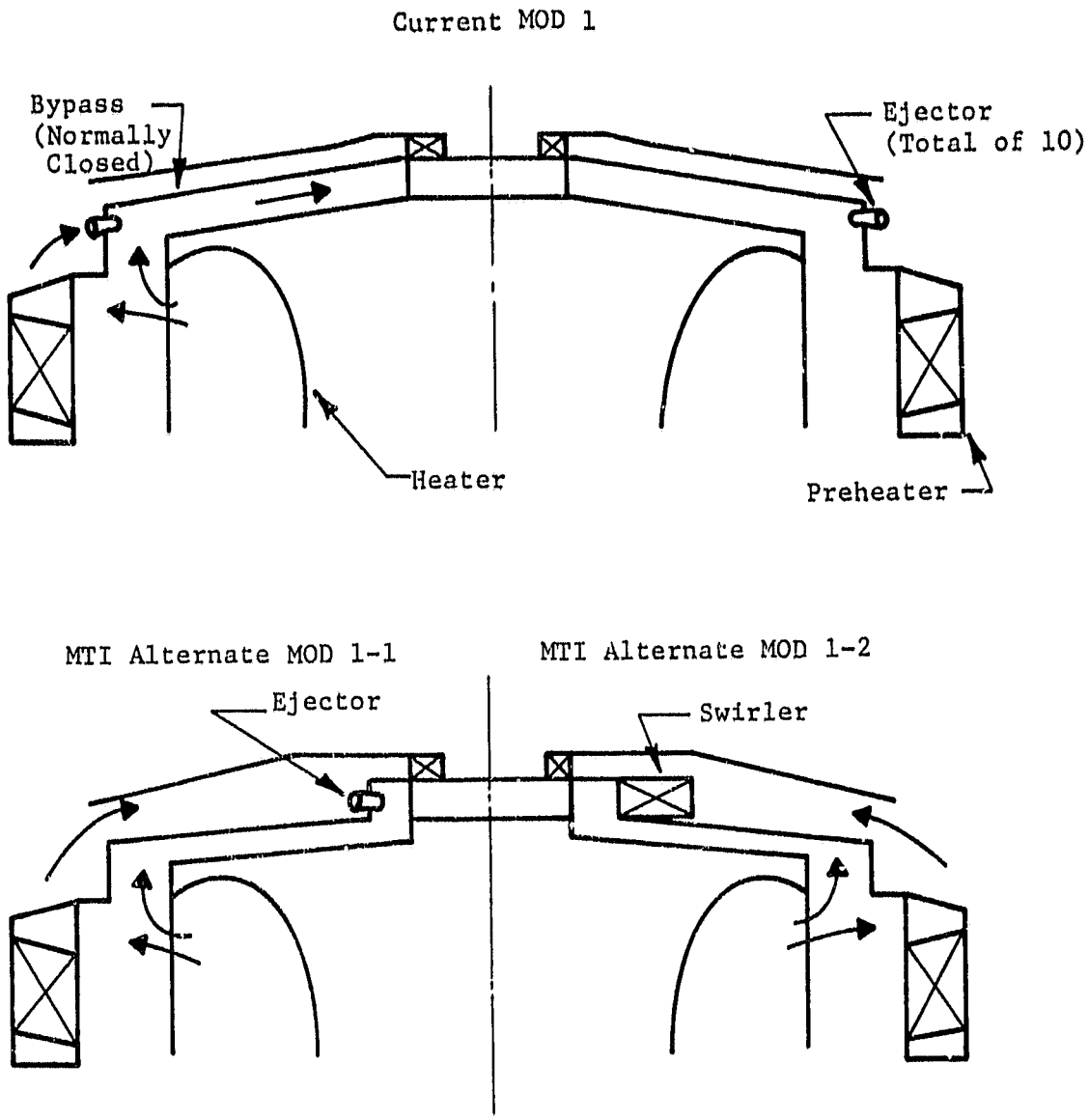

Figure 2.1-3 Mod I Combustors

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In support of the Vehicle Program, the possibility of running the P-40 Concord on alcohol fuels for a sustained period of time was evaluated at MTI in May. USSw experience with alcohol fuel is limited to combustor rig testing with methanol and a short demonstration in Washington burning whiskey (ethanol) in the P-40 Opel. Although these fuels can be burned in the P-40 Combustion System, several concerns exist. Due to the reduced heating value of methanol and ethanol (47% and 64% of gasoline on a mass basis), a much higher fuel flow is required, which implies a larger fuel pump and a modified K-Jetronic. Secondly, alcohols tend to attack elastomeric compounds, which necessitates the use of special materials for diaphragms and seals. Emissions would also be affected; one would expect lower NO_x and possibly higher CO. It was concluded that before running a vehicle on alcohol for anything other than a short demonstration, engine testing should be done.

Detail design layouts for the Parker-Hannifin and Delavan nozzle adapters, as well as CGR bypass valve actuators, were completed in May. In-house manufacture of the Parker-Hannifin adapter and bypass actuator was started and completed in June. Water spray tests to evaluate the spray distribution and quality will be conducted next quarter prior to evaluation in the Free-Burning Test Rig.

Screening tests of the Refractory Combustor Concept were begun. A schematic of the test setup used for this evaluation is shown in Figure 2.1-4. Although a large quantity of data was obtained, numerous problems with the water-cooled probe, gas analyzer, heated sample line, and test stand air leakage have precluded a definitive answer as to the validity of this concept in reducing NO_x.

A recurring problem with the emission measurements (until now) has been a disagreement between air/fuel ratios based on gas sample analysis and metered values of fuel and air. The problem was traced to inefficient removal of water (from combustion) from the CO/CO_2 sample stream. It was rectified by simple plumbing modifications to the sample line. A favorable comparison between metered and chemical air/fuel ratios was obtained in June in a subsequent P-40 engine test.

Combustor Development Test Rig

In April, this rig was modified to more accurately position the thermocouples flush to the perforated cone. This increased the accuracy of the simulation of the temperature profile into the first heater tube row. The number of thermocouples was increased from 9 to 17 to allow for circumferential measurements.

Baseline testing also continued in April. Data were obtained for the temperature distribution ("axial" and circumferential) on the perforated cone at several flow conditions, as shown in Figures 2.1-5 and 2.1-6. A comparison with United Stirling's data is given in Figure 2.1-7.

An early version of the Mod I combustor was modified at MTI in preparation for the ignition tests. The modifications consist of installing the 48-mm long CGR ejector nozzles (the current Mod I design) and altering mounting flanges to fit the rig. The individual temperature

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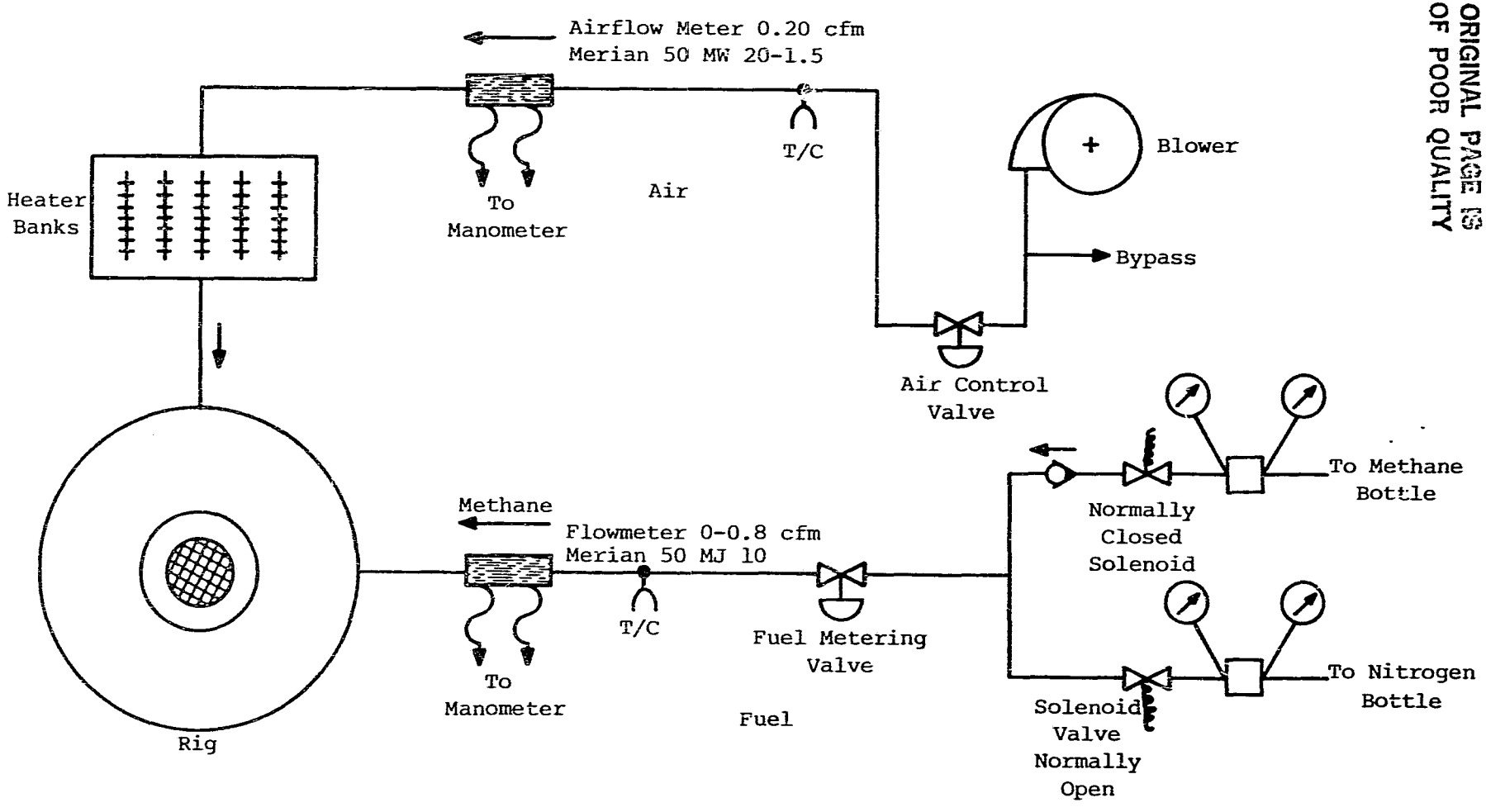

Figure 2.1-4 ASE — Refractory Combustor Test — Schematic

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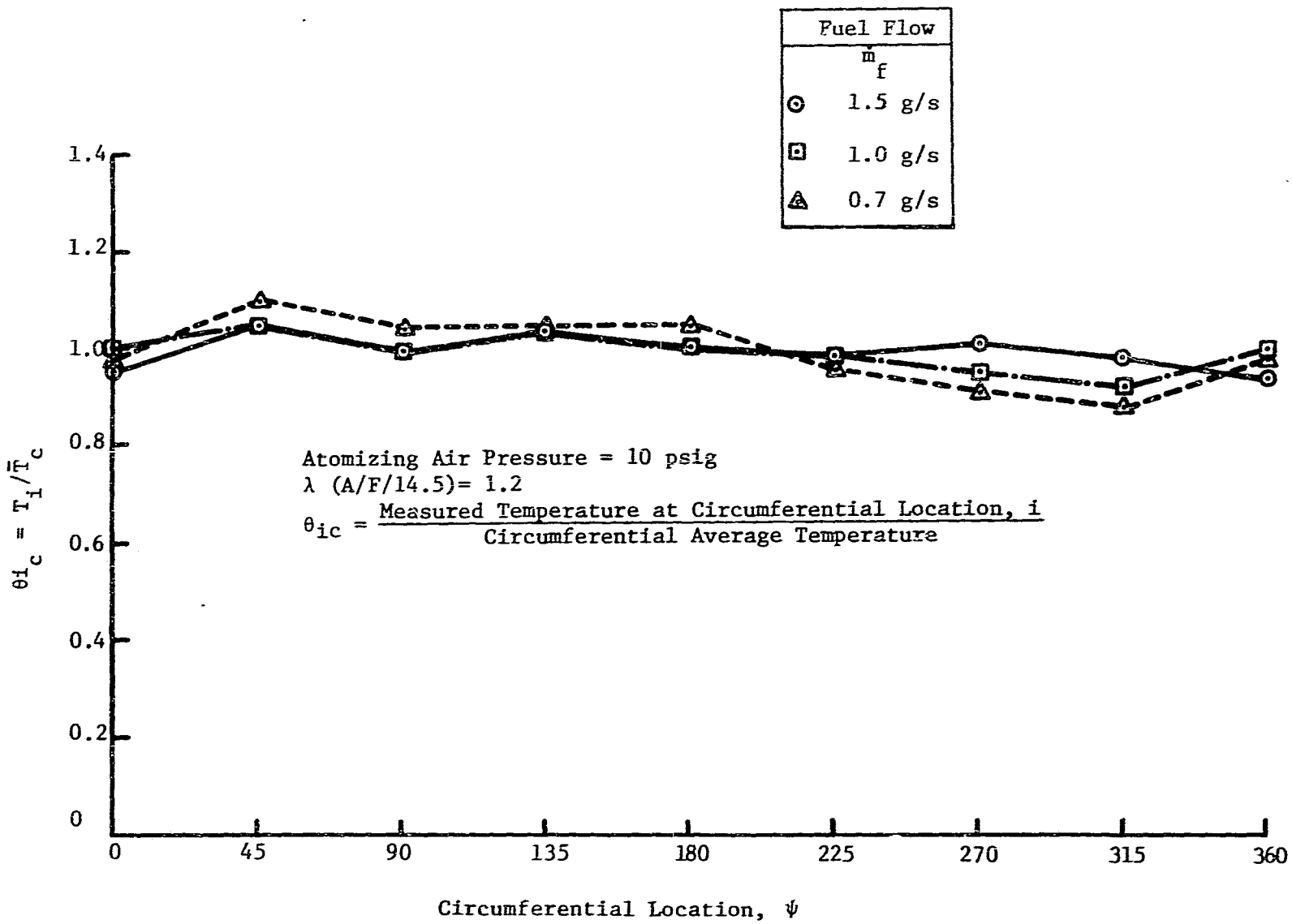

Figure 2.1-5 Circumferential Temperature Distribution at Various Fuel Flow Rates

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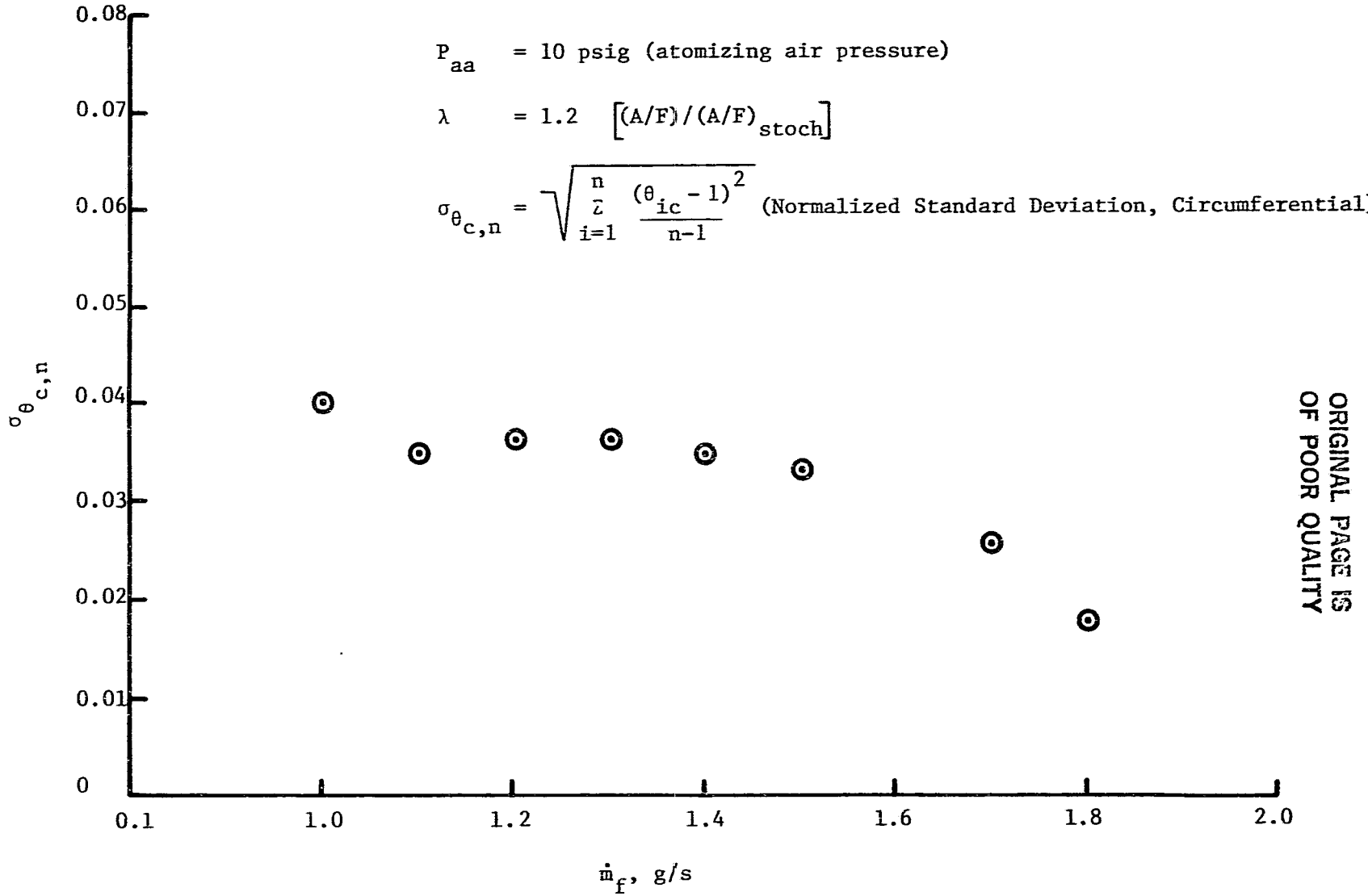

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Figure 2.1-6 Circumferential Nonuniformity at Various Fuel Flows

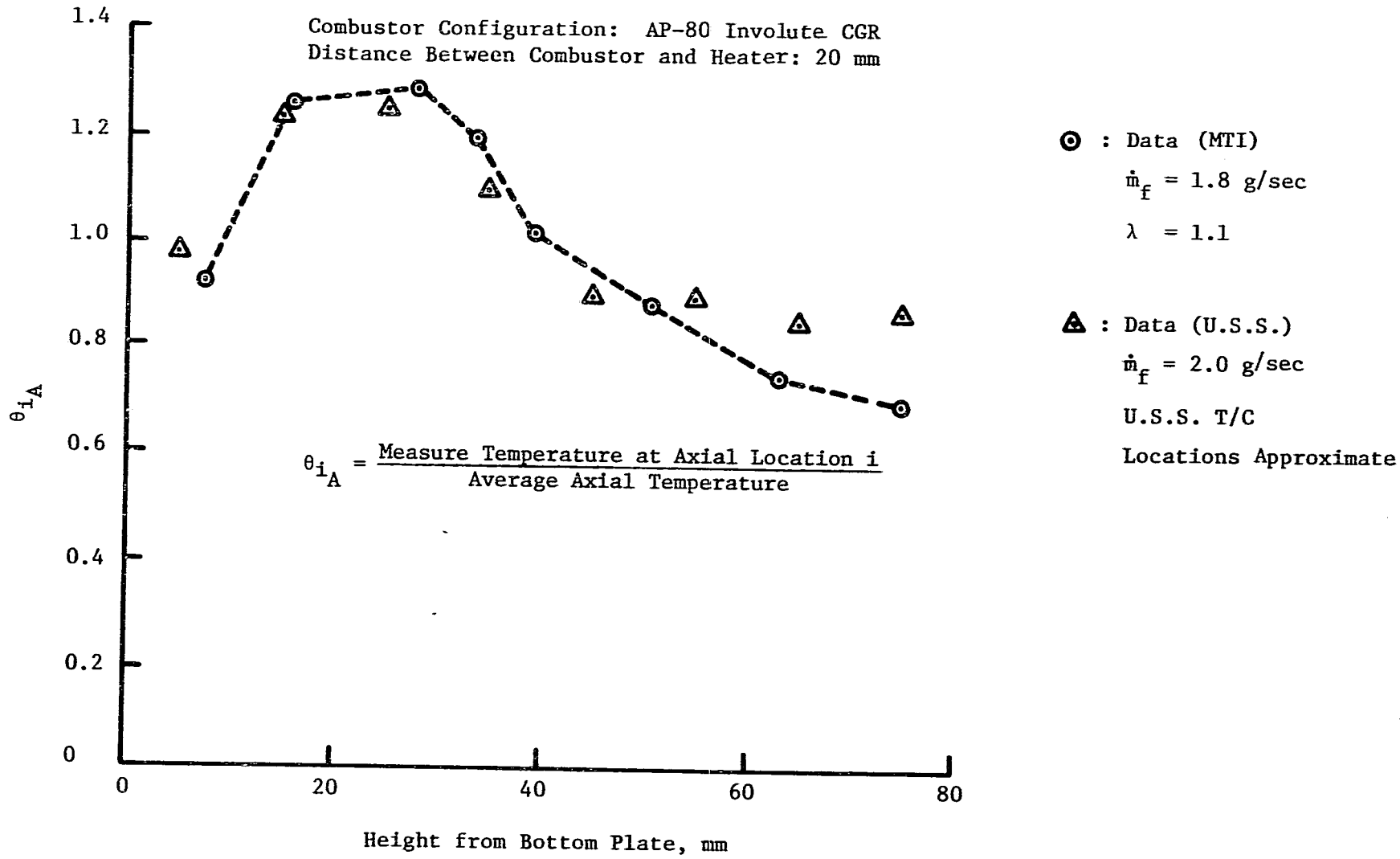

Figure 2.1-7 Temperature Distribution along a Generation of Perforated Cone

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readings were normalized to the calculated average axial and circumferential temperatures in order to minimize the affect of the uncertainty of thermocouple radiation loss on the interpretation of the data.

Combustor Endurance Test Rig

Commitments to obtain the fuel injector/igniter, combustor, preheater, and various covers and gaskets from United Stirling were confirmed in April, and all rig hardware is now under procurement.

The electric heater for the test facility was received in April; purchase orders were placed for the fuel, air, water, and the CO_2 cooling loop; a vendor was selected to install the CO_2 loop piping; procurement was underway for safety and control items; and purchase orders were written for the rig instrumentation.

In June, the two heat exchangers for the CO_2 cooling loop were received, and the electric heater was installed and checkout begun. Assembly of the CO_2 cooling loop plumbing was initiated. The heater tubes were bent for the rig and fins were procured. Thermocouple instrumentation was also received.

Task 2.2 Heat Exchanger Technology Development

Testing was conducted at USSw during May to assess Mod I regenerator flow distribution. A concern exists because the gap between the matrix and the housing is only 0.6 mm instead of the required 1 mm. Testing was conducted by using a cooler with some of the tubes blocked to give a ΔP equal to that of a regenerator. The conclusion is that the narrower gap does lead to flow maldistribution.

A limited study of the influence of preheater effectiveness on the CVS cycle mpg was completed in June. Using available data from the joint NASA/USSw/MTI Mod I Design Team, the effects of preheater performance at a single operating point representative of the CVS cycle are illustrated in Table 2.2-1 and Figure 2.2-1. Further analysis will be necessary since the λ and % of CGR used (1.34 and 38%) do not correspond to the nominal Mod I design values of 1.25 and 43%, and both parameters will affect preheater effectiveness.

Design and Analysis

Work continued on the Performance/Cost Study in May. The objective of this task is to determine the influence of the four Mod I Engine Heat Exchangers on CVS cycle combined cycle mpg. As a first step, it was decided to analyze the influence of preheater effectiveness on performance using a single operating point representing the combined urban and highway cycles, including cold start penalty. Utilizing a computer simulation for the standard Mod I Engine, a single operating point was determined as follows:

$T_{FLAME} = 1841^{o}C$ $T_{AMBIENT} = 30^{o}C$

Preheater Effectiveness	.7516	.7656	.78	.7949	.815	.83878	.85419
T_{OUT} °C	926.67	915.56	904.4	893	880	865.55	851.67
T_{EXH} °C	282	264	246	228	209	181.9	156
T_{AOUT} °C	704	708	712	716	723	726.67	731.86
Fuel Flow g/seconds	.89413	.88385	.87387	.864	.85227	.84055	.82931
mpg	25.335	25.63	25.92	26.218	26.572	26.95	27.3157
mpg Ratio	.9534	.96414	.9756	.9867	1.00	1.01422	1.02798
Effectiveness Ratio	.9222	.93958	.95705	.97534	1.000	1.02918	1.04808
Combustor Efficiency %	86.22	87.14	88.14	89.15	89.38	91.55	92.49

Table 2.2-1 Influence of Preheater Effectiveness on Combined Cycle mpg

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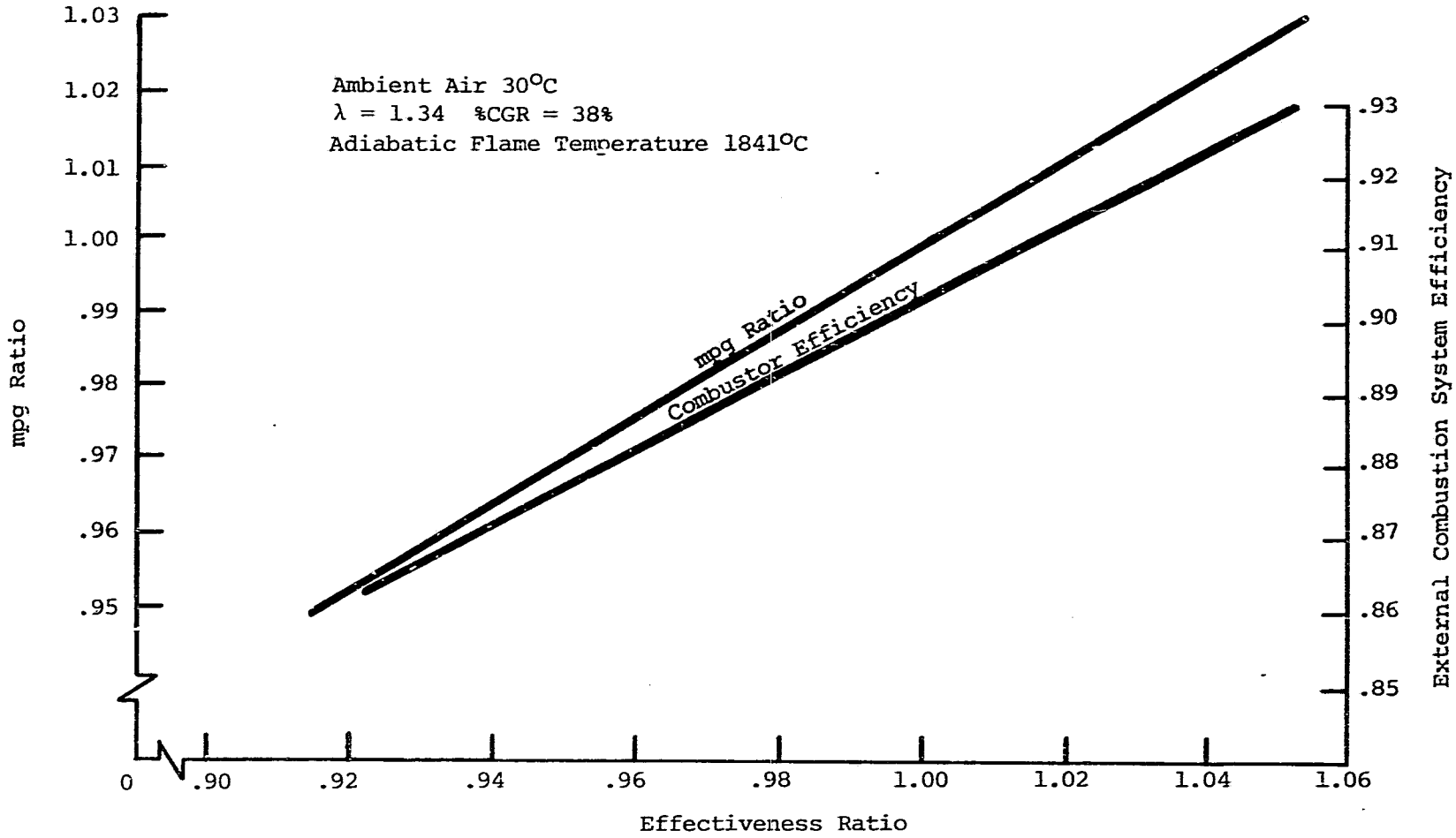

Figure 2.2-1 Mod I Combined Cycle mpg and External Heat System Efficiency versus Preheater Effectiveness

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For Urban Cycle	For Highway Cycle
Average rpm = 1220	Average rpm = 1785
Average HP = 8.2574	Average HP = 18.847
Auxiliary HP = 2.29	Auxiliary HP = 3.35
Brake Efficiency = 27%	Brake Efficiency = 33%
Fuel Consumption = .682 g/s	Fuel Consumption = 1.1718 g/s

The combined mpg including cold start penalty = 25.04.
The fuel consumption based on this combined mpg is .925 g/s.

Regenerator Development

Heat Transfer Rig - The isolation circuit was built and installed in May, enabling the Data Acquisition System (DAS) to perform as intended. Further testing with different orifice plates (taking account of humidity affects on air density) yielded flow measurement agreement within 5%. Tests were performed on the unsintered screen test section (porosity = .683) and the 30-layer sintered screen test section (porosity = .566). Graphs of the results (Nusselt Number, J-Factor, and friction factor versus Reynolds Number) are attached as Figures 2.2-2, 3, and 4. On the plot of Nusselt Number versus Reynolds Number, there is a line representing the experimental data from tests run by V. Vashista [2] at the University of Calgary. These tests used the same test technique and a similar test section as the unsintered test section run at MTI (200 x 200 wire cloth). The results agree fairly well. On the plot of J-Factor versus Reynold's Number, there is a curve taken from a plot in Kays & London [3] for a similar material configuration. Again, the curve agrees closely with the unsintered test section data. Comparing sintered (30-layer) to unsintered test sections, the latter appears to be superior from a heat transfer/friction standpoint. The increase in dead volume of the unsintered section needs to be traded off against the heat transfer and friction characteristics to determine the affect on cycle efficiency. Before this can be done, the differences in end losses between the engine regenerator and reduced length regenerator rig test section should be estimated. Future testing will utilize 20- and 40-layer sintered, coarse, unsintered, and Metex samples.

Tests were run in June on the 20-layer sintered screen and the coarse unsintered screen; tests on the 40-layer sintered screen will be run next quarter. Results of the coarse screen and 20-layer sintered screen test sections are shown in Figures 2.2-5/2.2-6. Results of the coarse screen support the use of fine screens; the use of coarse screens will result in a regenerator almost six times as large as the present regenerator. Any conclusions concerning the sintered sections of various thicknesses will be made after the 40-layer test section testing is complete.

Flow Test Rig (ΔP Rig) - MTI also ran tests in June on a new P-40 regenerator (S/N 181) at the same conditions that existed during testing at NASA/LeRC. The results were almost identical, as shown in Figure 2.2-7. A test was also run at MTI on a used regenerator (S/N 148 from ASE 40-8) after 124.5 hours of operation (this regenerator was previously tested at NASA/LeRC). Test results are shown in Figure 2.2-8.

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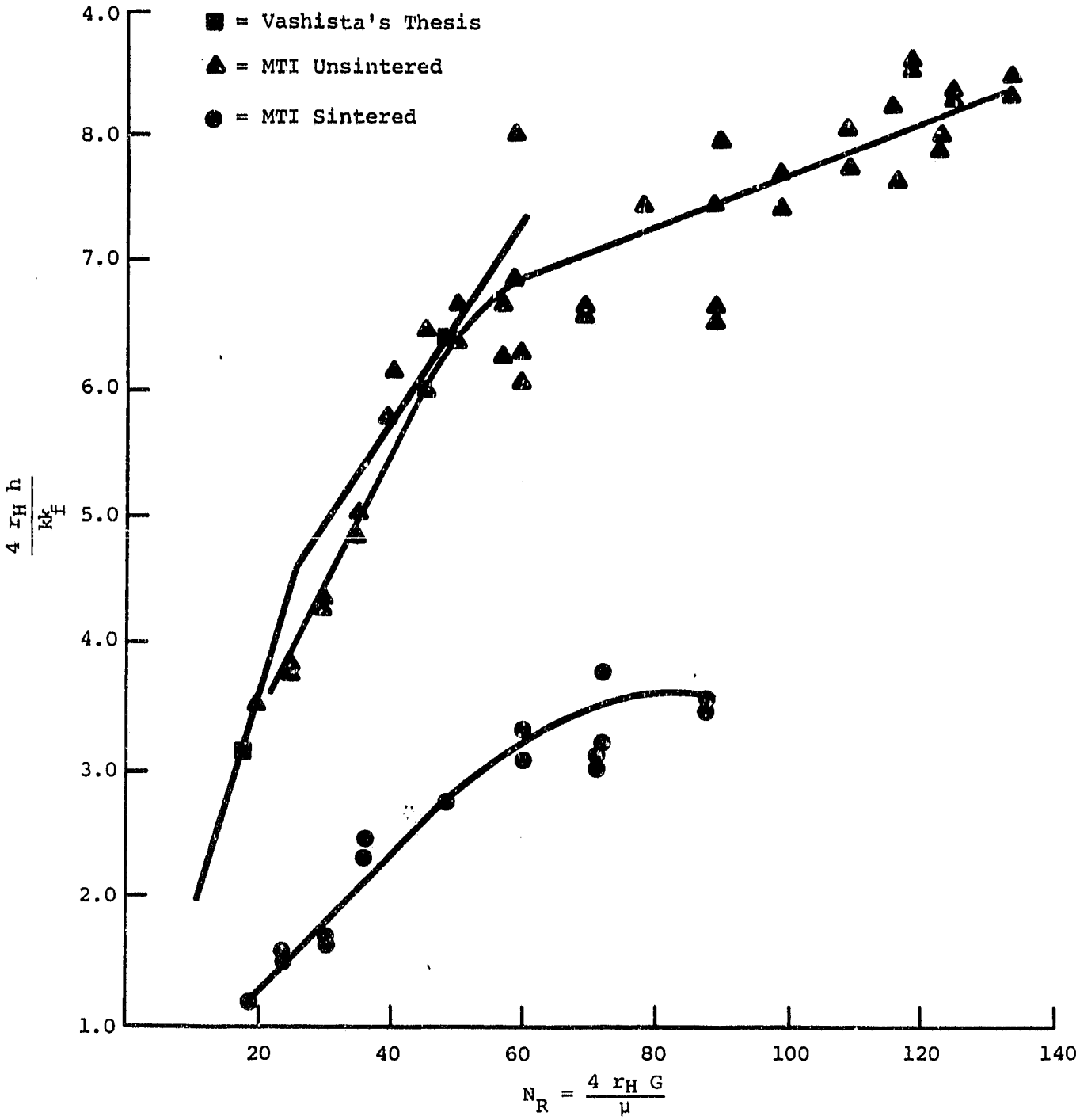

Figure 2.2-2 Nusselt Number versus Reynolds Number

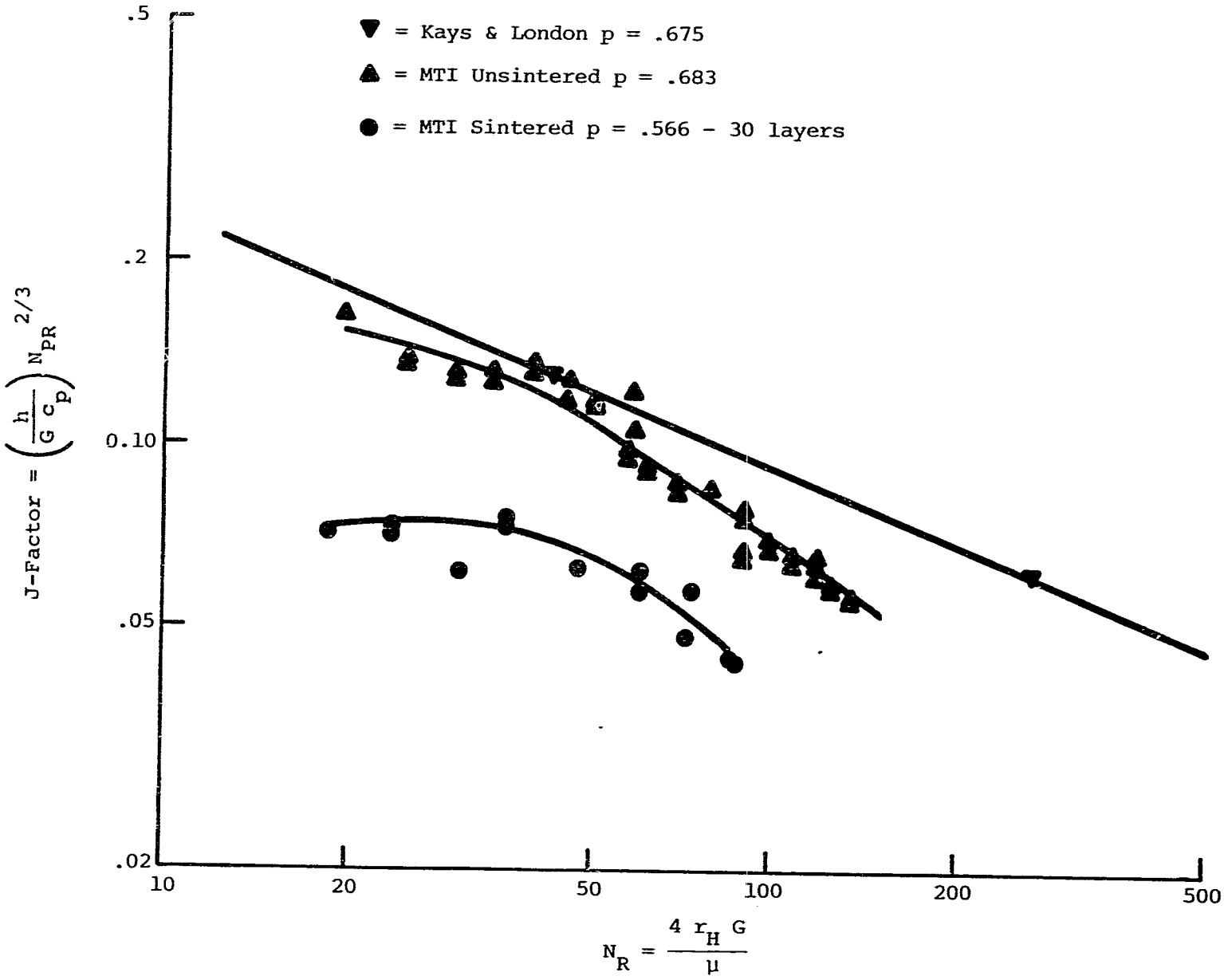

Figure 2.2-3 "J" Factor versus Reynolds Number

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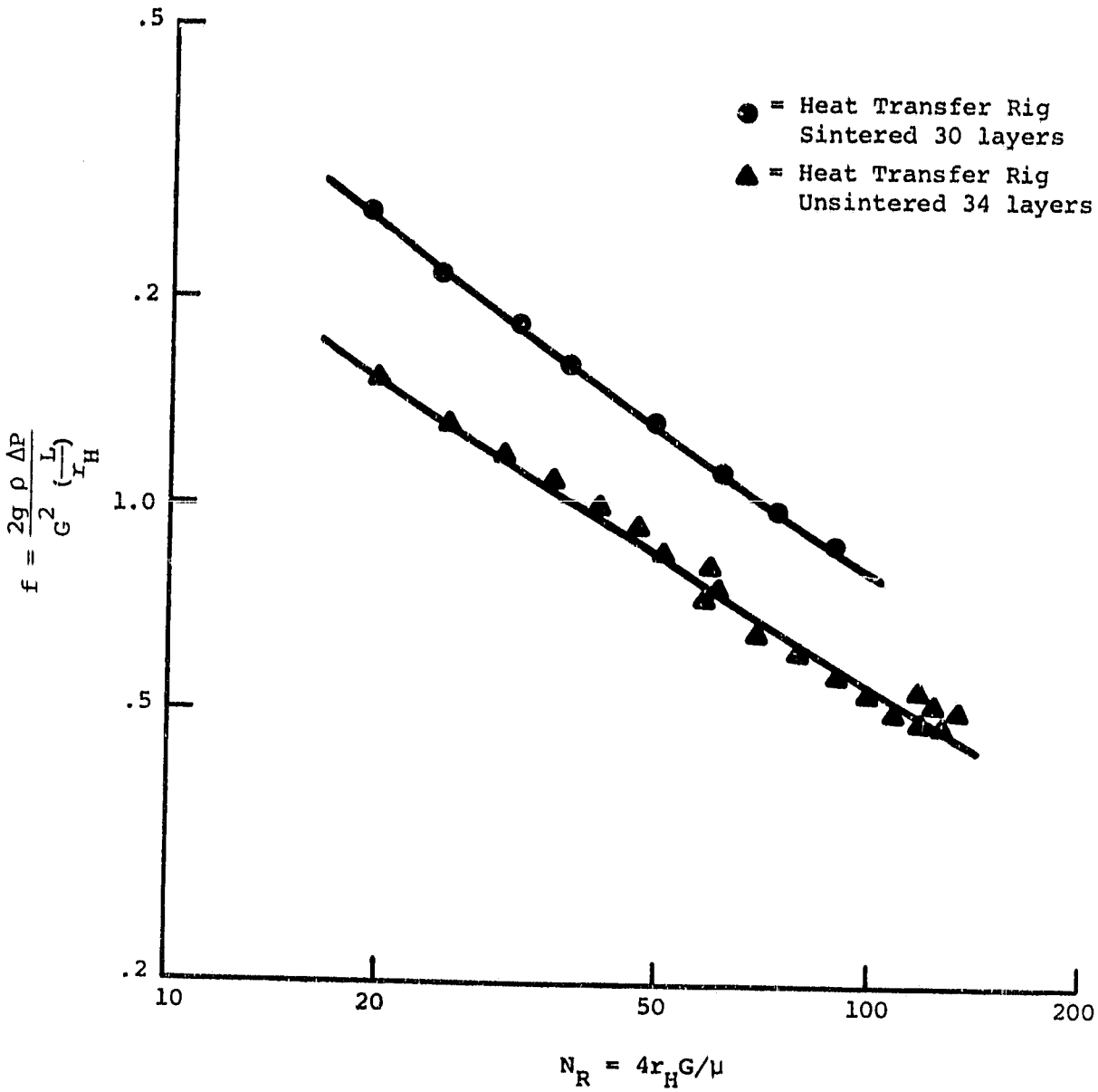

Figure 2.2-4 Friction Factor "f" versus Reynolds Number

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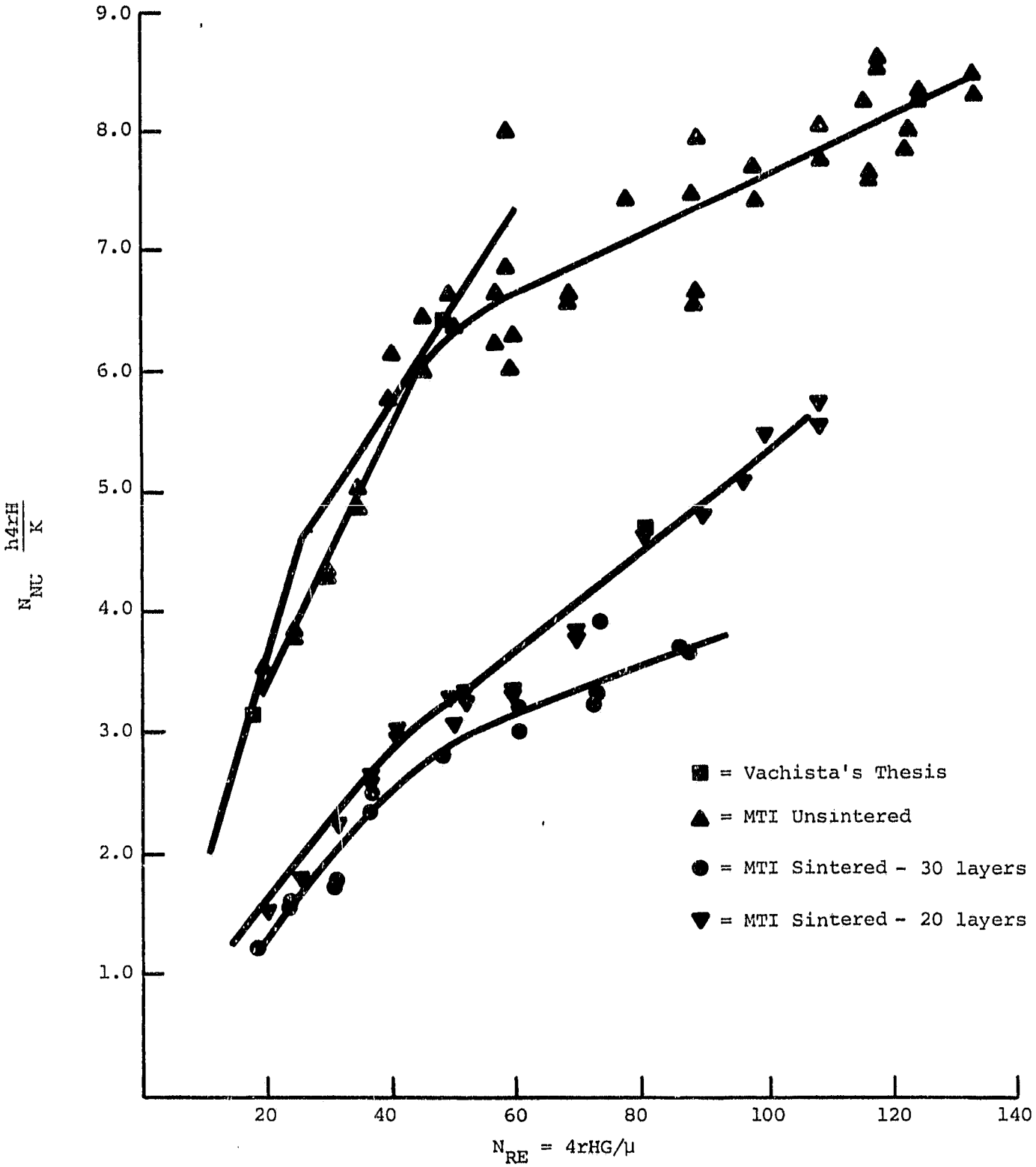

Figure 2.2-5 Nusselt Number versus Reynolds Number

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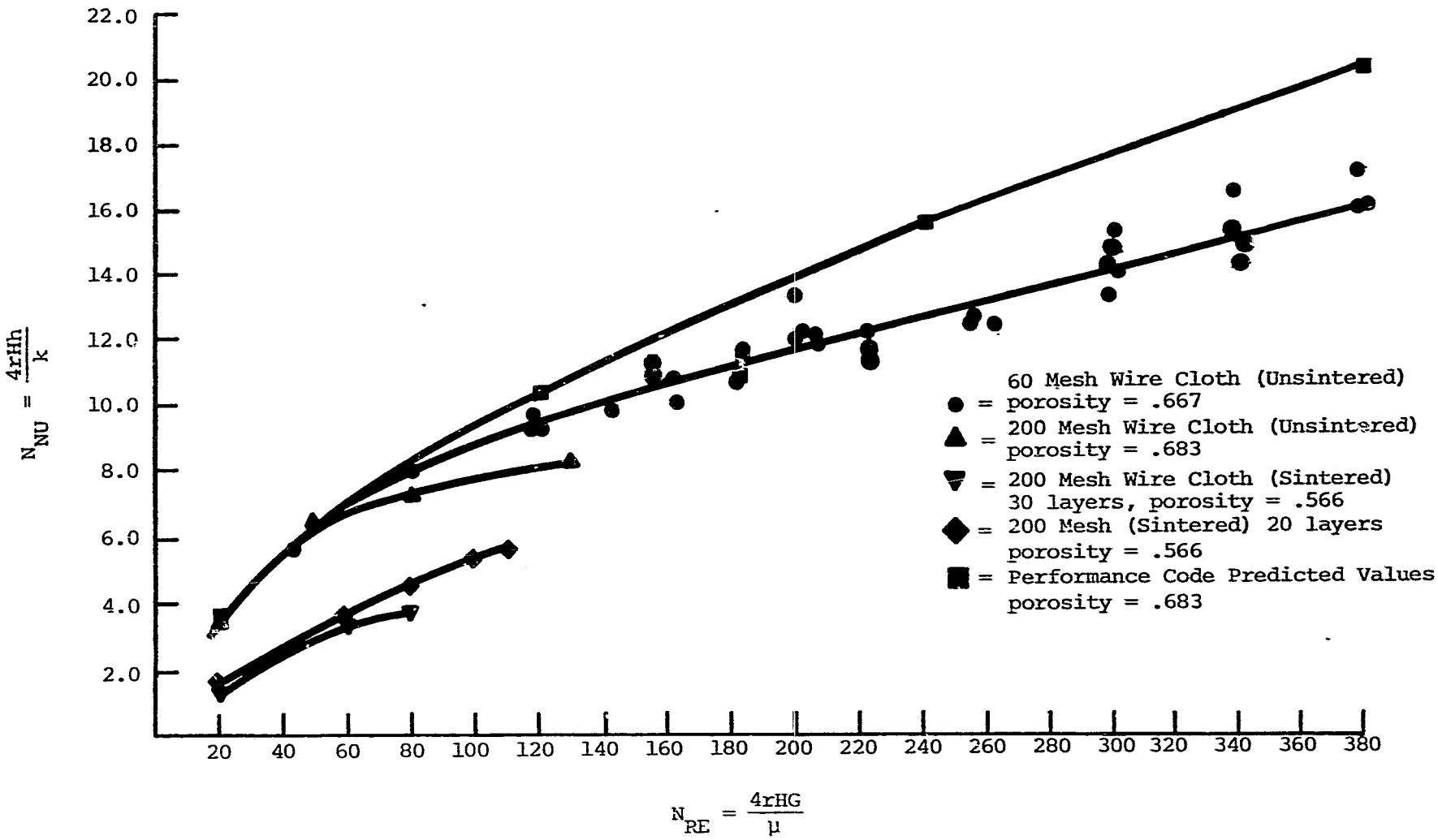

Figure 2.2-6 Nusselt Number versus Reynolds Number

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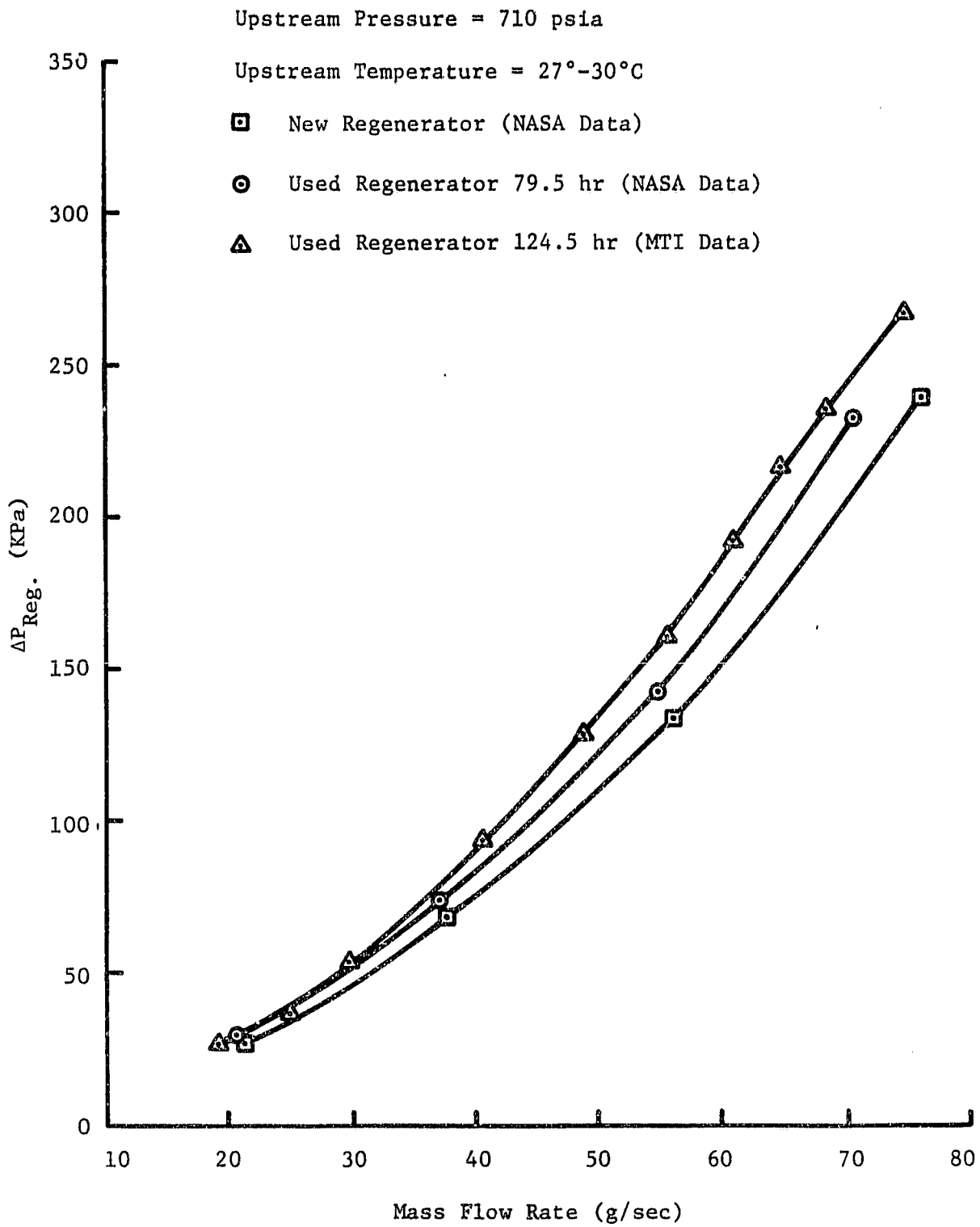

Figure 2.2-7 Regenerator Pressure Drop (Used)

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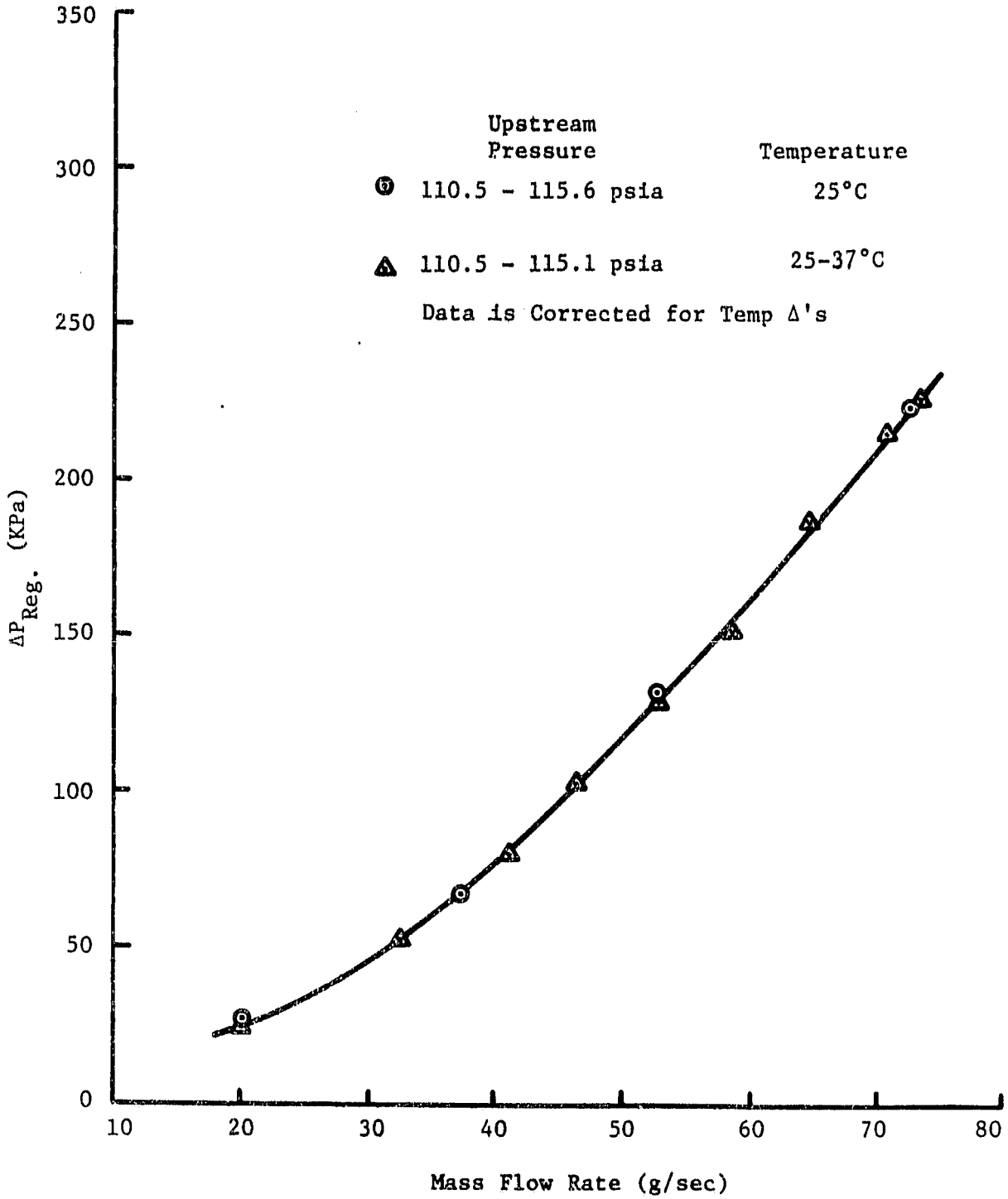

Figure 2.2-8 Regenerator Pressure Drop (New)

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Preheater Development - A trip to Corning Glass Works was made in May to discuss a ceramic preheater concept. A conclusion was reached that this concept was feasible, and that a test section will not require much development time. The test section would be machined from a currently available extruded core of either 200 or 300 cells per square inch. This could be done within two or three months after a detailed drawing of the test section was sent to Corning. The detail design of the preheater test section will be started in August.

Task 2.3 - Materials Development

Priority I - Development

Heater Tubes - The CG-27 tubing, which was cut to length and plated with nickel, was sent to USSw in April for fabrication into a quadrant.

Cylinder Heads and Regenerator Housings - Test bars of all the cast cylinder heads and regenerator housing materials were received from United Stirling in April. Groups of each of these test bars were heat-treated, and specimens of HS-31 and XF-818 were tensile-tested. Test bars of XF-818 and HS-31 were sent out for the machining of fatigue specimens.

In May, tensile specimens and low-cycle fatigue specimens of HS-31 were machined. The specimens, along with cast bars of XF-818, CRM-6D and SAF-11, were heat-treated at the actual brazing temperatures. Tensile specimens of XF-818 and HS-31 were given an additional heat-treatment of 50 hours at 800°C to reflect the experience in operation. Tensile tests were performed on the HS-31 and XF-818 specimens at room temperature and 800°C. This data will be used to estimate the strain levels required for fatigue testing.

Tensile testing on a group of XF-818 and HS-31 specimens over a range of temperatures (room temperature to 850°C) was completed in June. The results of tensile testing for HS-31 and XF-818 are summarized in Figures 2.3-1 and 2.3-2, respectively. The HS-31 test specimens were cast at the same time as the fabrication of cylinder heads and regenerator housings. The XF-818 was received from Climax-Molybdenum. Tensile testing was carried out under a constant load rate of .4 psi/s. With the exception of the case noted in Figure 2.3-1, all specimens were heat-treated with a simulated brazing cycle* followed by 50 hours at 800°C in order to stabilize the microstructure of the material.

Figure 2.3-3 shows strain levels as a function of a number of cycles to failure for fully reversed fatigue testing on HS-31 at 800°C.

Plotted along with the data is the empirical relationship of Coffin and Manson. The fatigue results are also summarized in Table 2.3-1. Each of the four specimens represented in this table were heat-treated with a simulated brazing cycle followed by 50 hours at 800°C.

*consisting of 1/2 hour at 1140°C for XF-818 and 1/2 hour at 1175°C for HS-31

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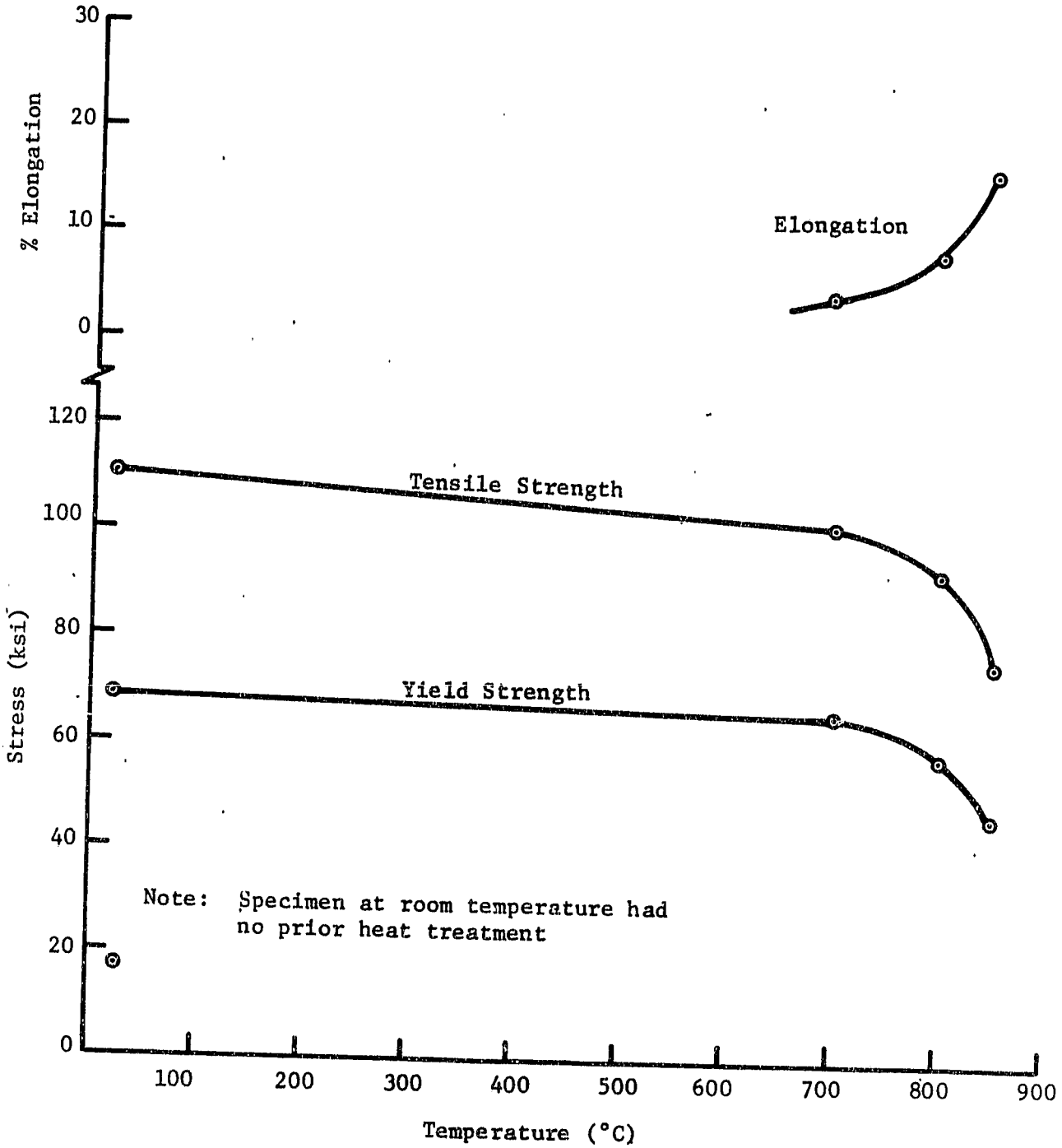

Figure 2.3-1 Tensile Test Results on HS-31

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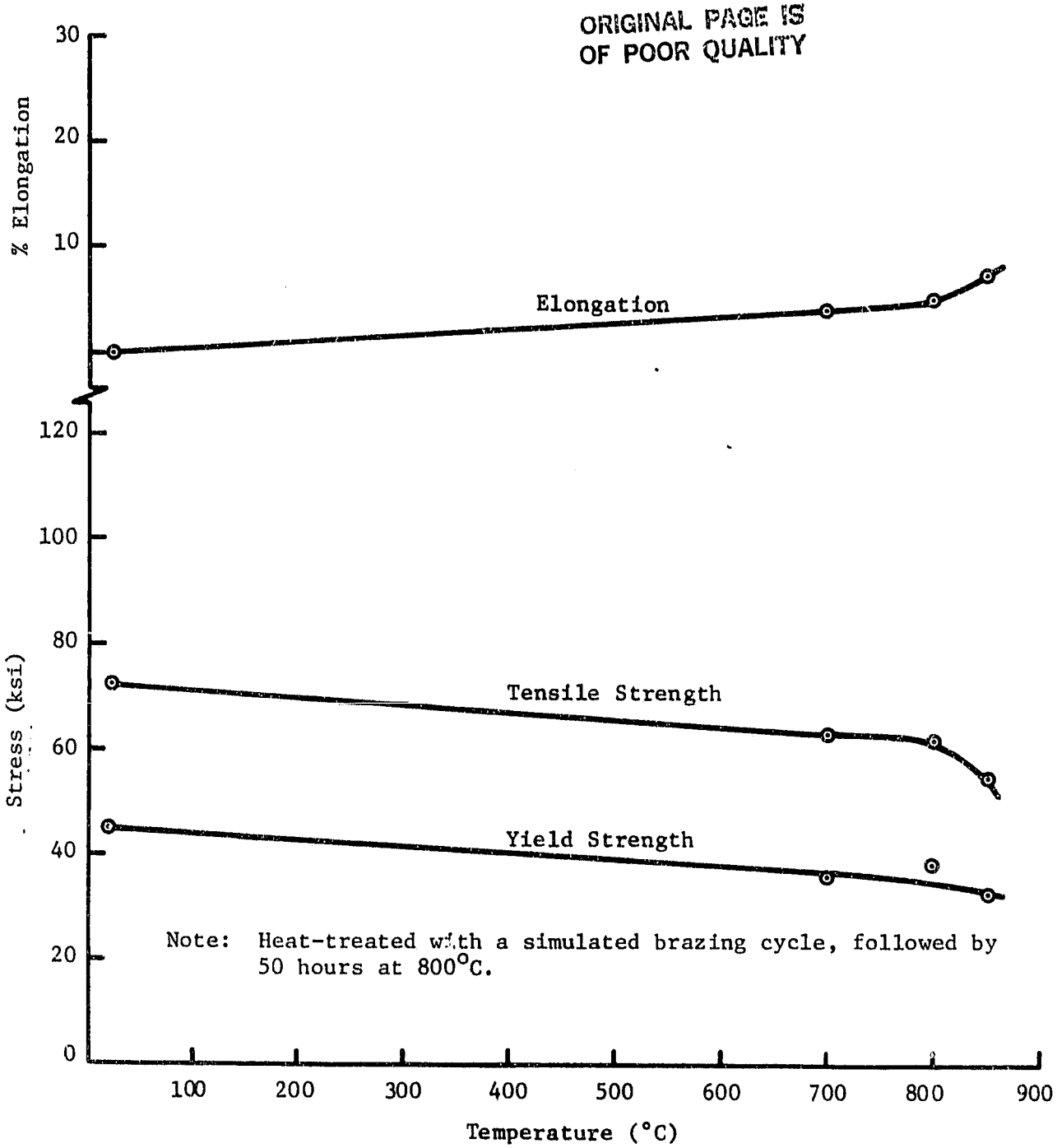

Figure 2.3-2 Tensile Test Results on XF-818 (Material Received from Climax Molybdenum)

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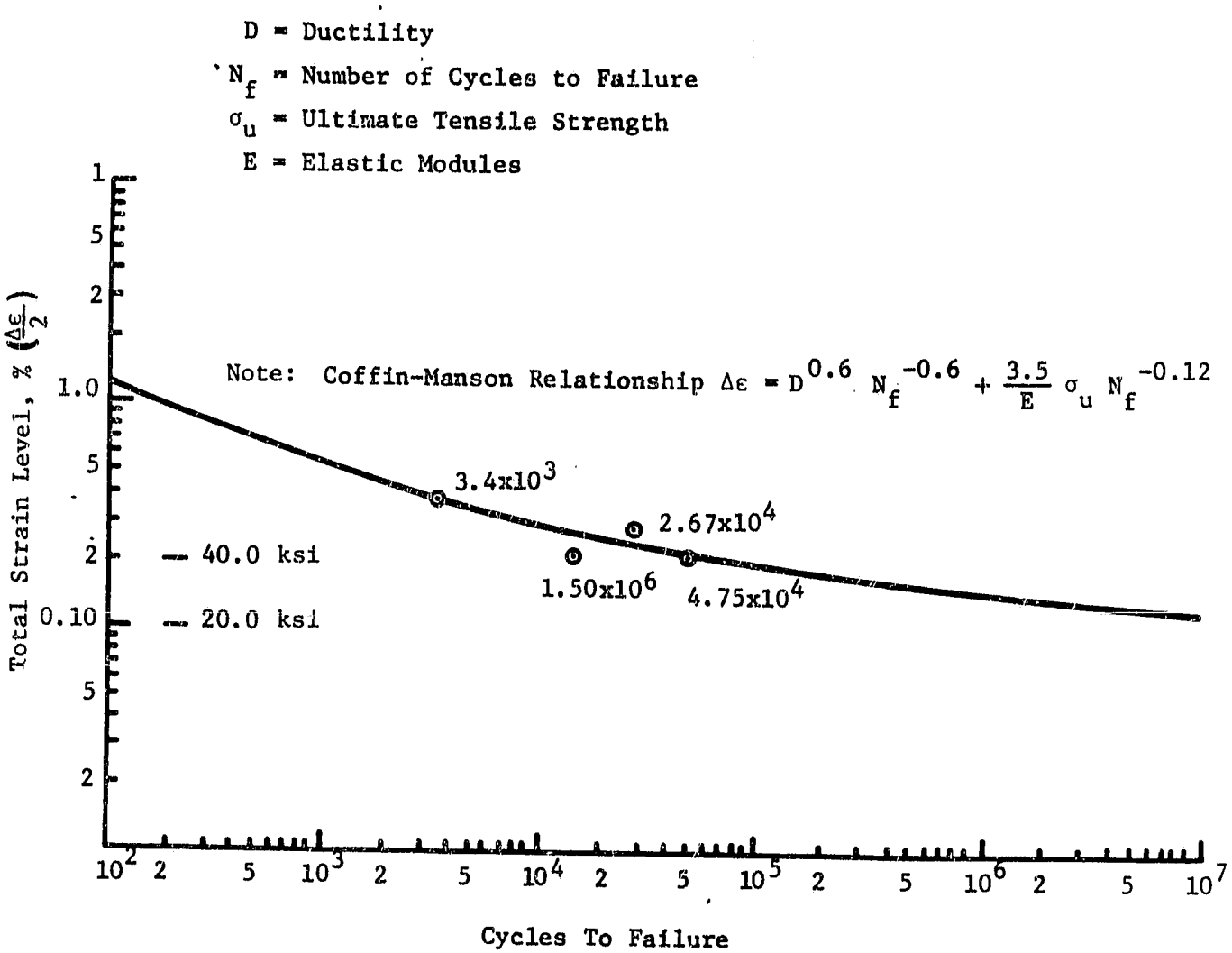

Figure 2.3-3 Fatigue Results on HS-31 at 800°C

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Task 2.4 - Mechanical Component Development - Seals

Project Engineering

The unsatisfactory behavior of the Mod I piston rings, as demonstrated by rig tests at United Stirling, at MTI, and in the engine, was reviewed with the modifications suggested by United Stirling. To address the long-term solution, plans were formulated in April for developing a new piston ring design and test program to be carried out at MTI. The study of piston ring operation led to a new concept, i.e., with development, the new ring design was potentially capable of reducing leakage, friction, and wear.

Design and Analysis

Computations of the gear losses in the Mod I engine were performed in April, and a report is being prepared which covers all the Mod I lower end friction losses.

Material Screening Tests

Tests to investigate the affects of lubricant on wear rate were completed in April. Testing showed that the lubricant prevented the buildup or destroyed the transfer film, and significantly increased the wear rate of the seal material. Also, the metal coupon not protected by the transfer film suffered wear. These tests mark the end of the formal screening investigations. A test report on the latest findings was drafted.

Exploratory Tests

Baseline testing (up to 2000 rpm) of the Mod I piston rings with helium was completed in April. Testing showed that the average life was approximately 20 hours under severe laboratory conditions.

An order was placed in May for a 5-hp, 1750-rpm, explosion-proof motor to facilitate testing with hydrogen at rig speeds up to 2000 rpm. Consideration was also given to an alternative uprated drive system to provide coverage of the full range of test conditions. At present, with the size limitations in the test cell and rig, a hydraulic drive system appears to be most attractive. Hydraulic drive system proposals were solicited and evaluated, and an order was placed in June, with delivery expected in August.

Repeat tests of the Mod I solid ring were carried out in June to establish the effect of honing the cylinder; however, friction and leakage measurements indicate that honing has made no significant difference.

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Strain Level $\Delta\varepsilon/2$	Stress Level $\Delta\sigma$	Cycles to Failure
0.382%	57,000 psi	3,405
0.285%	49,360 psi	26,745
0.218%	42,675 psi	47,502
0.218%	45,223 psi	14,988

Note: All specimens will be heat-treated with a simulated brazing cycle followed by 50 hours at 800°C. All tests were conducted at 800°C using fully reversed cycling with strain control.

Table 2.3-1 Summary of Fatigue Testing on HS-31

Task 2.5 - Mechanical Component Development - Engine Power Chain

Mod I Motoring Test Cell

The following was accomplished in April: the test table base fabrication was completed; inputs from the Sweden trip to review the Motoring Test Rig were incorporated in the test cell schematic; and the work-around stand and associated hardware were removed from the Motoring Test Cell in preparation for the installation of the Motoring Test Rig. All components were specified with the exception of shafts, flexible couplings, and speed transducers.

The Motoring Test Rig preliminary design layout was initiated in April, with completion scheduled in mid-July.

Mod I Drive Gears

Analysis indicates that the flexing of the drive shaft is sufficient to cause nonuniform tooth loading and resultant breakage of the 0.8 module gears.

As a short-term modification to permit the continuation of testing, USSw will incorporate a combination of a larger diameter shaft and 2.0 module gears in the Mod I drive to eliminate further breakage of the gears.

MTI is evaluating the potential for adding an intermediate or outboard shaft support in conjunction with an improved gear shaft attachment.

The proposal to incorporate an outboard rolling element bearing on the output gear, thereby eliminating drive gear tooth breakage on the Mod I engine, was completed.

Task 2.6 - Controls Development

Project Engineering

A test plan and schedule for controls development testing on ASE 40-7 was developed and drafted in May. The plan calls for testing of the engine to verify the EHSTR (External Heating System Transient Response) Code and to determine MPC parametric sensitivity. All tests will be performed with both analog and digital controls.

A meeting with AMG was held in May to establish the location of control components in the Lerma Vehicle. A plan and schedule was also prepared for the training of MTI personnel in the use of Mod I microprocessor electronic control, and for the installation of the electrical systems in the Lerma Vehicle.

Representatives of AMG, MTI, and USSw addressed the final location of components in the engine compartment of the Lerma vehicle, and defined the specifications for instrumentation and wiring harness during a meeting held at AMG in June.

Systems Analysis

The EHSTR Code for the P-40 engine ran reasonably well in April, although it was still in the shakedown phase. Figures 2.6-1/2 show a preliminary version of how the throttle valve position, airflow, and fuel flow (fixed λ for this run), heater head temperature, and hot hydrogen temperature respond to simulated up-power transient (shown in Figure 2.6-3). In May, improved modeling of the heater node was incorporated (the earlier, more approximate modeling permitted the exhaust temperature to fall below the heater temperature). In support of ASE 40-7 control tests, EHSTR Code predictions were made in June for normal up-power maneuvers, up-power maneuvers with constant airflow, step decrease in airflow, and fuel flow interruption.

The Harlan White* Control Simulation Code (CONSIM) was incorporated into the Vehicle Code in April. The short circuit limitation was included, but was not yet fully debugged. Discussions with Harlan White during May clarified the understanding of compressor modeling.

Development began on the CINTER Routine in June, generating a steady state torque map and acting as an interface between the Vehicle Performance Code and CONSIM.

Baseline steady state and transient controls data were taken on the ASE 40-7 engine in June using the analog control system. The USSw microprocessor control system was installed so that comparable data can be taken to evaluate the digital control system.

Low-Cost Transducers

Dither testing of the position transducers was completed in April, and the transducers were rated as acceptable for automotive use. Endurance testing of the pressure transducers was completed in May, and the performance was rated acceptable. The testing consisted of pressure cycling the transducers for 10,000 cycles, using nitrogen as the working fluid.

Combustion Control

In April, the monitor, executive, and simplified control programs for the air/fuel control were placed in EPROM (Erasable Programmable Read Only Memory) and the system was successfully operated in a stand-alone mode. Work was initiated on writing the more elaborate control software, which will include the scaling and linearization routines for the sensors and system diagnostic capability. Work in this area was scaled down between May and August to provide an opportunity for familiarization and training on the Mod I Microprocessor Control System.

A photonic (MTI) sensor was also installed in the K-Jetronic unit of the ASE 40-7 engine so that arm rotation could be recorded during the controls tests. Figure 2.6-4 shows the bench calibration curve obtained with the calibration setup shown in Figure 2.6-5.

* consultant to MTI

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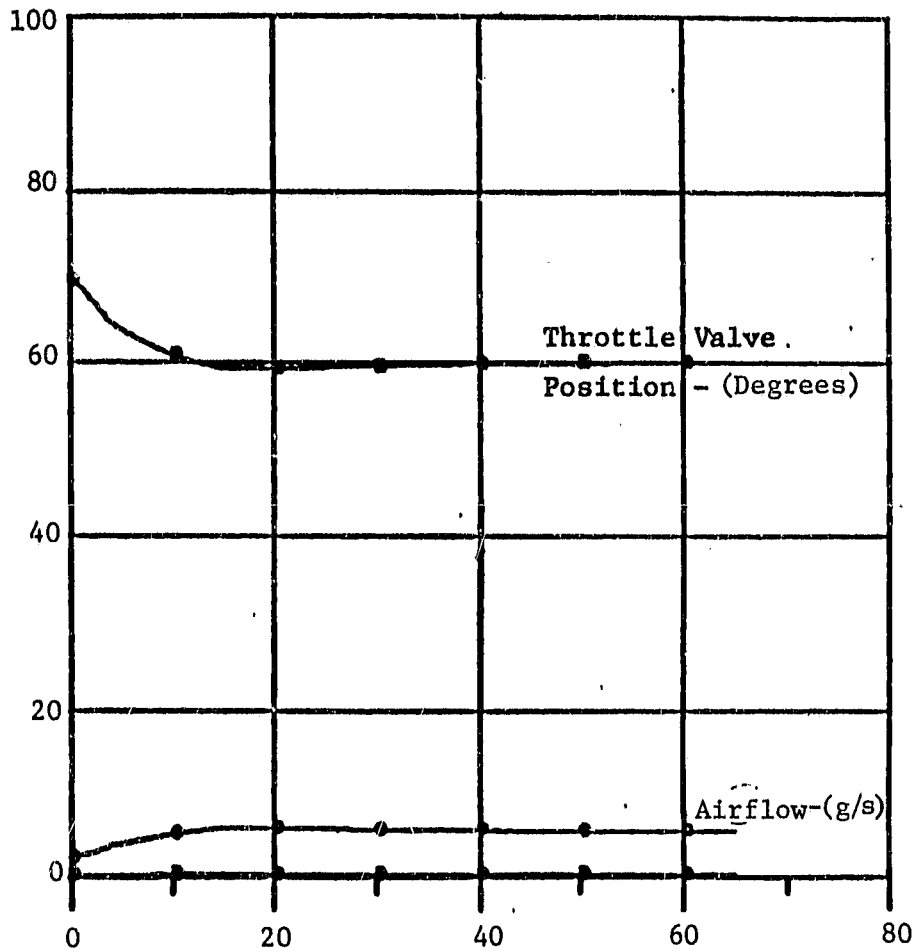

Figure 2.6-1 Calculated Response of the P-40 Due to an Up-Power Transient (3000 rpm)

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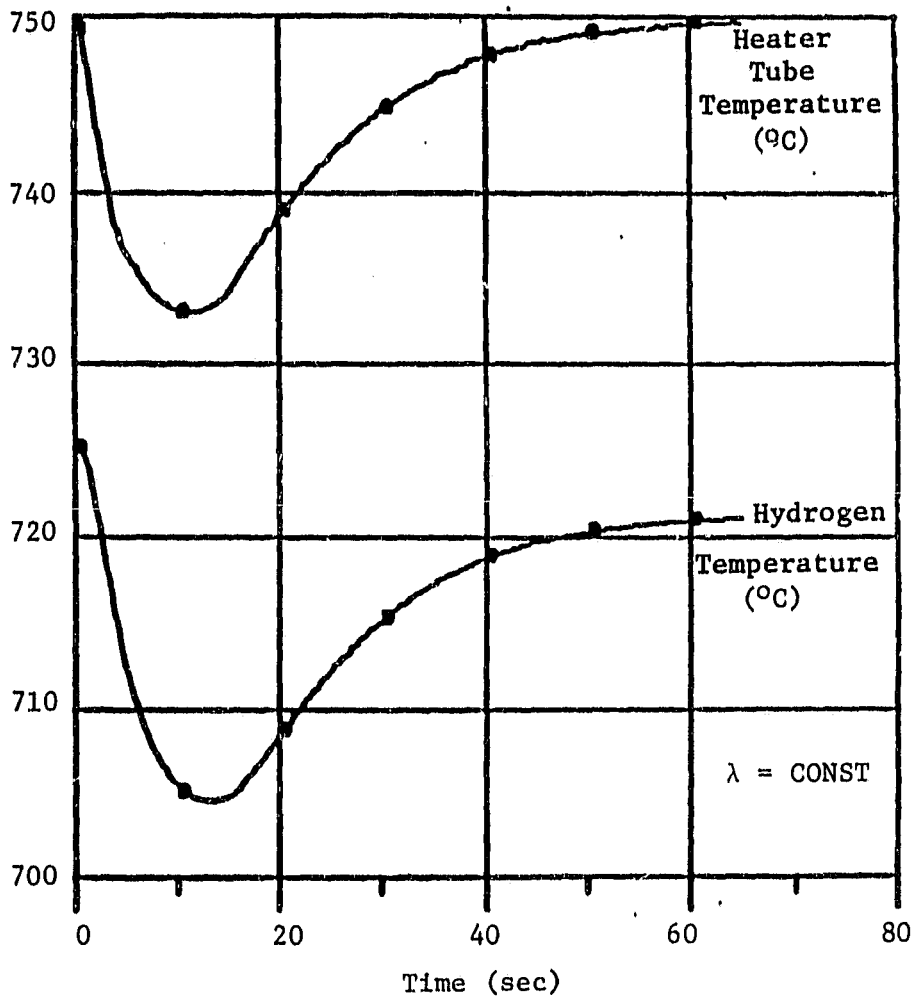

Figure 2.6-2 Calculated Response of the P-40 Due to an Up-Power Transient (2000 rpm)

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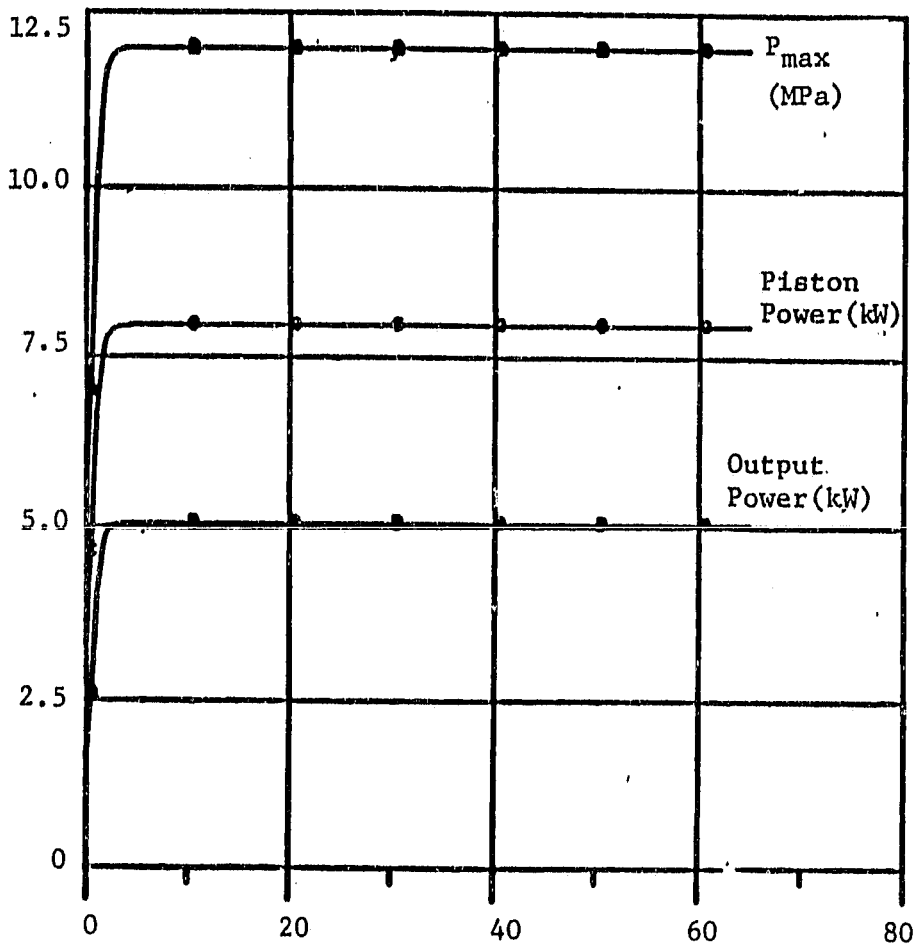

Figure 2.6-3 Calculated Response of the P-40 Due to an Up-Power Transient (2000 rpm)

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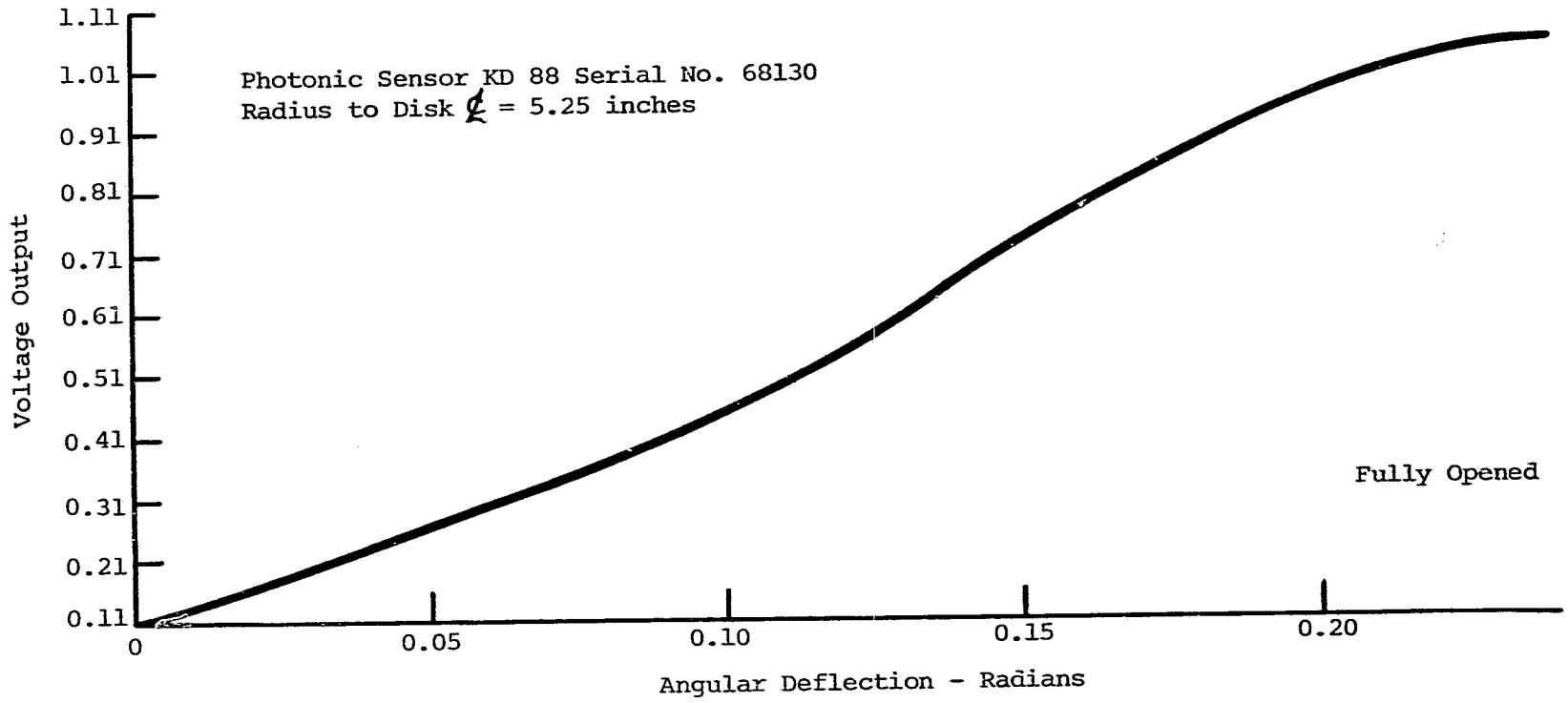

Figure 2.6-4 K-Jetronic Arm Deflection Calibration (ASE 40-7)

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Figure 2.6-5 Calibration Setup for Air Valve Travel Measurement on K-Jetronic

MTI-20650

Electric Actuator

A failure of the pinion shaft was observed during testing of the electric actuator in April. An analysis of the actuator assembly operation during extreme conditions indicated the forces were adequate to deform the pinion, and that an over-torque slip clutch would be required. Further work will be postponed until 1982.

Variator

The stock Salsbury parts for the "driver" portion of the ASE P-40-7 variator had its plastic bushings replaced by steel.

At the end of June, this rebuilt Salsbury variator had approximately 11 hours of running on ASE P-40-7, with many speed transients and no sign of any problems.

Flow Sensor Calibration

The shakedown of the Airflow Calibration Test Rig and the comparison of indicated flows by sharp-edged orifice, Datametrics airflow sensor, and J-Tec airflow sensor were pursued.

Mod I Electronic Controls Training

The first weeks of May were involved with reviewing the Mod I digital electronic control hardware and software provided to MTI by USSw. MTI personnel visited USSw from May 18-22 to obtain training in the Mod I microprocessor control. A detailed review of the software and hardware was presented. Several hours of actual operating experience were gained with the control on P-40-17. The flow of information was clear, concise, and complete. Other aspects of the system discussed included power and air throttle valve alignment, future plans, and problems. The latest copies of the hardware and software documentation were received. The microprocessor control and associated inputs, outputs, and simulation equipment was scheduled to be shipped to MTI at the end of May.

Training was also conducted at MTI in conjunction with the preparation for the P-40 Controls Tests.

Task 2.9 - Component Development at USSw

Subtask 2.9.2- Mod I Engine at USSw

Control Systems and Auxiliaries

Air/Fuel System

Burner Blower - An efficiency test with the complete blower was finished in April.

Atomizer - Compressor - The compressor with cast-iron parts was tested in April giving favorable results. A performance test with the commonly driven compressor and servo oil pump was performed in May. The performance test of the unit indicated about 100 W higher power requirement than the predicted values.

Electronics - Engine tests were performed successfully in April with the microprocessor system. During the tests, the following points were added or changed:

- rpm - measurement was changed; and,
- power control valve (Moog valve) output (in electronics) was changed to higher voltage in order to get increased resolution.

All software documentation was ready in May. During the next quarter, a complete hardware documentation will also be available. In a short time, work will begin with an updated microprocessor system with the same software possibilities, but with more suitable hardware.

Subtask 2.9.3 - Mod II Engine at USSw

Seal Systems Seal Development

1-Cylinder Capseal Material Screening Test Rig - The following materials were run against nitrided steel rods during this quarterly period:

Materials	No. of 70-hour runs
Dixon Rulon LD	2
Dixon 7035	4
Dixon Rulon J	4
Dixon Rulon E	4
Pampus 9926	4
Simrit PTFE 551	4
Advanced Products K	4
Crossflow 905	4
Fluon VX1	4
Dixon TFE-GL-HL-880-2	2
Dixon TFE-GF-HL-800-2	2
Koppers K-30-W	2

The total time accumulated at the end of the quarter was 5655 hours.

1-Cylinder Piston Ring Materials Screening Test Rig - During June, one test run at 90°C; two run at 50°C were performed. The total test rig running time at the end of the quarter was 592 hours.

1-Cylinder Cold Start Test Rig - All testing according to the test plan was finished during this quarter. The total test rig running time for the quarter was 801 hours.

P-40 No. 15 Motored Engine - The second 500-hour test run was stopped in May after 403 hours because of a check valve failure and piston ring leakage. The Dixon TFE-G1-M1-800-2 piston rings showed considerably greater wear than the Rulon LD rings. A new test run with Rulon LD piston rings, two Rulon LD, and two Koppers K-33-W capseals was completed in May. The Koppers K-30-W capseals functioned well, with wear comparable to Rulon LD. The total test rig running time for the quarter was 1543 hours.

Piston Dome Development

EB-welding (EBW) of piston domes with three different joint designs was performed in April. The objective was to find a welding technique for manufacturing domes with sound joints and small heat-affected zones. Joint Design No. 1 has a ring on the inside that prevents penetration and also serves as a guide, as shown in Figure 2.9.3-1a. Design No. 2 has a fixed guide on the outside that serves as both a guide and filler metal during welding, as shown in Figure 2.9.3-1b. Design No. 3 has a pure butt design, as shown in Figure 2.9.3.1c, that demands a fixture during welding. The welding was carried out by two different machines and two different sizes of rings. For Design No. 1, P-40-size rings were used and were aimed for the HT P-40 and P-40 R. The others were tested with Mod I-size rings.

Design No. 1 makes it possible to weld domes without sputtering on the inside. The test weld was sound except in the area between the dome wall and the ring. The weld had cracked partly around the joint, separating the ring from the dome, probably because of thermal stresses during welding. The cracks are oriented parallel to the dome wall and, therefore, perpendicular to the bending stresses which, together with a low-stress level make a low failure risk. A dome, EB-welded with the same technique, was fatigue-tested in April to 10^7 cycles with an internal overpressure of 15.75 ± 5.25 MPa. There were no failures.

The joint with outer fixed guiding and filler metal in Design No. 2 was welded with rings of type C and D, as shown in Figure 2.9.3-2. The pure butt joint in Design No. 3 was only welded with type-C rings. The welding of the pure butt-type joint did not perform well; internal cracks were found, especially in the start/stop regions. Joint Design No. 2 was not completely penetrated, not even with maximum welding power. In order to improve the penetration, a new set of D-type rings with less filler metal were tested, and an extra "cosmetic" weld was also added. The result was a sound and completely penetrated weld. Small defects of the cold flow type were found on the root side. These kinds of defects are very difficult to avoid if the inside of the domes have not been machined; therefore, a design must be chosen that will minimize these types of defects.

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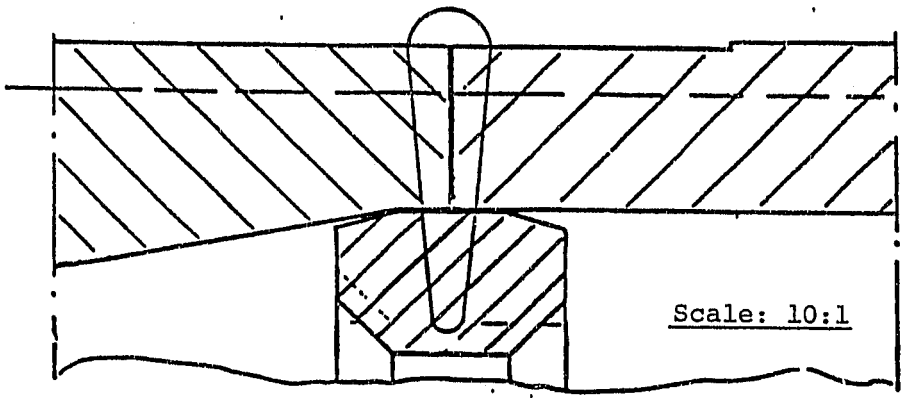
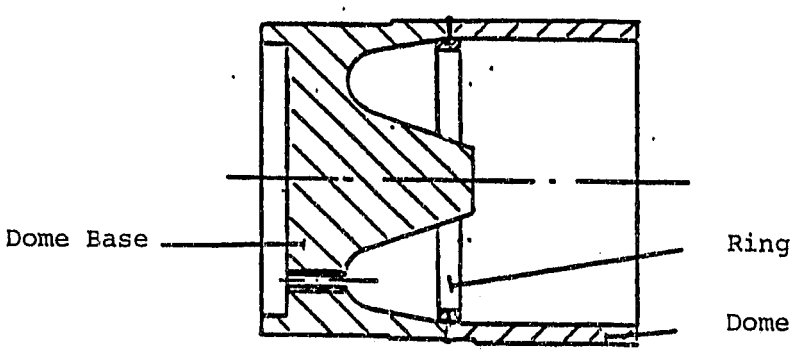
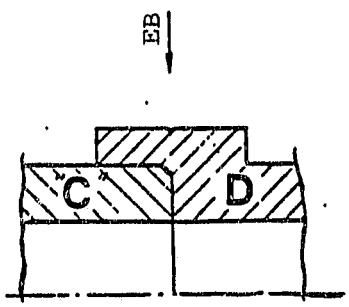
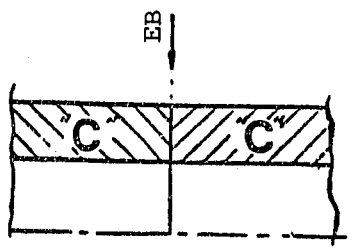




a. Joint Design Number One, Internal Ring.



b. Joint Design Number Two, Outer Fix Guiding and Filler Metal.



c. Joint Design Number Three, Pure Butt.

Figure 2.9.3-1 Alternate Joint Designs of Piston Domes

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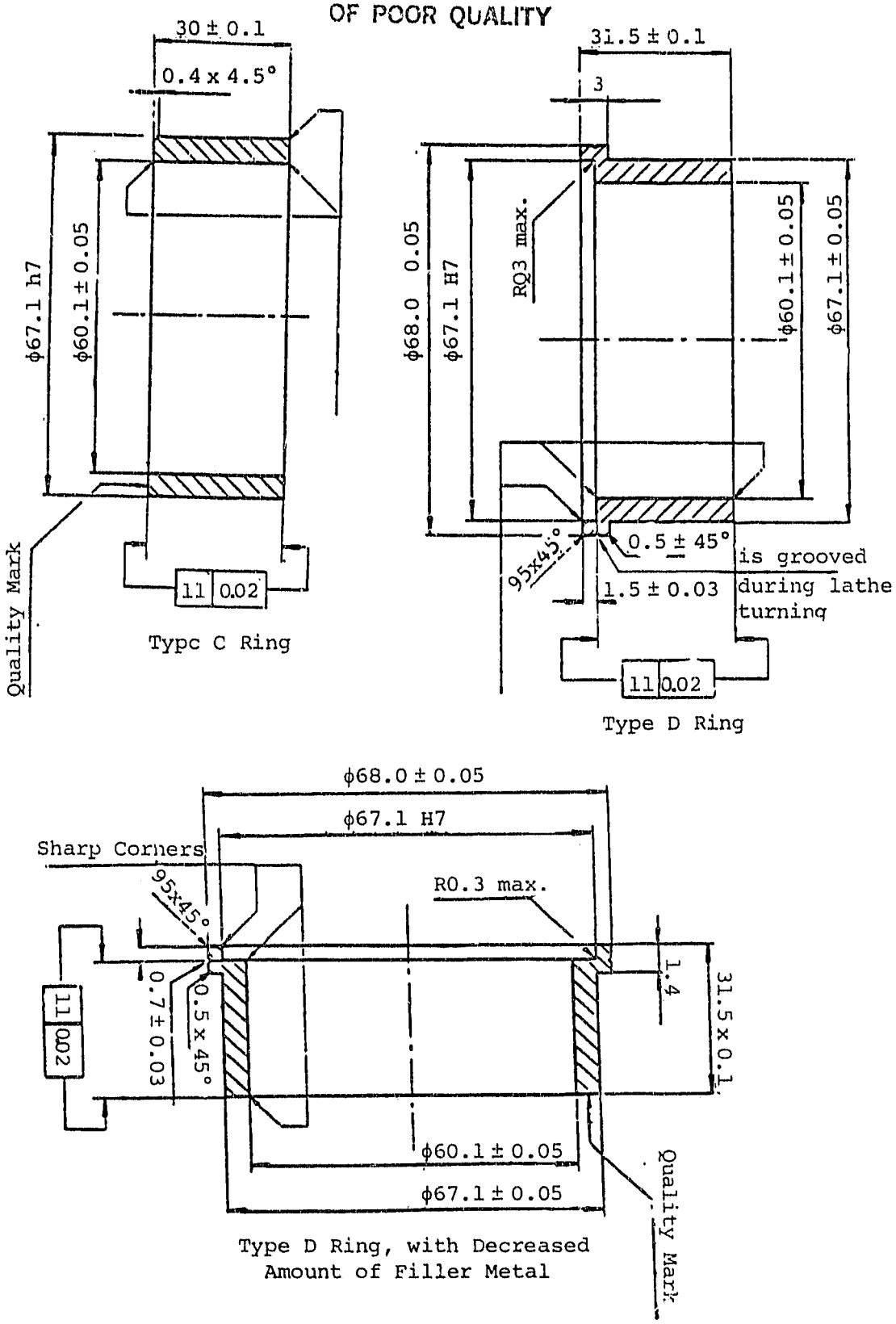

Figure 2.9.3-2 Type C and D Ring Designs

An X-ray investigation in June showed suspected root defects in five TIG-welded domes. Metallographical investigation of one of these domes showed a crack resulting from an insufficient inert gas shield inside the dome.

Endurance Test of P-40 Engine - At the end of April, running-in of the new components was finished and the permeation loss tests were resumed during the first week of May.

Tests of hydrogen permeation using hydrogen with 0.2% CO_2 were performed in June at a heater tube temperature of 820°C and 620°C. Hydrogen tests with 1% CO_2 will begin in the beginning of July.

Metallographical Investigation of an Outer Involute Heater - In June, a P-40 heater was examined metallographically after 875 hours operating time with an increased operating temperature of 100°C. The examination showed that the tested cast material (CRM-6D) is a possible candidate material for an automotive Stirling engine.

MAJOR TASK 3 - TECHNOLOGY TRANSFER (BASELINE ENGINE)

Task 3.1 - P-40 Program

ASE 40-7 -In April and May, ASE 40-7 was inactive because ASE 40-8 testing was taking place in the MTI Engine Test Cell.

During the month of June, ASE 40-7-10 was installed in the test cell (June 9-11), transient data recording equipment was hooked up and checked out, and engine mechanical problems were discovered and eliminated.

The analog portions of the Analog/Digital Control System Test were run, and control system data obtained during the last week of June. The overall purpose of this test was to evaluate the new, digital, Mod I control system (relative to the existing P-40 analog system) on a P-40 engine in the United States. Three series of test points were run on each configuration:

- normal engine steady state and transient characteristics;
- verification and updating of the EHSTR Control Code; and
- control system response sensitivity to control function changes.

Table 3.1-1 contains a summary of ASE 40-7 operating times for this quarter.

ASE 40-8 -In April, the engine (Build #11) was rebuilt at AMG and installed in the MTI test cell. After a number of checkout runs, the H_2 compressor failed and had to be rebuilt; however, engine performance was still below the desired levels (see Figure 3.1-1). The engine was then torn down and rebuilt again in an effort to improve performance. No significant problems were identified during the rebuild.

Build 12 of the engine was operated during the first half of May. At a given gas temperature/engine speed, engine performance did not show improvement over prior testing. Problems were observed in heater tube temperature maldistribution. Pressure transducers were installed on the cold side of Cycles 1-3 to try and locate possible seal-leakage problems around piston rings; pressure traces indicated that seal leakage was occurring. A decision was made to disassemble the engine and investigate the leak. During disassembly, the following was found: overheated dome O-ring (Cycle #4), uneven piston ring seating/sealing, differences between surface roughness on cylinder walls, and no significant deterioration of heat exchanger components. The rebuild of the engine (Build 13) included reworking the pistons to a new USSw-supplied dome O-ring configuration, and honing all cylinder walls to a 16 μ-inch surface finish. Test results since this build (shown in Figure 3.1-2) show a performance improvement with the laboratory combustor at a constant working gas temperature. (Note that when the working gas temperature level was increased, power followed the predicted characteristics.) The difference in temperature distribution between ASE 40-8 and ASE 40-9 needs to be investigated, since a higher test set temperature is required in ASE 40-8 to achieve the same average working gas temperature.

	Monthly Time (Hours)	Total Time (Hours)
March 31, 1981	-	241.6
April 31, 1981	0.0	241.6
May 31, 1981	0.0	241.6
June 30, 1981	17.1	258.7

Table 3.1-1 Summary of ASE 40-7 Operating Times for April/May/June 1981

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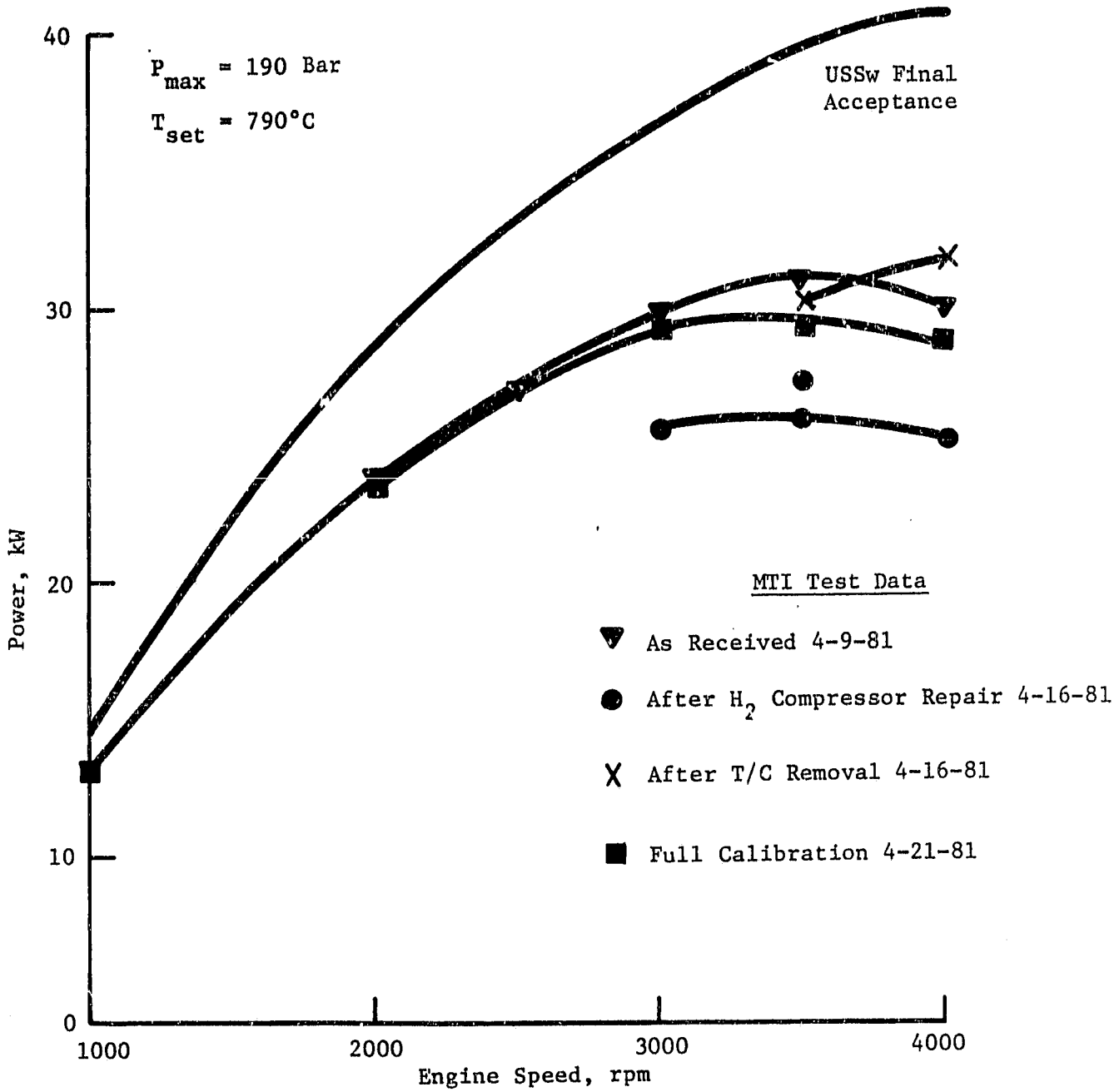

Figure 3.1-1 ASE 40-8 Performance — Build 11

In June, ASE 40-8 was removed from the MTI test cell in order to begin preparations for the testing of ASE 40-7 with the Mod I microprocessor-based control system. A more detailed summary of the ASE 40-8-13 test data is contained in Table 3.1-2, and maximum power for each configuration is plotted as a function of speed in Figure 3.1-3. As previously mentioned, the highest power obtained with the laboratory combustor and the maximum measured power with an automotive-type combustor was 31 kW at a set temperature of 780°C.

After testing, the engine was shipped to AMG for rebuild and installation in the Spirit. Once the vehicle is operational, an assessment will be made of the engine's health, and a decision reached on whether to continue the test program. The following problems must be resolved during the rebuild of the engine: leaking short-circuiting valve, leaking power control valve, leaking check valves, warped combustion liner, broken bolts in preheater cover, sluggish air throttle, and broken variator.

ASE 40-12

An adaptor for mounting a fifth wheel was added to the Concord in April. ASE 40-12 was rebuilt in May with a replacement heater head quadrant. Difficulties were experienced with P_{max} guard shutdowns and poor performance. A decision was then made to tear down and rebuild the engine. The following was found during rebuild: broken dome O-ring, failed cap seal, leaking PL seal, worn supply guide bushings, and dirty coolers. The engine rebuild was completed in May; during checkout, problems were found with the after-cooling pump, the compressor short-circuit valve, and P_{max} guard shutdowns.

The engine was repaired in June; the compressor short-circuiting valve and the after-cooling pump were replaced. In addition, the control electronics were moved and shielded from electronic noise that was causing P_{max} guard shutdowns. The vehicle is running well and is available for demonstrations.

Control System/Vehicle Anlysis

By the end of the quarter, the mean pressure control code was operational and was being debugged.

Vehicle Testing

A design approach for the installation of the Go-Power engine dynamometer was selected in May. It will incorporate a drop box that will accommodate both the Mod I and P-40 engines. The dynamometer will then be mounted to the vehicle frame. The detailing of the parts for the Go-Power Dynamometer installation was completed in June.

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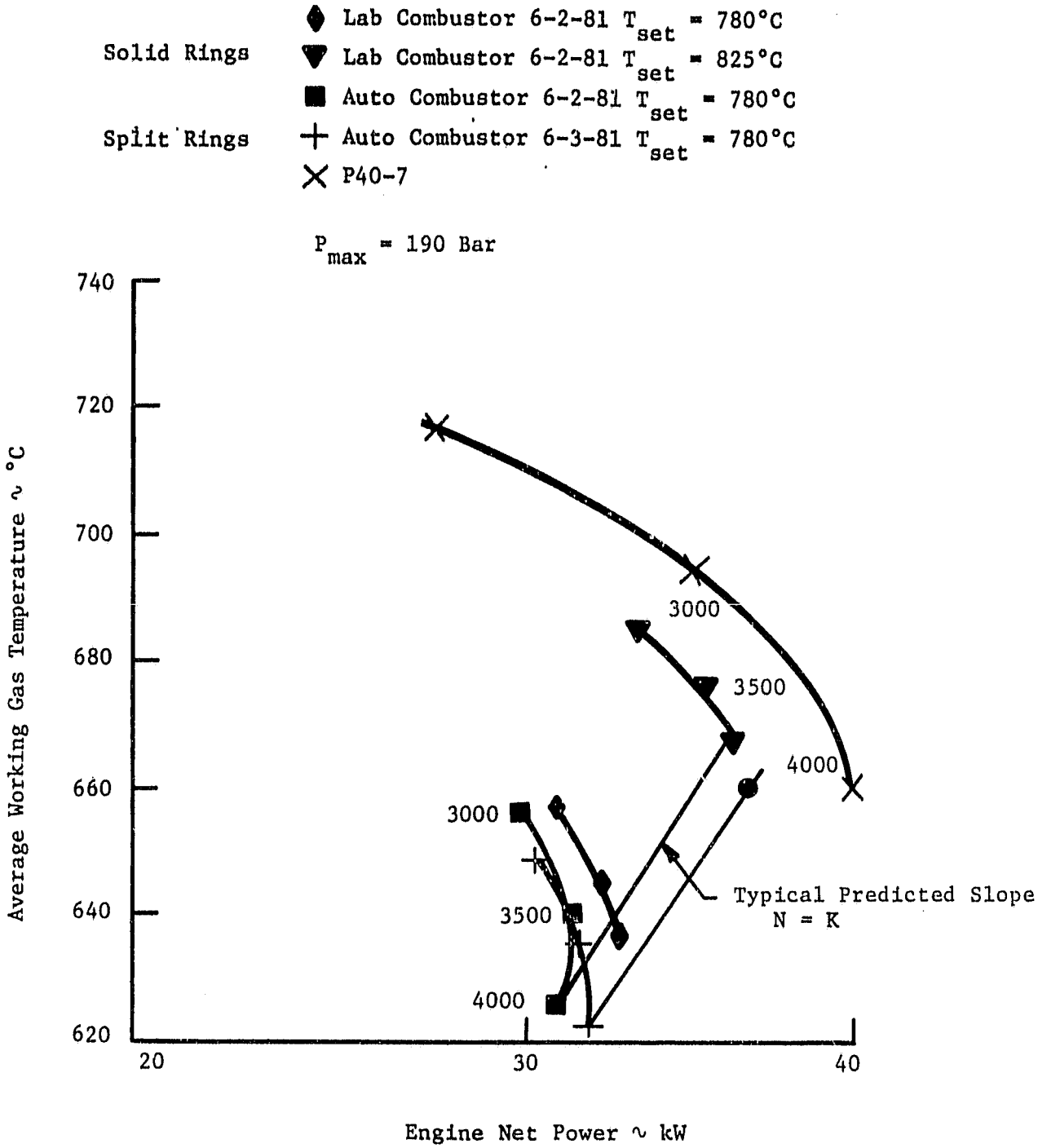

Figure 3.1-2 ASE 40-8 Performance — Build 13

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STD* Rings Auto Comb** #12 No EGR				Cycle Number
rpm	kW	$\dot{m}_a$	$\dot{m}_f$	Highest T
1000	12.4	22.7	1.27	#1
1500	18.3	31.1	1.76	#1
2000	23.5	39.6	2.18	#1
2500	27.2	46.2	2.60	#1
3000	29.8	52.6	3.01	#1
3500	31.4	59.2	3.43	#1
4000	31.0	65.6	3.82	#1

STD* Rings Lab Comb** #12 No EGR				Cycle Number
rpm	kW	$\dot{m}_a$	$\dot{m}_f$	Highest T
1000				
1500				
2000	23.9	36.9	2.15	#1
3000	30.5	49.2	2.95	#1
3500	32.5	56.1	3.40	#1
4000	32.9	62.5	3.81	#1

SPT*** Rings Auto Comb** #12 Spare No EGR				Cycle Number
rpm	kW	$\dot{m}_a$	$\dot{m}_f$	Highest T
1000	12.4	20.2	1.20	1, 2
2000	23.7	35.4	2.07	3
3000	29.1	50.5	2.94	3
3500	31.0	56.1	3.38	3, 1
4000	30.9	62.6	3.82	3, 1

SPT*** Rings Auto Comb** #12 Spare EGR				Cycle Number
rpm	kW	$\dot{m}_a$	$\dot{m}_f$	Highest T
2000	20.7	35.2	2.08	3
3000	24.4	47.6	2.81	1, 3
3500	24.4	54.1	3.24	1, 3
4000	23.8	60.3	3.66	1, 3

*Standard Solid P-40
**Lab Combustor
***Standard Split P-40

Table 3.1-2 Effect of Ring and Combustor Configurations on Power Output and 19 MPa, 780°C Set Temperature

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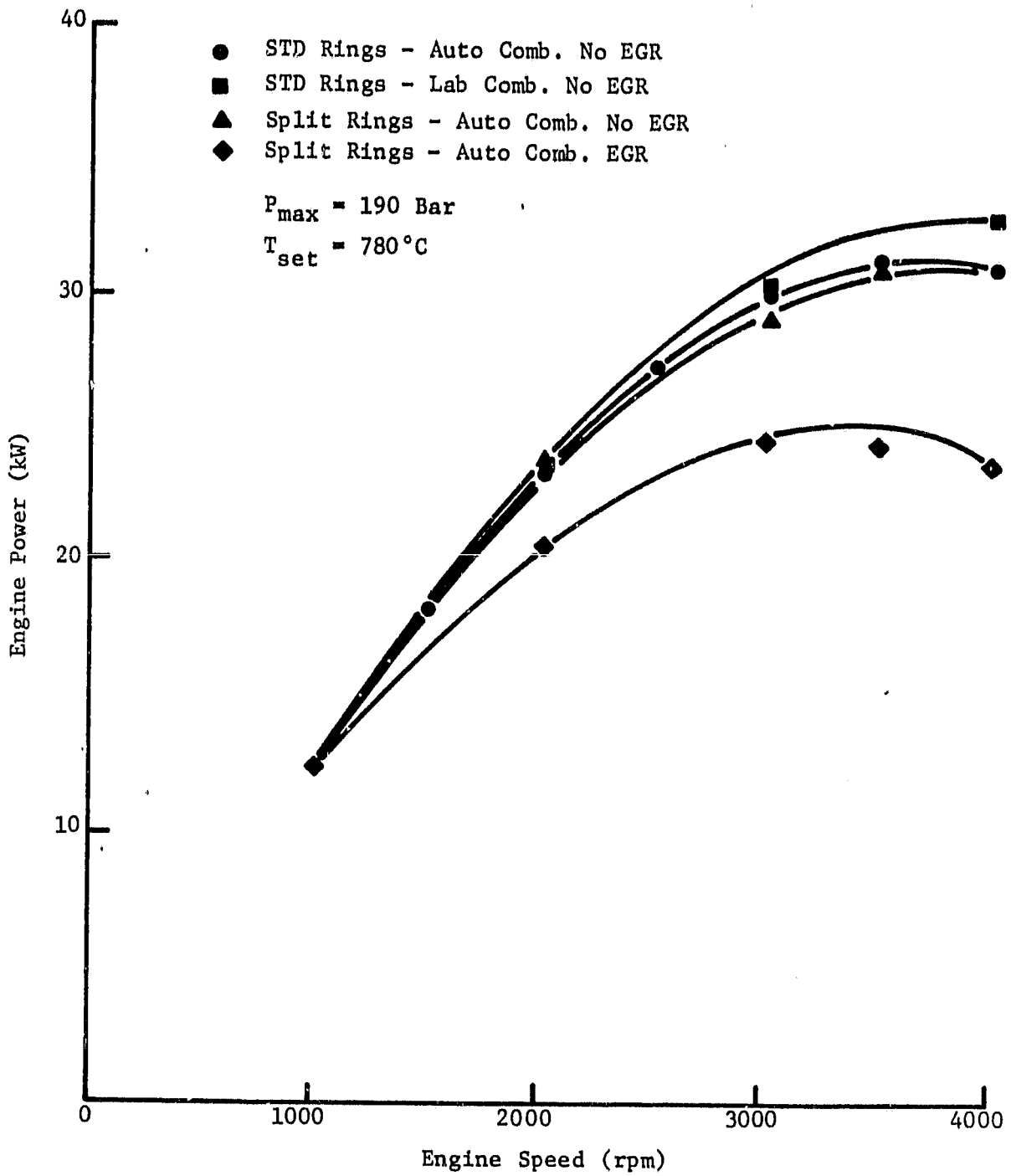

Figure 3.1-3 Stirling Engine Performance Data Power versus Speed

812609

Task 3.2 - Integrated Facility

Work continued on the component rigs during April; specific activities included:

- design of the Motoring Cell in process;
- parts for the Exploratory High-Temperature Heat Transfer (HTHT) Rig ordered;
- Combustion Test Cell Air Heater received with installation scheduled for completetion by June 1, 1981; and,
- installation of the Combustion Cell Cooling Tower System 90% complete (to be finished by August, 1981). The Combustion Cell CO_2 Charging System, the Fuel Distribution design, and the Fuel Farm Fence were also completed.

The mechanical and electrical design of the Motoring Cell was 75% complete by June; the total Motoring Cell will be complete by the end of October. Most parts for the HTHT Test Rig were received, with installation to begin next quarter. In the Combustion Test Cell (Endurance Rig), the combustion air heater was installed and checked out. During checkout, several thermocouples were found to be faulty or improperly located. The vendor agreed to supply replacement thermocouples and pay for the installation; completion is scheduled for July 31st. The Cooling Tower water supply and return is 90% complete, and the flow meter with installation is expected to be complete by August 1st. The CO_2 Cooling Loop installation was started, with completion expected during the next quarter.

The Fuel Distribution System for the Combustion Cell was installed in June; however, checkout was delayed until the CO_2 piping system was completed.

A new bypass line for the Emissions Bench was installed in June; this will allow the refrigeration bath to function (remove water) properly. CO and CO_2 reading accuracy will also be improved.

MAJOR TASK 4 - ASE MOD I - ENGINE DEVELOPMENT

Task 4.1 - Project Engineering

A trip was made to NASA/LeRC in May to discuss pressure-volume (PV) measurements and analysis. The topics discussed were:

- IMEP Scanner;
- Pressure Instrumentation;
- Shaft Angle Encoder;
- Dynamic Pressure Information;
- FM Data - Batch Output Plot;
- Comparison between Analytical Prediction and Experimental Data

An MTI engineer and technician also visited USSw in May for training and familiarization on the Mod I Engine.

Mod I Performance Code Validation

Using a detailed Control Volume (CV) model of the Mod I engine and a current version of the MTI Harmonic Stirling Code, a number of comparisons were made relative to USSw code predictions at 5 and 15 MPa, and actual engine data from USSw testing at 5.1 MPa. Initial MTI Code predictions underpredicted indicated power/efficiency levels relative to the USSw code and actual engine data. For comparative purposes, the actual engine test data was corrected to add measured shaft power plus an estimate of motoring losses from motoring test results in order to obtain indicated values. Figures 4.1-1/2/3 display the results of these first comparisons. In each figure, the indicated power and efficiency were less than the USSw values, and the deviations increased with speed. This comparison, along with an examination of the method of loss calculation in the MTI model, suggested an excessive level of gas pumping loss. To reduce this level, friction and heat transfer enhancement factors of the code were removed. The resulting output is displayed in Figures 4.1-4/5/6; the output shows a marked improvement in agreement. A revision of the CV model improved agreement further at the 5 MPa level, but caused 15 MPa estimates to be optimistic. Further validation effort is necessary to understand the remaining differences in power/efficiency estimates.

Task 4.2 - Design and Analysis at USSw

Stress Analysis of the Heater

A stress analysis of the Mod I heater tubes was performed in April, including thermal expansion and creep rupture analysis based on linear damage theory. The analysis covers low-cycle fatigue based on a combined metro/highway driving cycle. The results, in terms of design factors, show that the design stress criteria were met.

Engine Drive System

All parts required for the conversion of Drive Unit No. 4 to accept smaller main/revised end bearings were detailed and issued in April. The parts required to modify the Drive Unit No. 4 Mod I were issued

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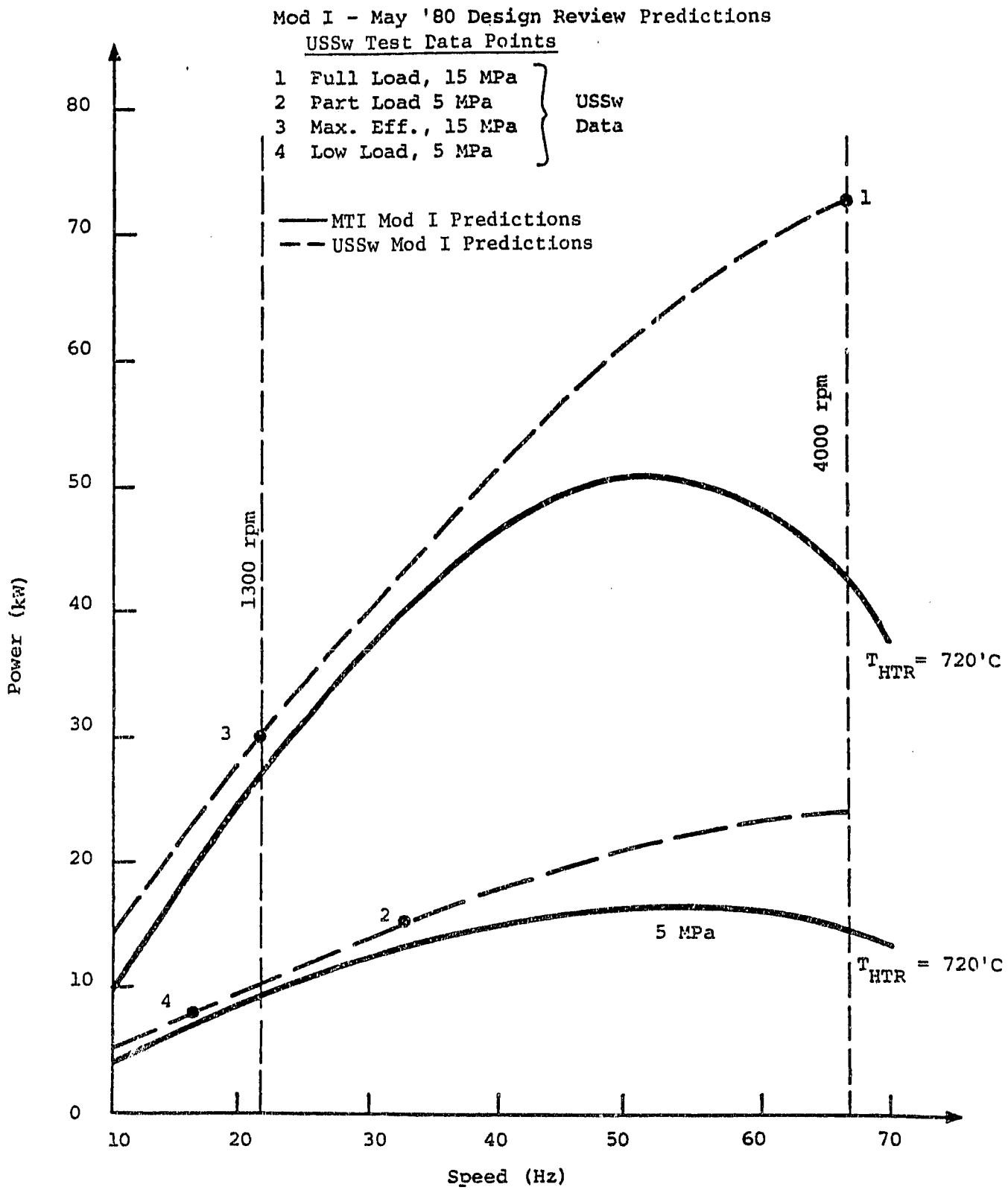

Figure 4.1-1 Indicated Power versus Speed

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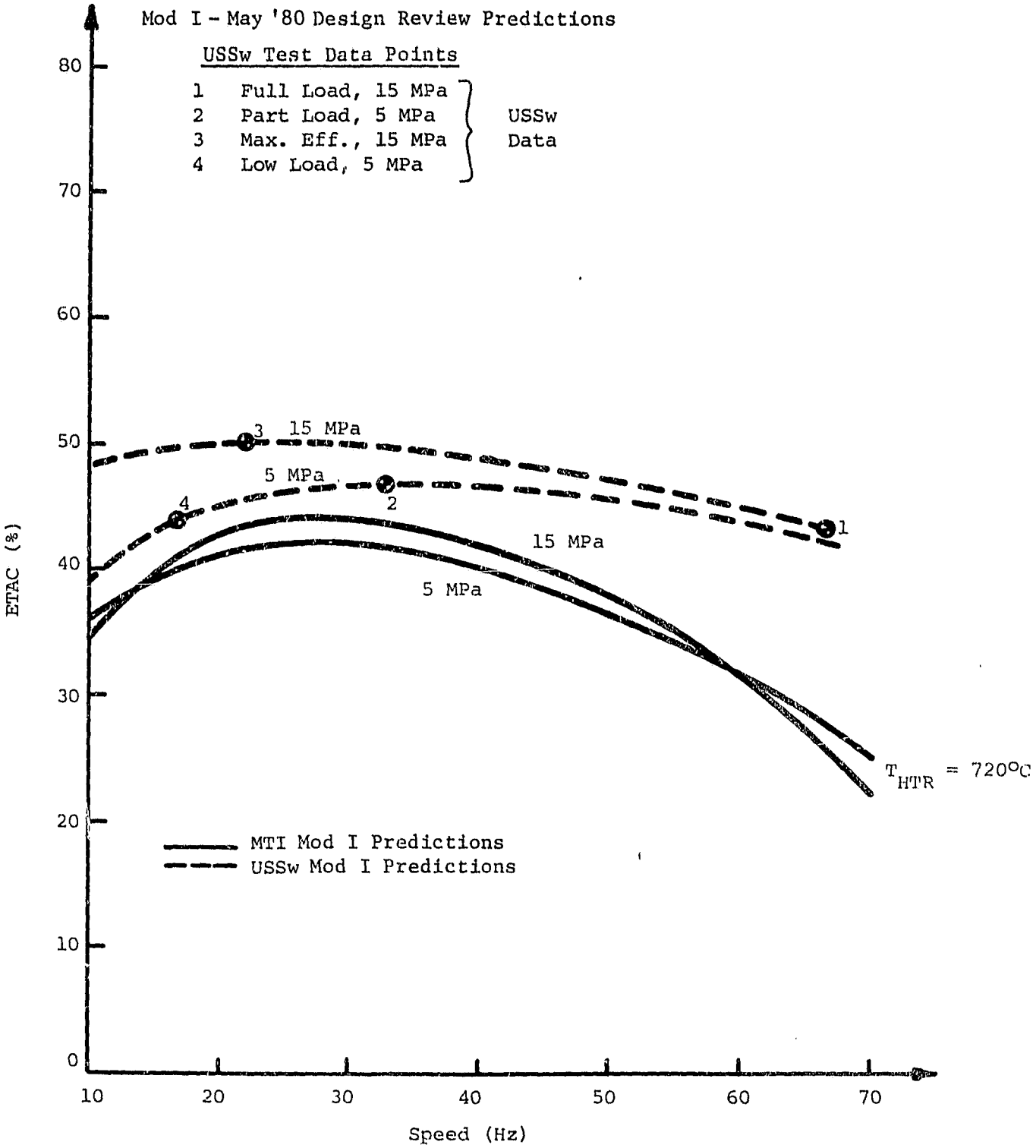

Figure 4.1-2 Indicated Efficiency versus Speed

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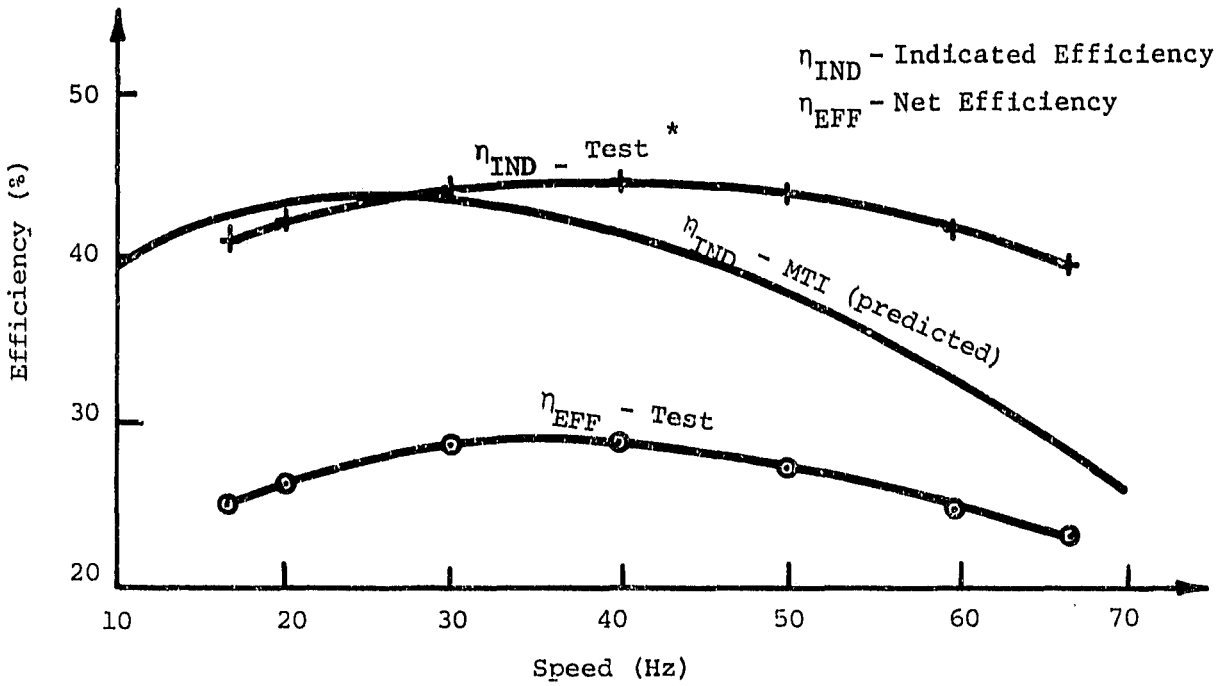

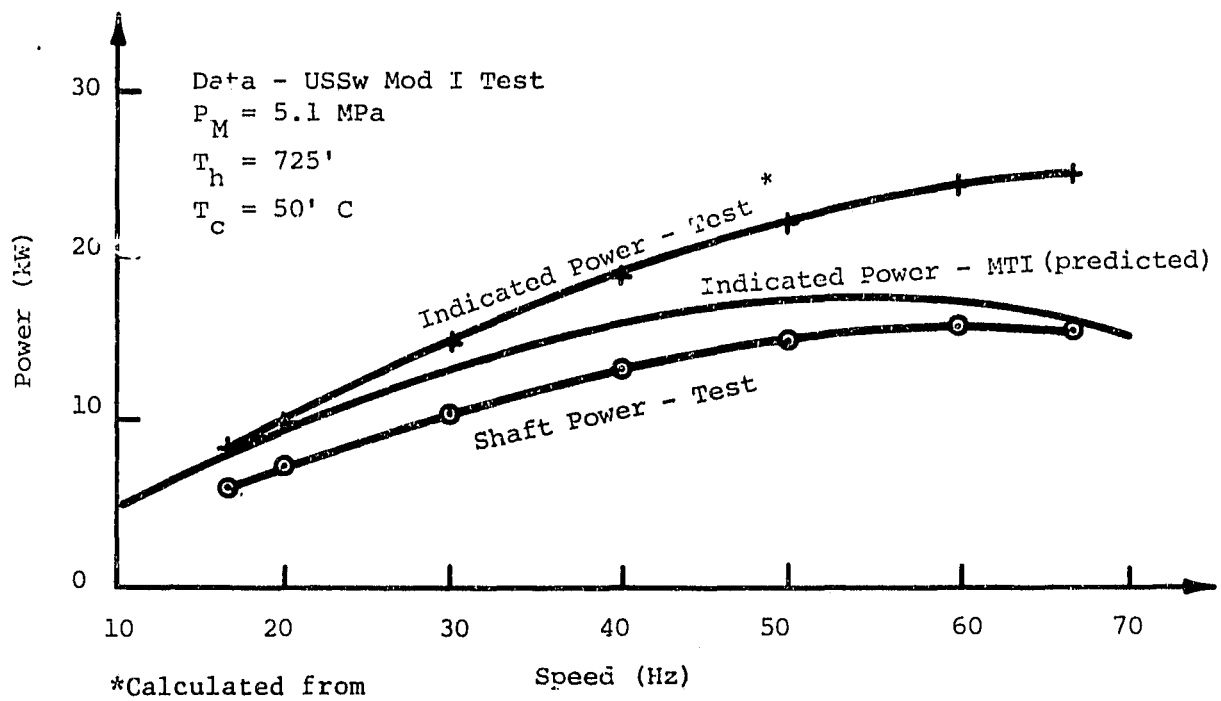

*Calculated from test data.

Figure 4.1-3 Predicted and Measured Efficiency versus Speed (top)
Predicted and Measured Power versus Speed (bottom)

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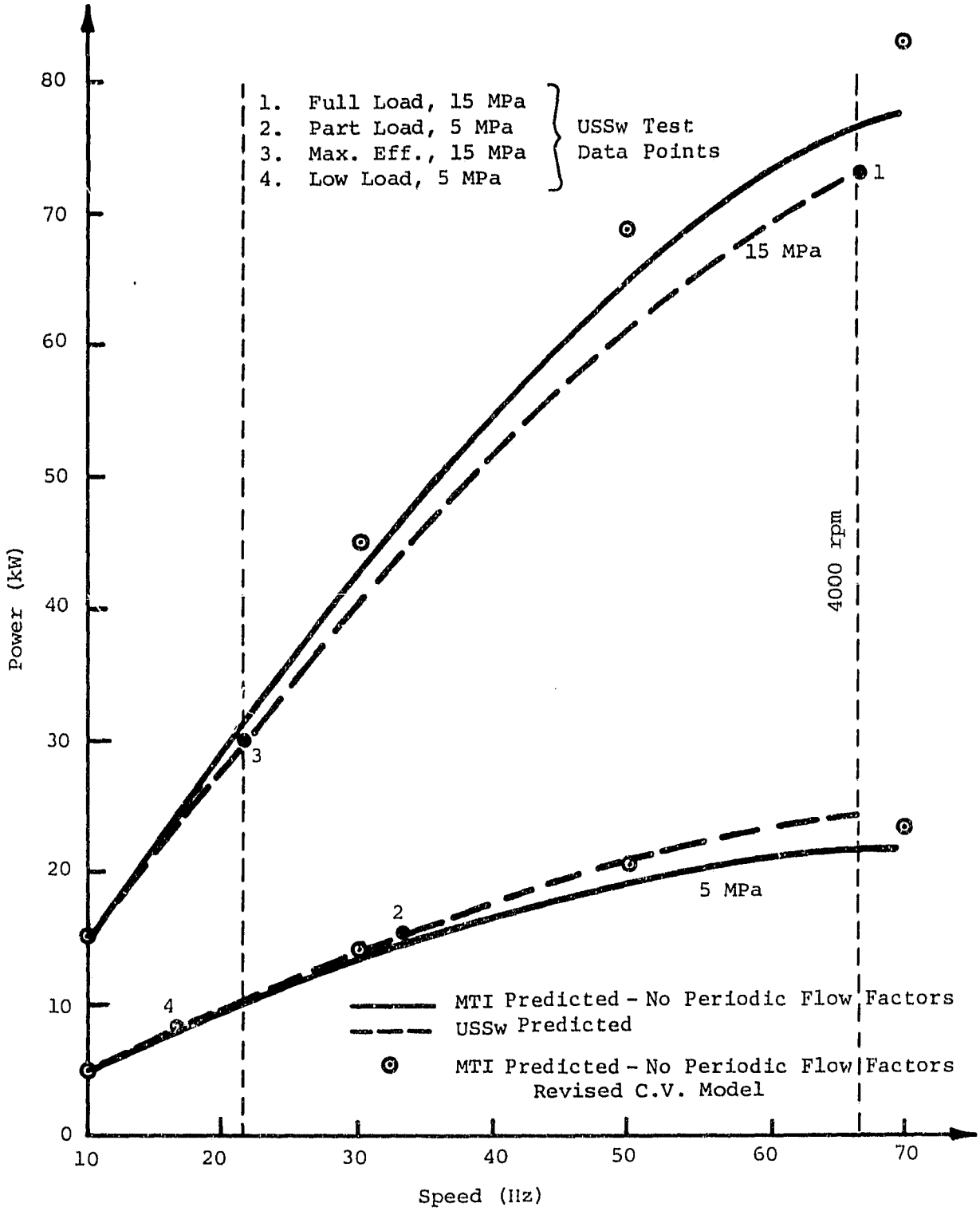

Figure 4.1-4 Indicated Power versus Speed (predicted)

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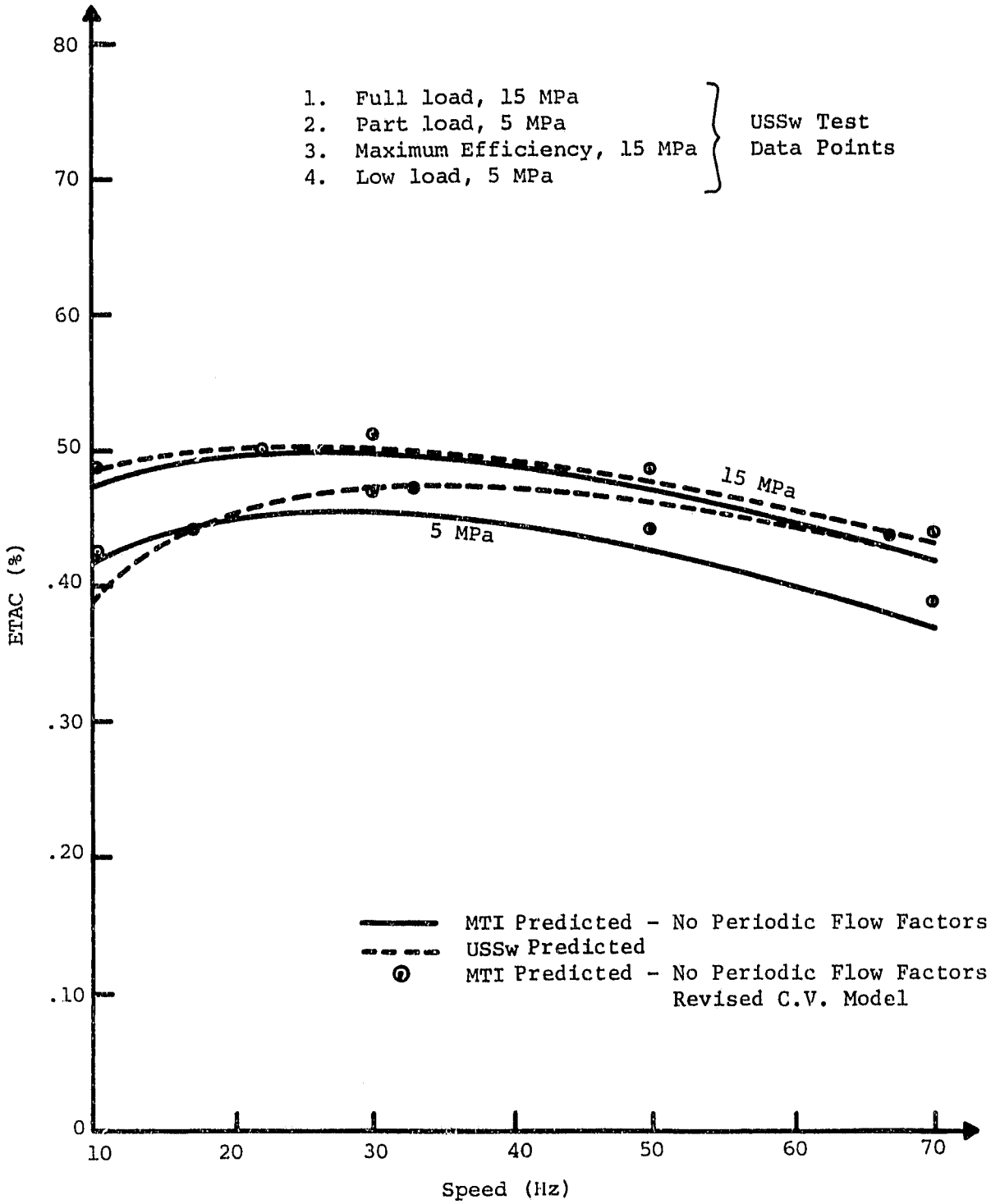

Figure 4.1-5 Indicated Efficiency versus Speed (predicted)

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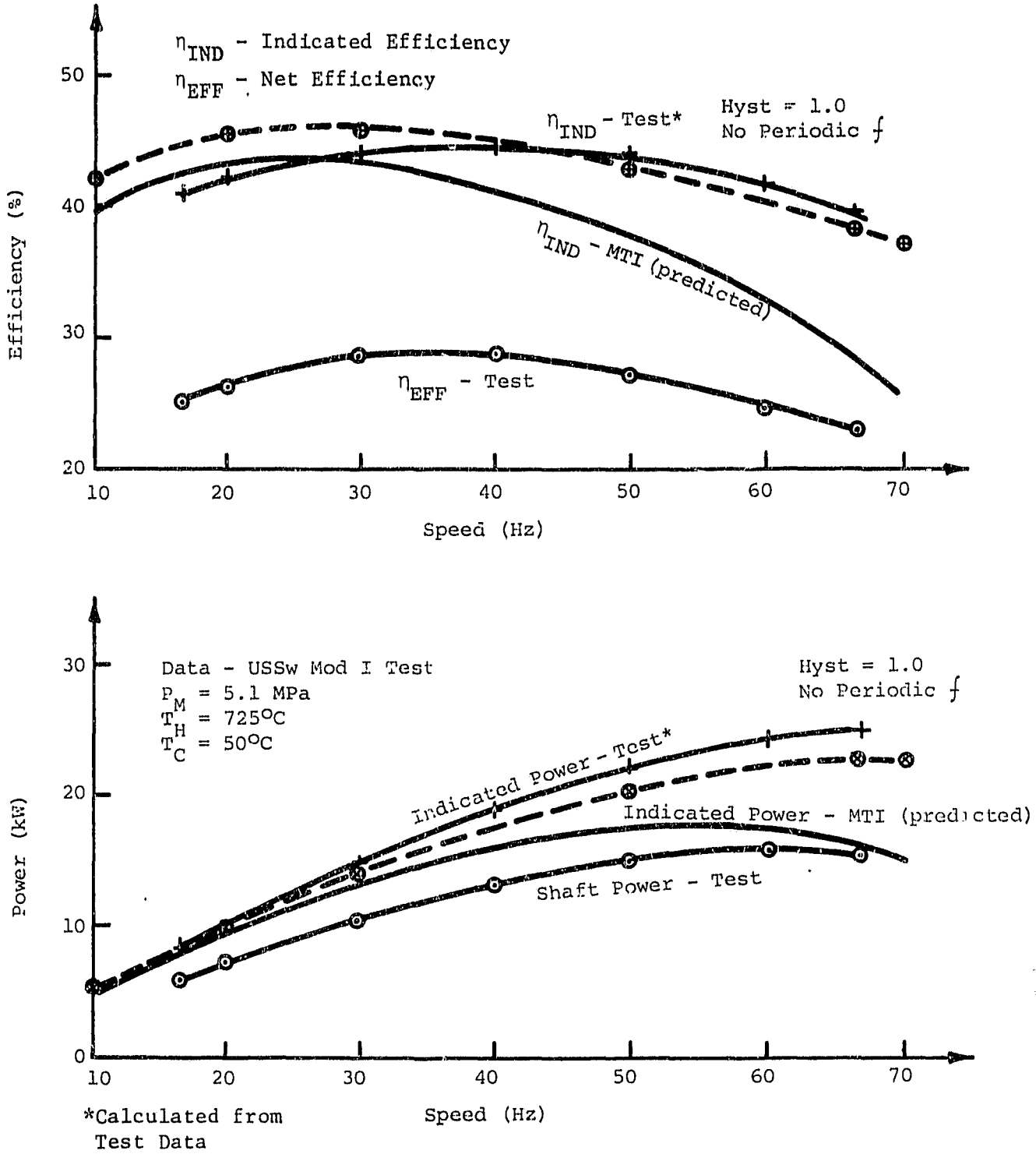

Figure 4.1-6 Predicted and Measured Efficiency versus Speed (top)
Predicted and Measured Power versus Speed (bottom)

812611

for manufacture in May. The parts include a pair of crankshafts, big end and main bearing shells, and connecting rod castings.

Engine System Design and Analysis

Tests concerning flow distribution through the Mod I regenerator were finished in May, and a preliminary analysis of the test results was performed, indicating a rather poor flow distribution pattern for the current gap above the matrix in this version of the engine. If the gap is increased by 0.5-1.0 mm, it should be possible to achieve a gain in engine efficiency; however, the final recommendation of the change in height of the gap above the matrix cannot be made until some additional analysis is performed. Note that the gas height in the current hardware is 0.7 mm less than was intended. The reason for this is partly the height of the folded edge of the regenerator mantle, which was drawn to be 1.0 mm, but in the hardware is 0.6 - 0.7 mm.

Task 4.3 - Engine Manufacture and Procurement

Heater Head

The regenerator castings from Bulten Kanthal were completed in April. At that time, six satisfactory regenerator housings of the original design were available. The area on top of the regenerator housing, including the manifolds, was reinforced.

Engine Drive System

The crankshafts for the chain drive conversion of Drive Unit No. 4 were received and inspected in April. All parts necessary for the conversion were available, and the unit was assembled and prepared for motoring and noise level tests.

Three sets of module two gears were ordered. By June, all parts for the Mod I Drive Unit No. 4 chain drive were received. Assembly and motoring tests will begin next quarter.

Cylinder Liner

Cylinder liners of nodular iron will be mounted in the drive unit for testing and evaluation of friction losses.

Task 4.4 - Mod I Assembly and Acceptance Test at USSw

Mod I Engine Test Results (BSE)

The quantity Q_{WOC} (the heat flow rate transmitted through the oil cooler as indicated by the DAS) was erroneous in the readings made before March 27. The indicated values were far too large due to a bad electrical contact in an amplifier. Corrections were made in April to correct the problem.

Analysis of Measured Engine Performance

Comparisons between measured and calculated BSE power and efficiency is shown in Figures 4.4-1 through 4.4-6. The diagrams in Figures 4.4-1 and 4.4-2 present data from the beginning of February with a water temperature of 30°C. The diagrams in Figures 4.4-3 through 4.4-6 contain acceptance test data for the BSE with a water temperature of 50°C.

Analysis of Measured Motoring Unit Performance

A comparison between motoring test results on Drive Units #2 and #3 indicated an increase in friction losses in Unit #3 (see Figures 4.4-7/8). It was found that the friction losses in Drive Unit #3 could be reduced by adjusting shaft locations within manufacturing tolerances (Figure 4.4-9). Unit #3 was doweled to maintain the desired critical component location; the final test results are shown in Figure 4.4-10.

The measured data from the motoring tests was corrected for gas cycle pumping losses and internal leakage losses, but not for the power consumed by the thermal hysteresis, due to heat transfer in the cycle. Thus, the results shown in Figures 4.4-7 through 4.4-10 encompass friction plus thermal hysteresis effects.

Concerning the analytically calculated friction power, it is not yet possible to make meaningful conclusions because the thermal hysteresis is still unknown, and the true bearing clearances have not yet been introduced in the computer code.

Task 4.5 - Engine Test Program

Mod I - Stirling Engine System

In the beginning of April, the engine was rebuilt from a Mod I Basic Stirling Engine (BSE) to a Mod I Stirling Engine System (SES). The engine was motored for the first time on April 3; the first start was made four days later. The auxiliary drive unit was adjusted, and the electronic control unit was tuned to the engine. Idle speed was set to 700 rpm, giving optimal performance for the present engine setup. An initial performance test was made at 3 and 5 MPa mean working gas pressure (P_{wgm}). The test results are shown in Table 4.5-1 and Figures 4.5-1/2. During testing, the tolerance band for engine parameters was exceeded as follows:

d T_{tubm}	29-96°C	< 50°C is specified
d T_{wgbm}	33-90°C	< 20°C is specified
d P_{wgm}	0.20-0.55 MPa	< 0.3 MPa is specified

At the end of April, the engine was stopped for the rectification of the high difference between the four cycles' mean working gas pressure.

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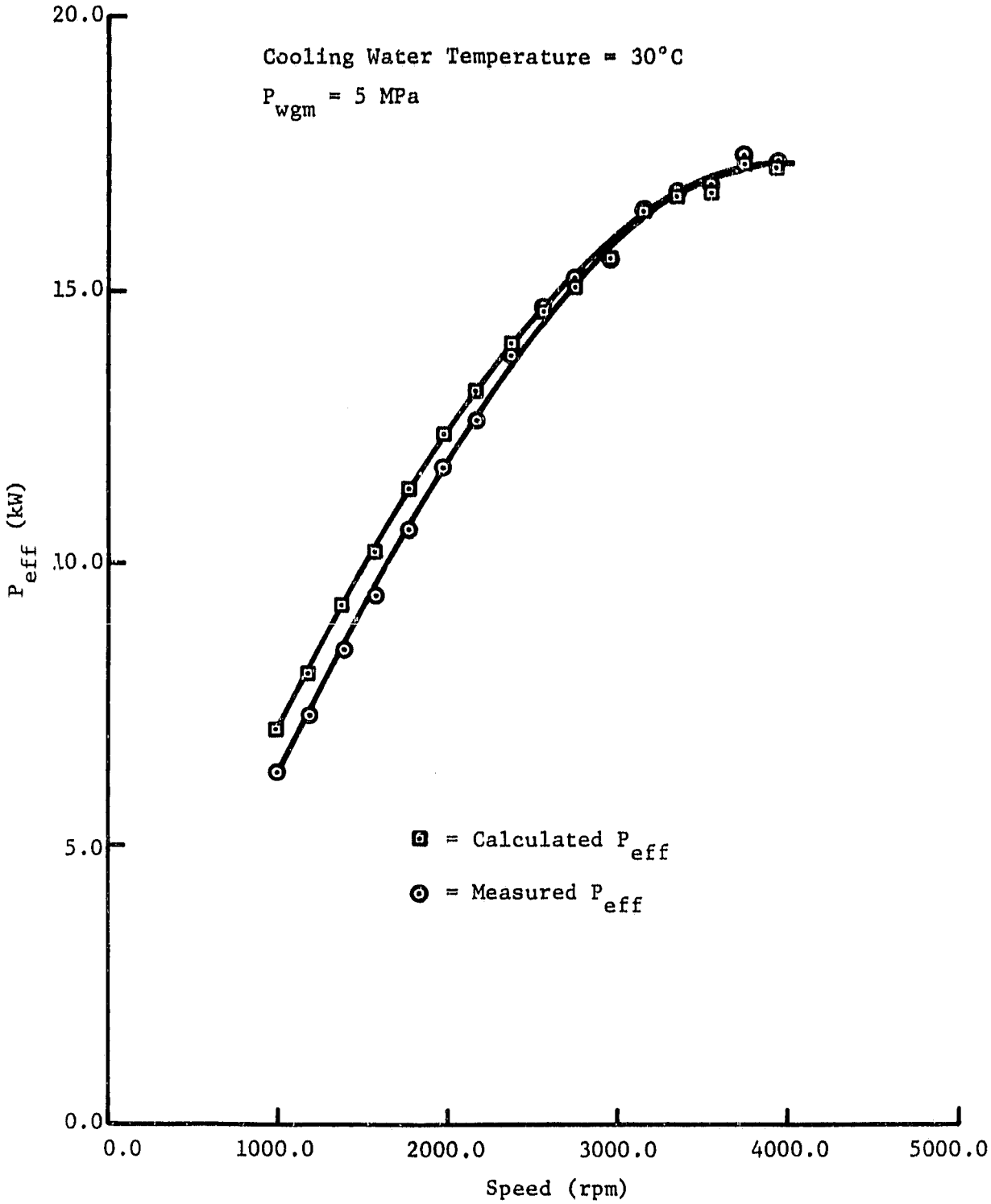

Calculated Power Output with Measured:

P_{wgm}, Speed, T_{wgbm}, T_{wcin}, M_{wc} and T_{oilae}

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Figure 4.4-1 Comparison of Measured and Calculated Power Output for Mod I BSE No. 1

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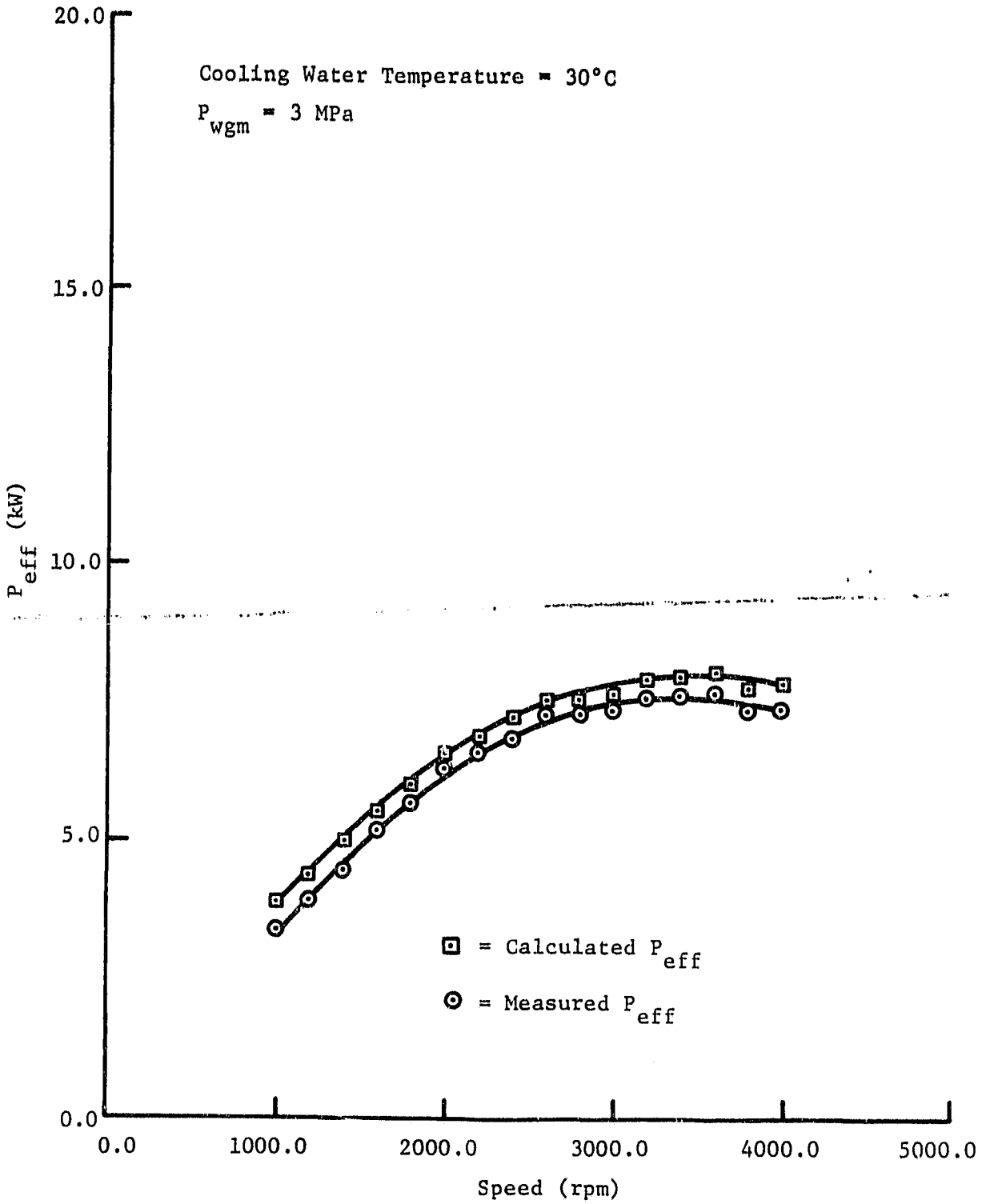

Calculated Power Output with Measured:

P_{wgm}, Speed, T_{wgbm}, T_{wcin}, M_{wc} and T_{oilae}

813352

Figure 4.4-2 Comparison of Measured and Calculated Power Output for Mod I BSE No. 1

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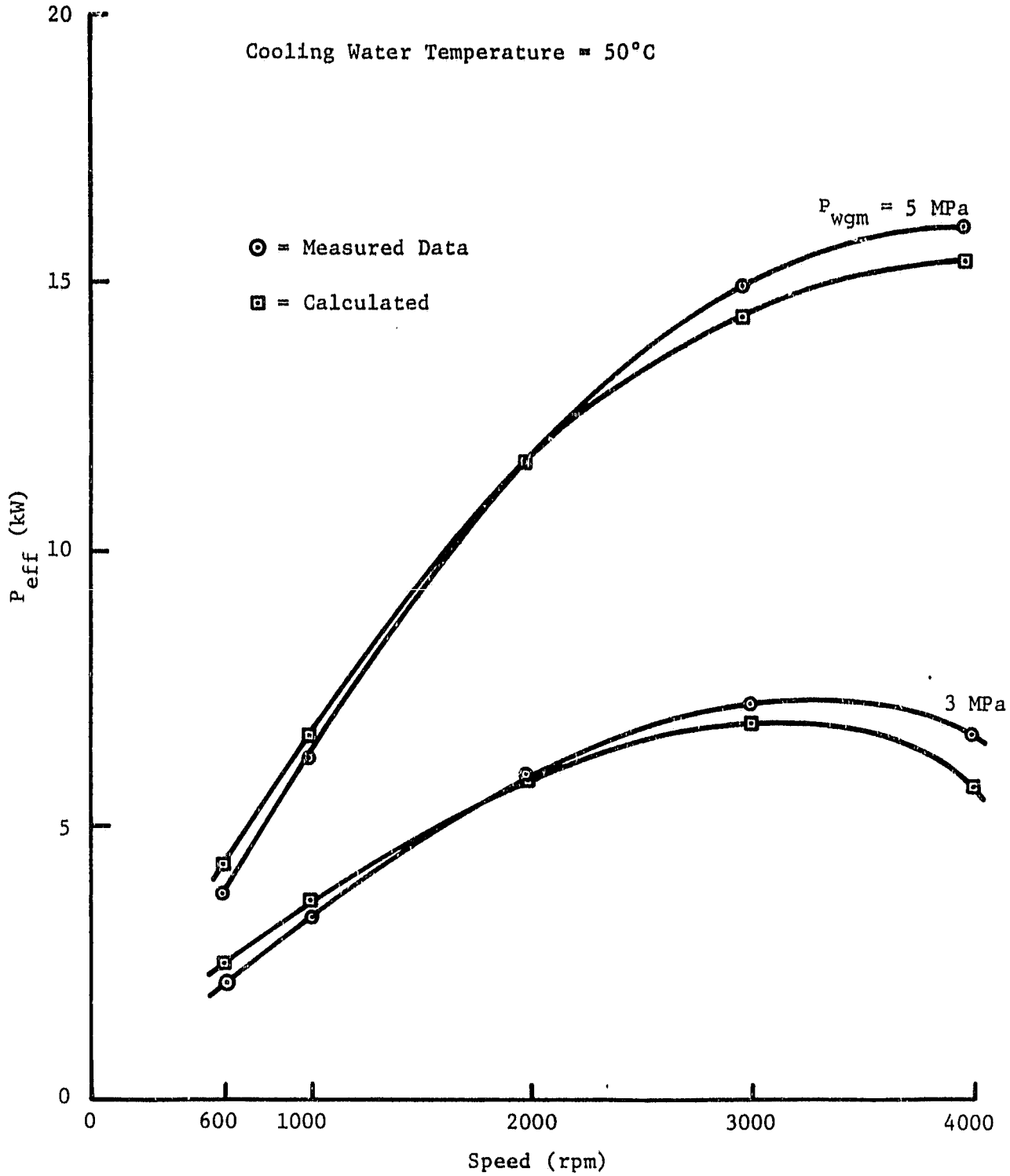

Calculated Power Output with Measured:

P_{wgm}, Speed, T_{wgbm}, T_{wcin}, M_{wc} and T_{oilae}

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Figure 4.4-3 Comparison of Measured and Calculated BSE Shaft Power for the Mod I BSE No. 1

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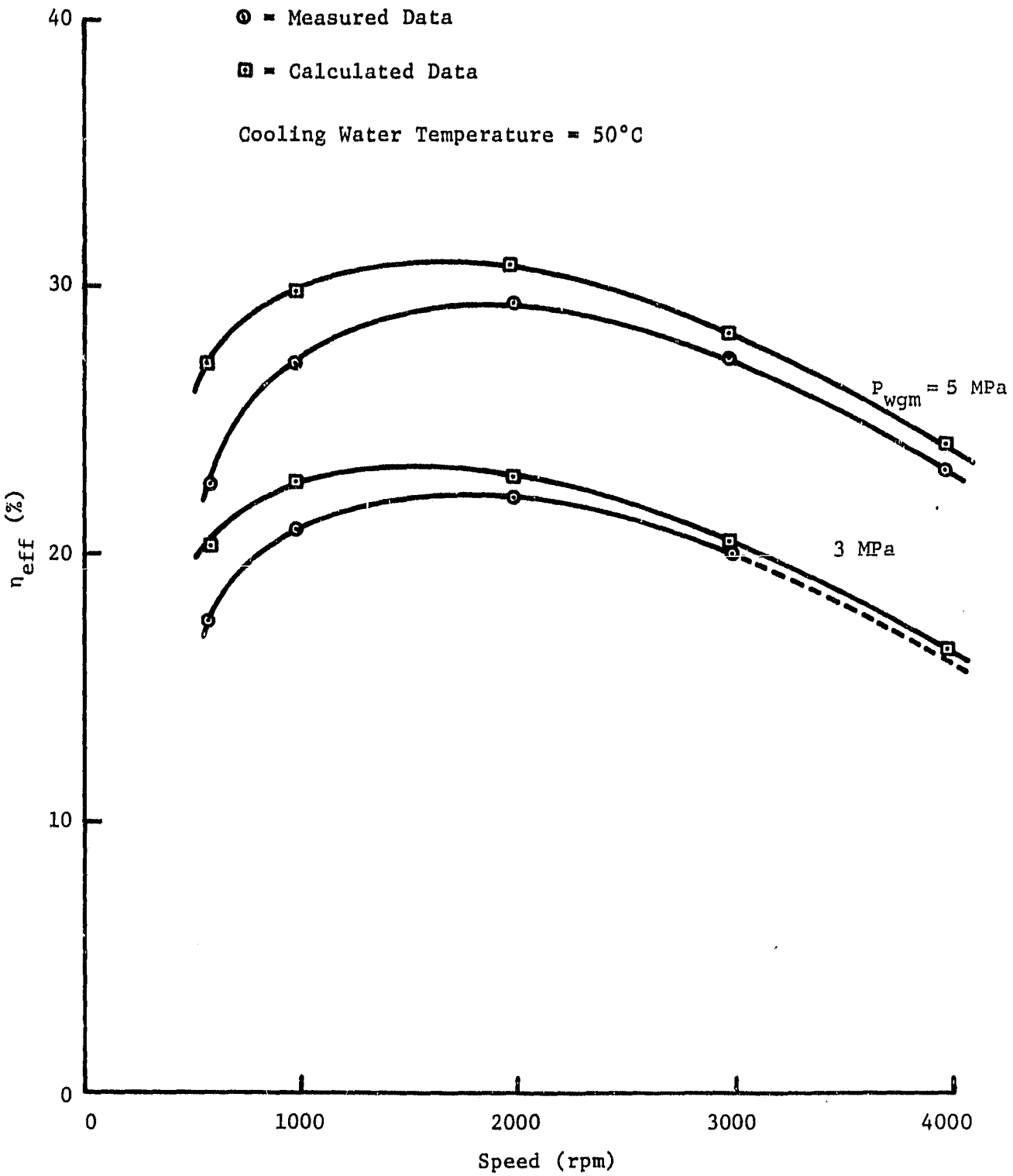

Calculated Power Output with Measured:

P_{wgm}, Speed, T_{wgbm}, T_{wcin}, M_{wc} and T_{oilae}

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Figure 4.4-4 Comparions of Measured and Calculated Efficiency of Mod I BSE No. 1

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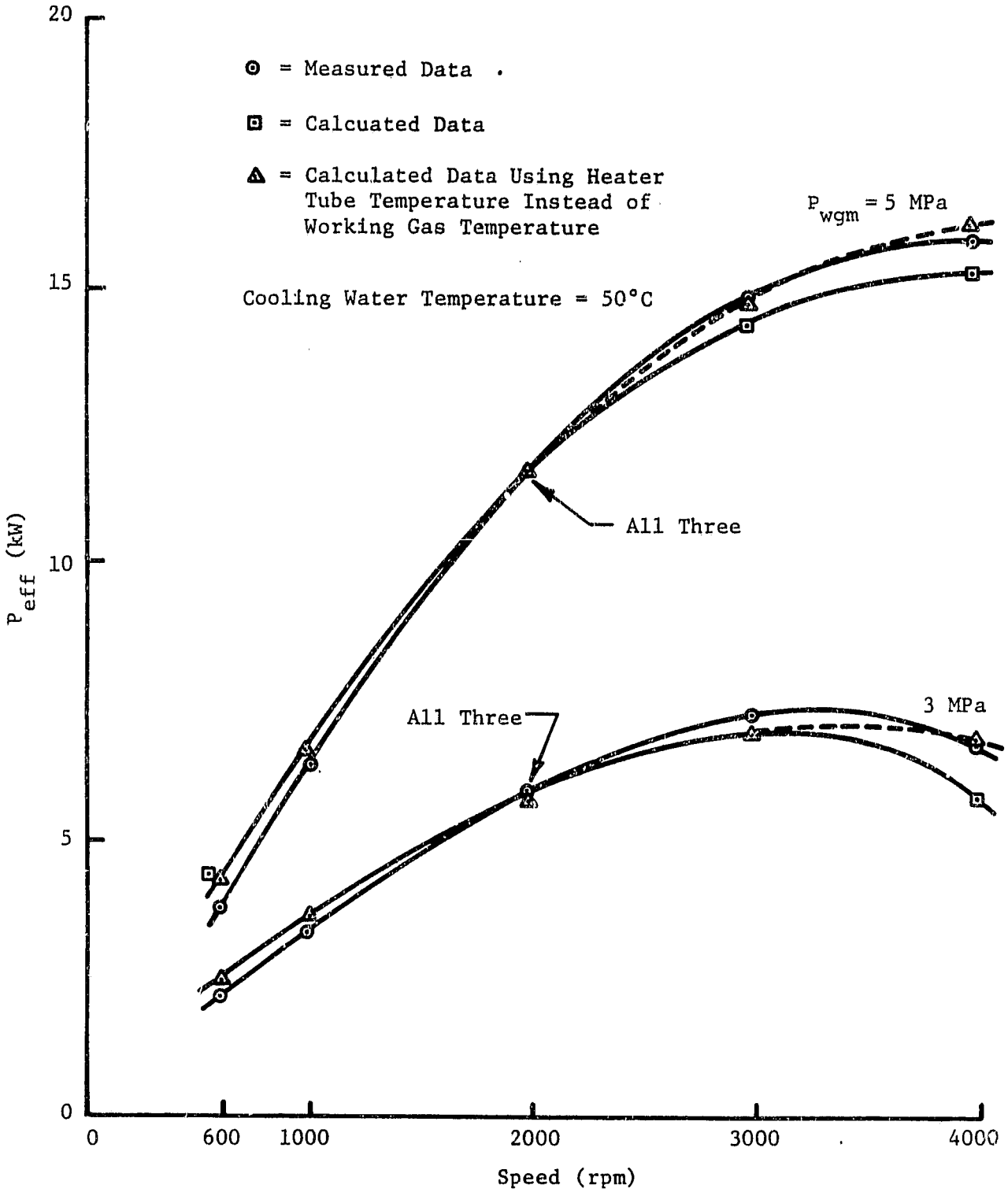

Calculated Power Output with Measured:

P_{wgm}, Speed, T_{wgbm}, T_{wcin}, M_{wc}, and T_{oilae}

813355

Figure 4.4-5 Comparison of Measured and Calculated BSE Shaft Power for the Mod I BSE No. 1

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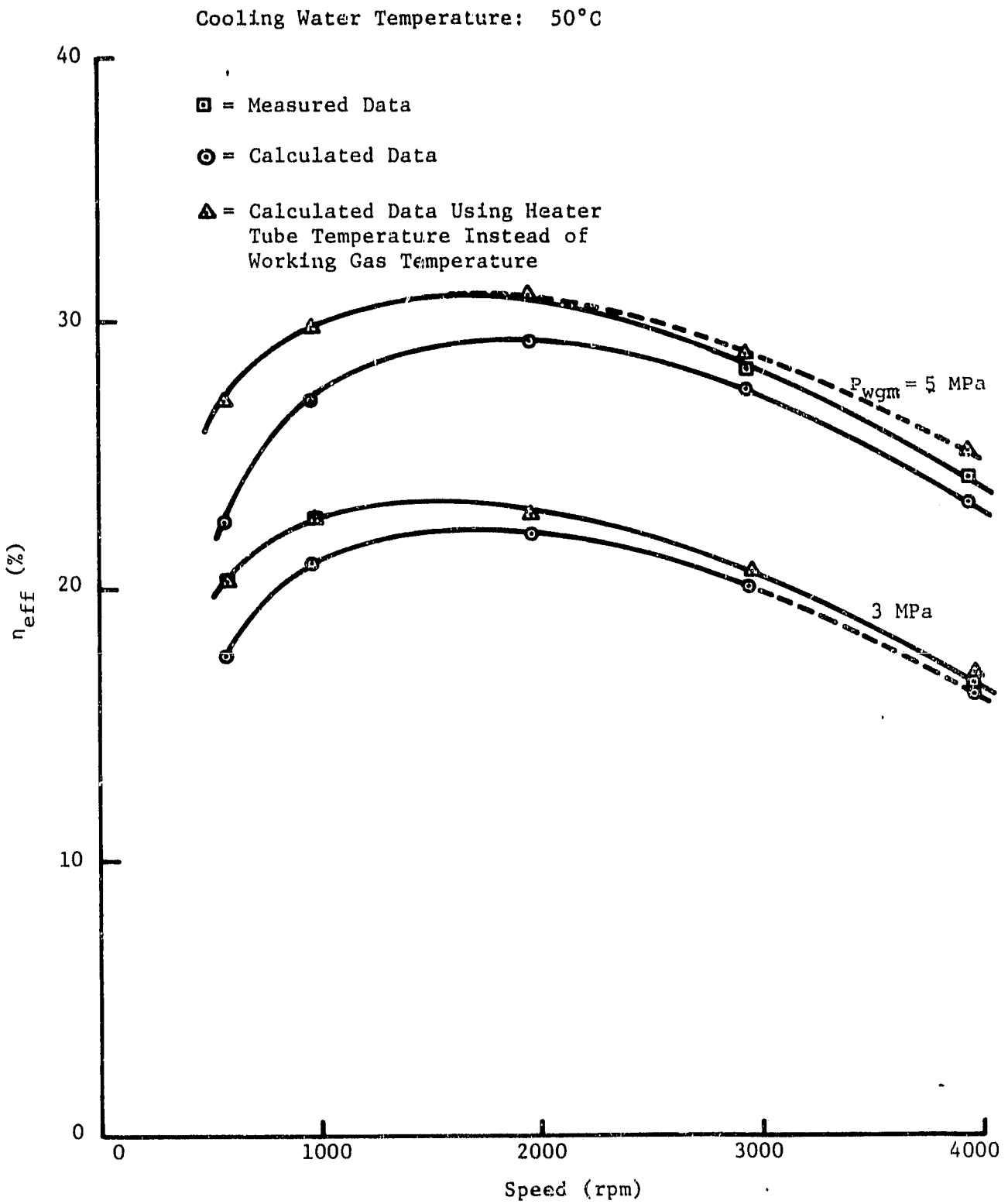

Calculated Power Output with Measured:

$\dot{P}_{wgm}$, Speed, T_{wgbm}, T_{wcin}, M_{wc} and T_{oilae}

Figure 4.4-6 Comparison of Measured and Calculated Efficiency of Mod I BSE No. 1 813355

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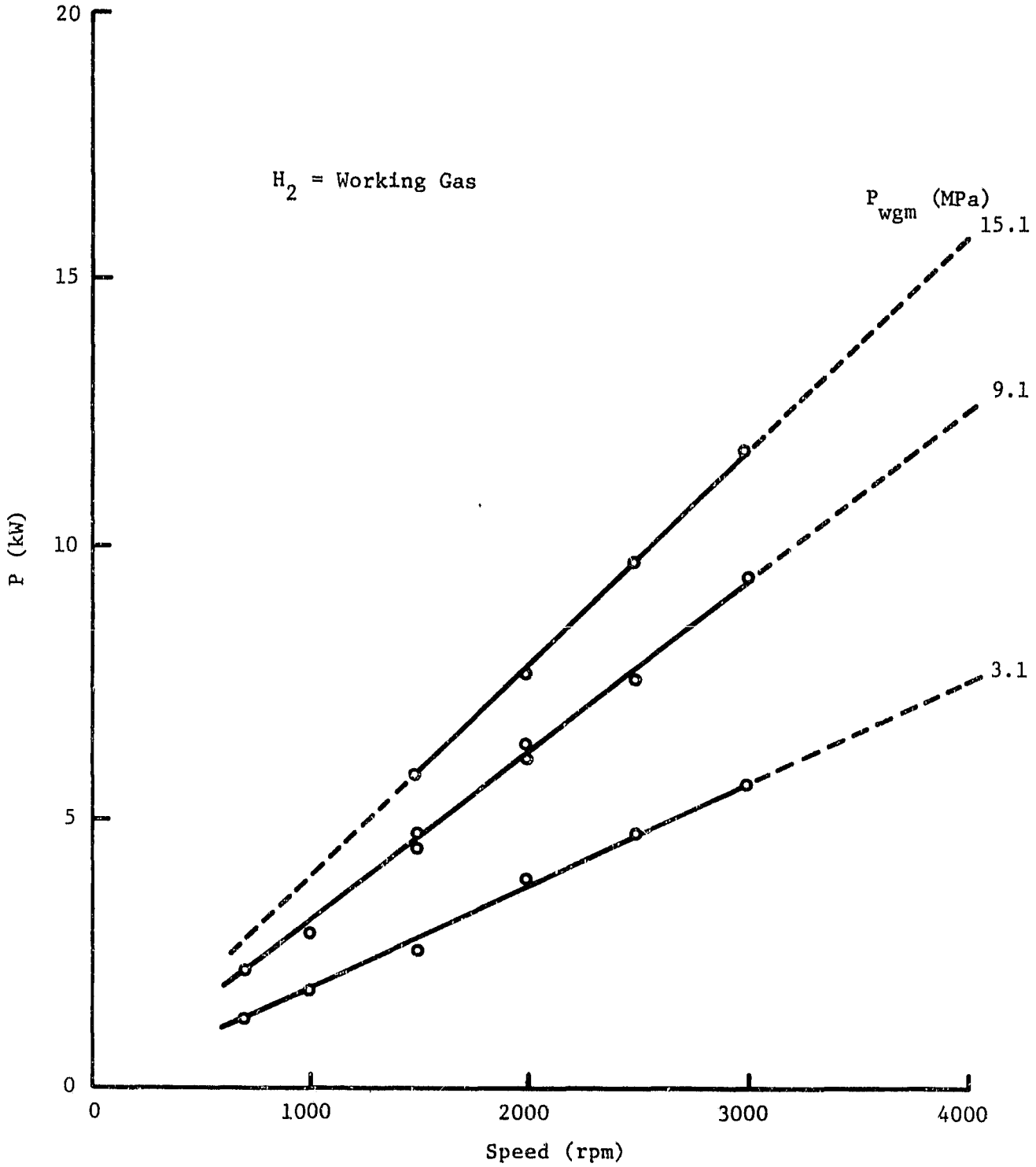

Figure 4.4-7 Mod I Drive Unit #2 Motoring Power

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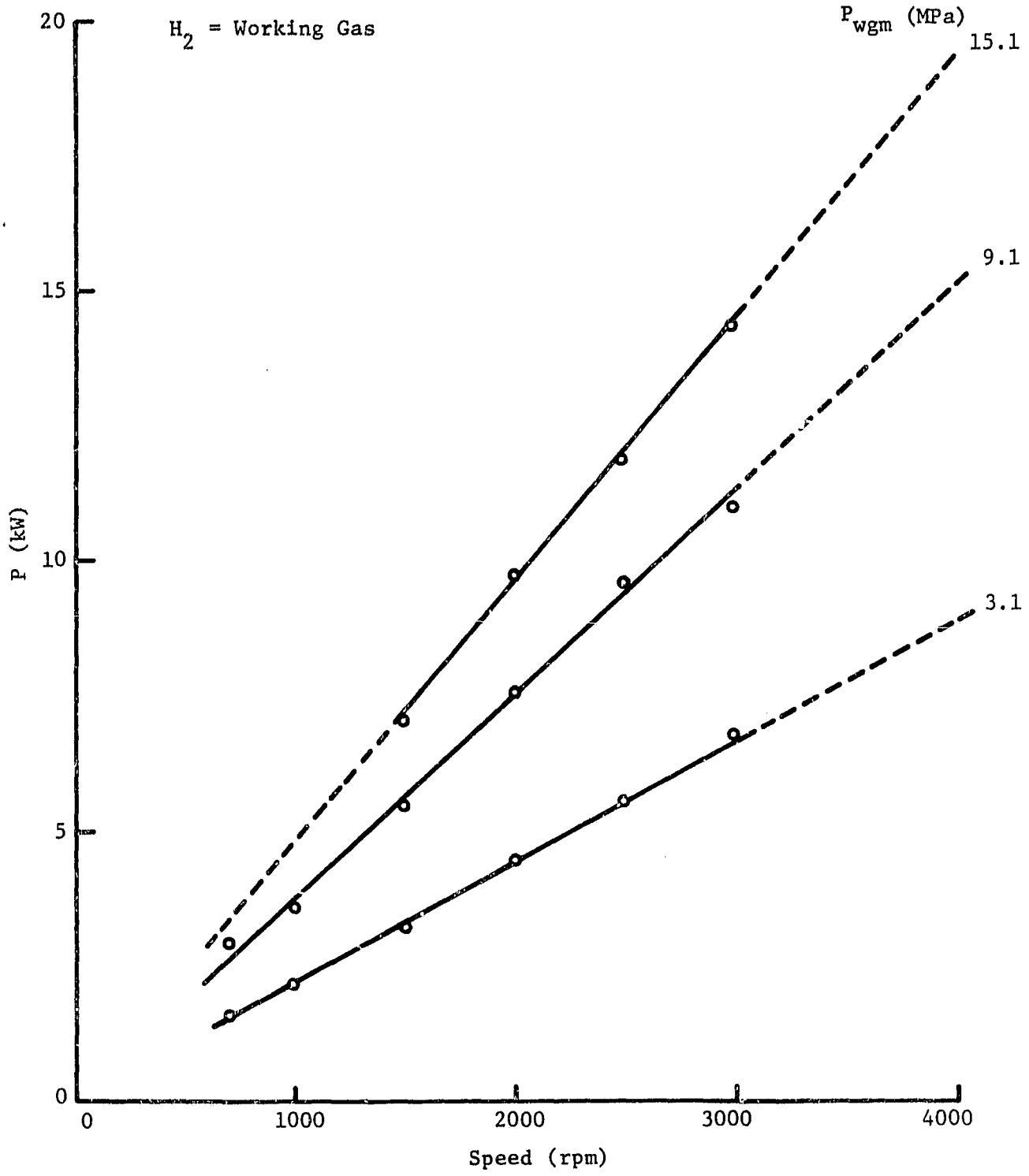

Figure 4.4-8 Mod I Drive Unit #3 Motoring Power*

*Early Data Prior to Modification

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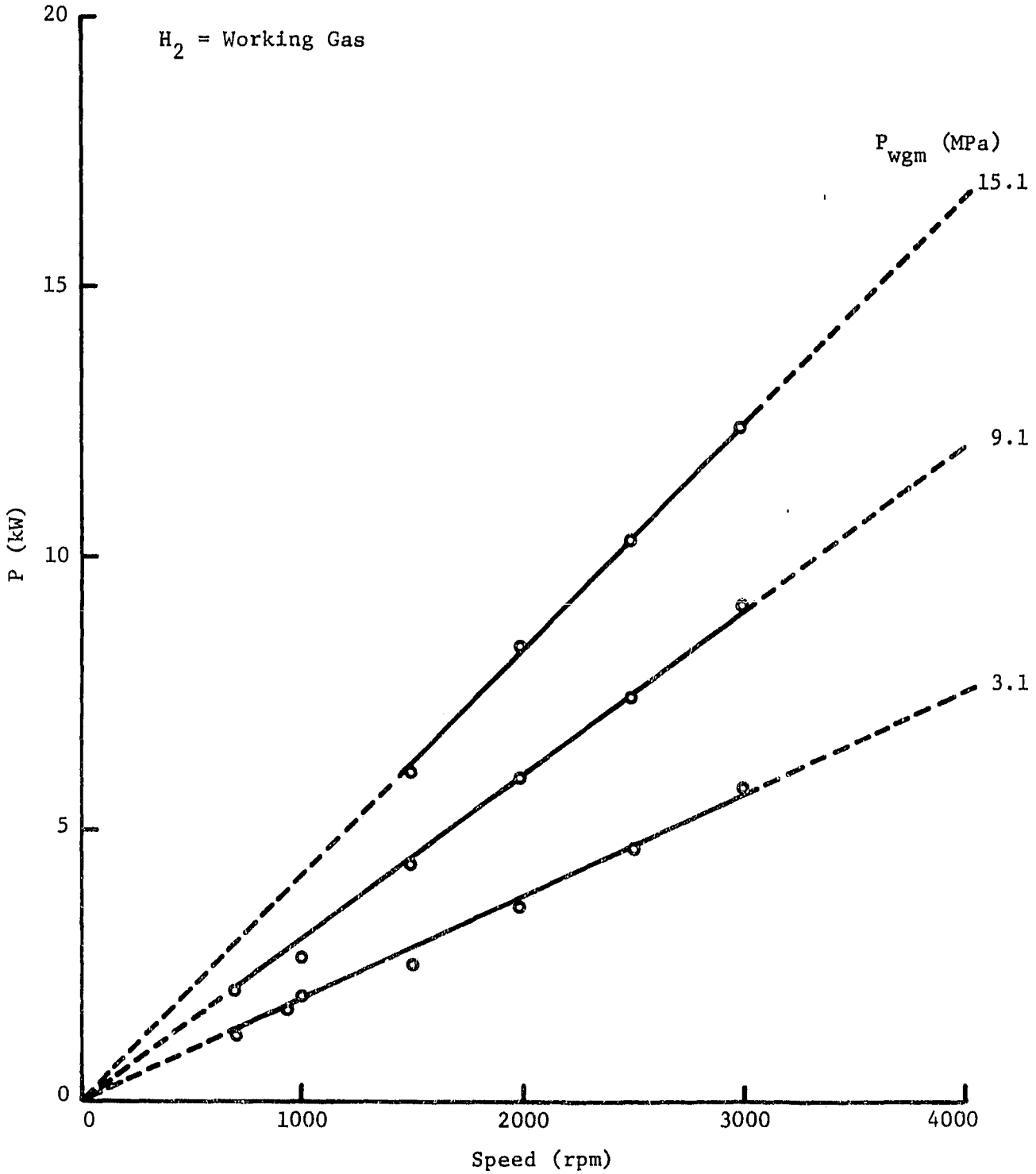

Figure 4.4-9 Mod I Drive Unit #3 Motoring Power*

*Data Recorded Just Prior to Modification

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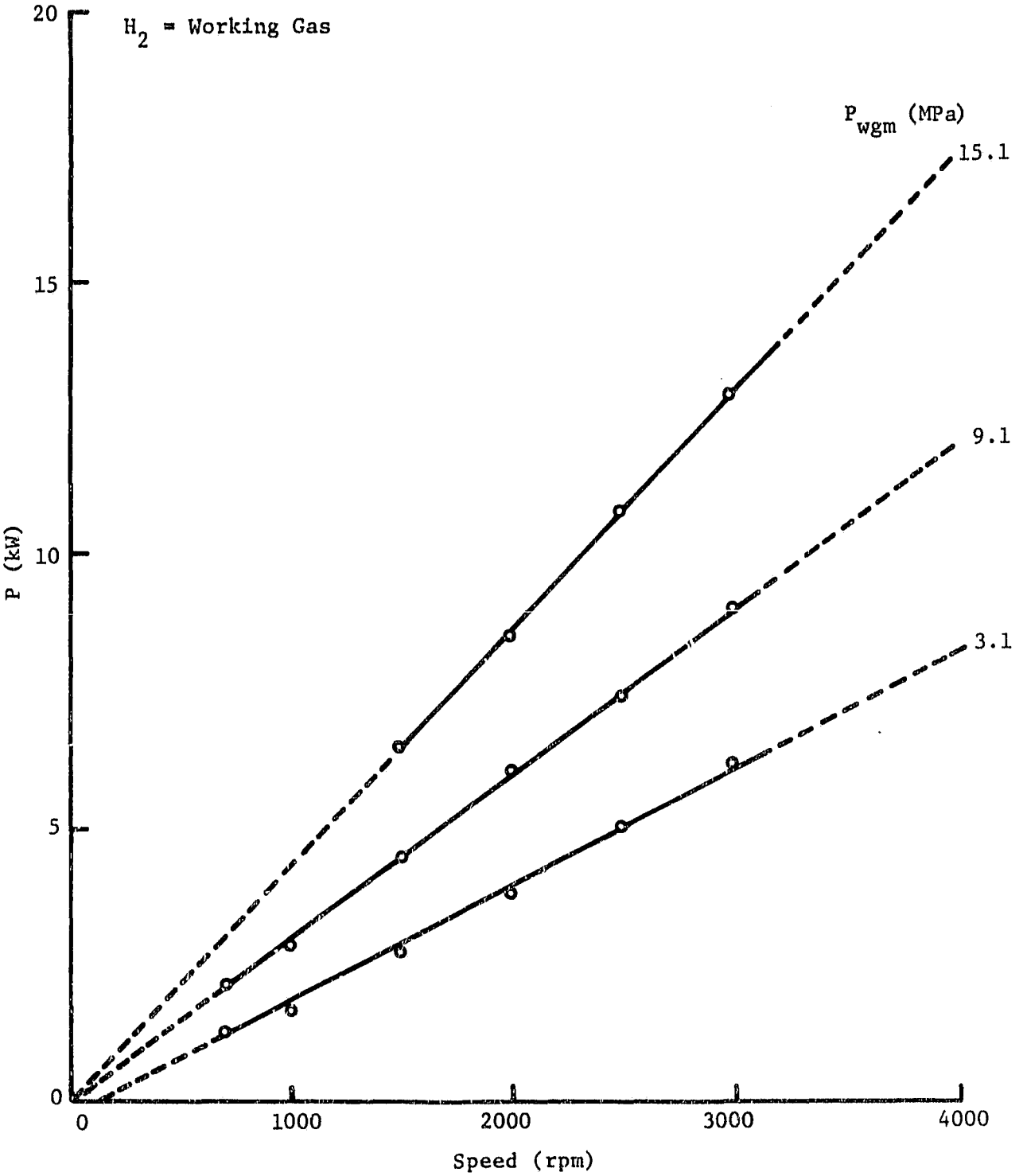

Figure 4.4-10 Mod I Drive Unit #3 Motoring Power*

*Data After Modification

813360

ENGINE: 4-123 NO: 001 VERSION: 01

READNO*		105	106	107	108	109	110	111	112	113	114
W GAS		H2	H2	H2	H2	H2	H2	H2	H2	H2	H2
Pwgm	MPa	3.06	3.05	3.07	3.07	3.07	5.02	5.08	5.09	5.09	5.08
Pratio	-	1.64	1.68	1.78	1.81	1.88	1.59	1.59	1.69	1.70	1.71
SPEED	rpm	701	1002	2002	3002	3999	703	1001	2000	3002	4000
Ttubm	deg C	725	722	721	724	721	724	721	724	722	719
dTtubm	deg C	29	60	49	44	52	48	55	49	65	96
Twgbm	deg C	719	713	706	705	697	716	709	701	691	681
dTwgbm	deg C	33	69	49	43	45	55	55	47	62	90
Twcin	deg C	49.8	49.9	50.0	49.2	49.1	49.3	49.3	49.3	49.3	49.3
Ttufm	deg C	761	762	753	766	767	760	756	770	786	804
dTtufm	deg C	33	77	42	27	36	64	50	23	14	9
Twgfm	deg C										
dTwgfm	deg C										
Twgcm	deg C										
dTwgcm	deg C										
Tcgatm	deg C	699	700	710	717	718	703	706	719	725	730
Tcgm	deg C	198	201	186	176	172	200	189	175	170	174
Toilae	deg C	59.2	61.3	73.1	79.5	85.2	67.1	66.2	74.8	79.9	87.3
LAMDAi	-	1.65	1.53	1.38	1.32	1.28	1.49	1.42	1.30	1.29	1.29
LAMDAo	-	1.34	1.32	1.28	1.25	1.24	1.29	1.28	1.22	1.22	1.23
Mfu	g/s	.34	.41	.65	.88	1.09	.45	.57	.98	1.35	1.69
Mwc	kg/s	4.02	4.07	4.30	4.63	5.07	4.02	4.08	4.32	4.66	5.08
Ma	g/s	6.9	7.8	11.9	15.7	19.1	8.5	10.5	17.3	24.1	30.4
Paaf	kPa	.24	.31	.67	1.10	1.51	.38	.54	1.30	2.24	3.23
Peff	kW	1.26	1.81	3.30	3.89	2.07	3.56	5.17	9.49	11.89	11.15
ETAeff	%	8.99	10.68	12.14	10.57	4.57	19.03	21.82	23.27	21.13	15.87
Qfu	kW	14.06	16.96	27.20	36.80	45.42	18.69	23.71	40.80	56.26	70.25
Qa	kW	.23	.28	.41	.56	.70	.32	.38	.61	.93	1.32
Qaa	kW	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04
Qog	kW	1.77	2.01	2.71	3.33	3.91	2.15	2.46	3.63	4.83	6.15
QRADp	kW	.93	.94	.95	.97	.98	.94	.95	.97	1.00	1.02
Qe	kW	11.64	14.33	23.98	33.11	41.27	15.96	20.72	36.84	51.41	64.45
ETAb	%	82.75	84.49	88.18	89.96	90.86	85.40	87.38	90.31	91.37	91.74
Qwc	kW	5.90	8.00	14.86	21.61	29.53	8.60	10.97	21.46	32.27	44.34
Qwoo	kW	.05	.05	.13	1.98	3.13	.09	.08	.20	1.98	3.51
QRADor	kW	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75
dQ	kW	3.68	3.72	4.94	4.87	5.79	2.96	3.74	4.94	4.52	4.69
dQ%	%	26.16	21.91	18.17	13.24	12.74	15.85	15.78	12.10	8.04	6.68

Table 4.5-1 Mod I Initial Performance Test Data

*See Appendix A (Engine Instrumentation Listing) for explanation.

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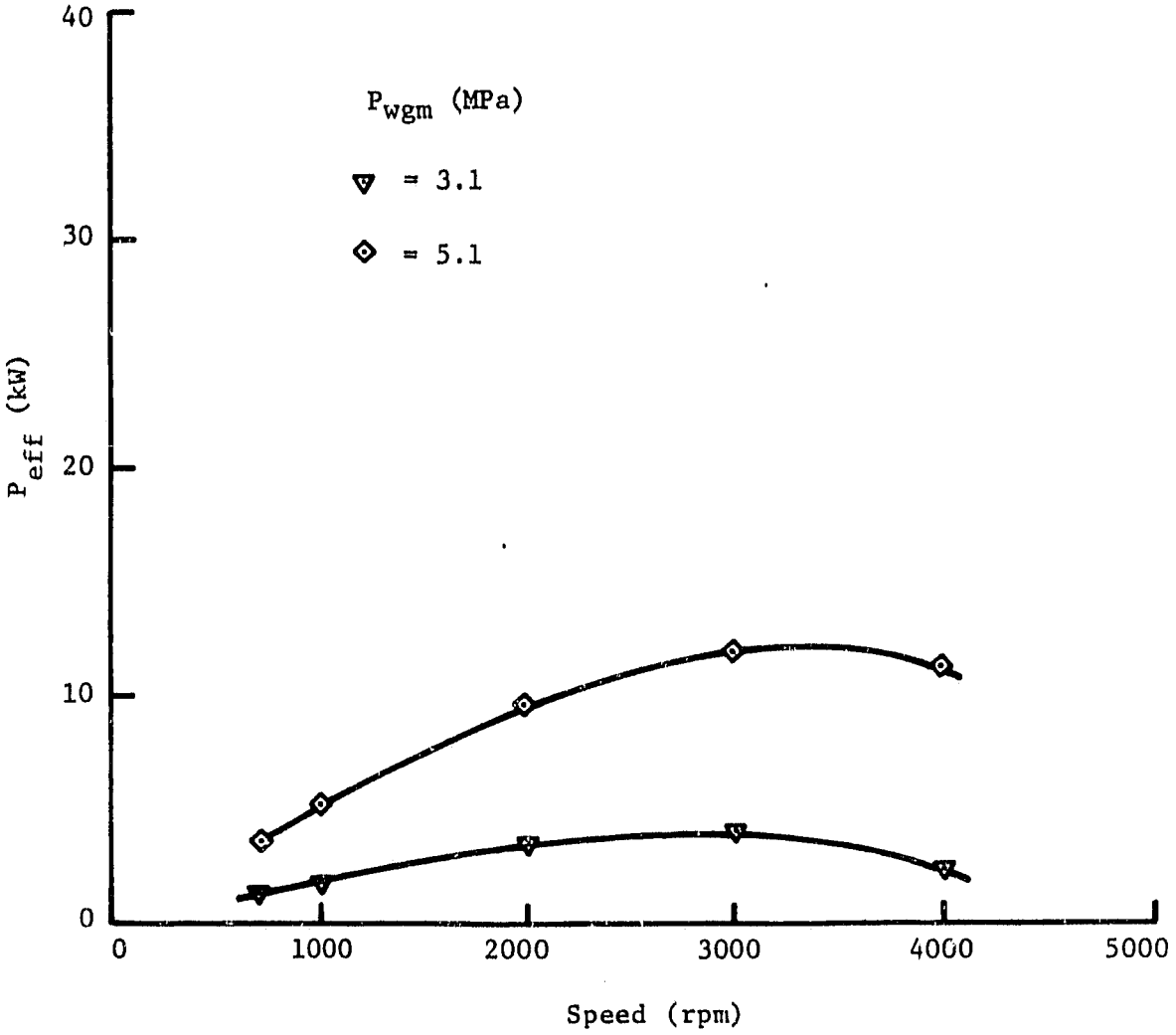

Figure 4.5-1 Mod I No. 1 — Initial SES Performance Tests Measured Power

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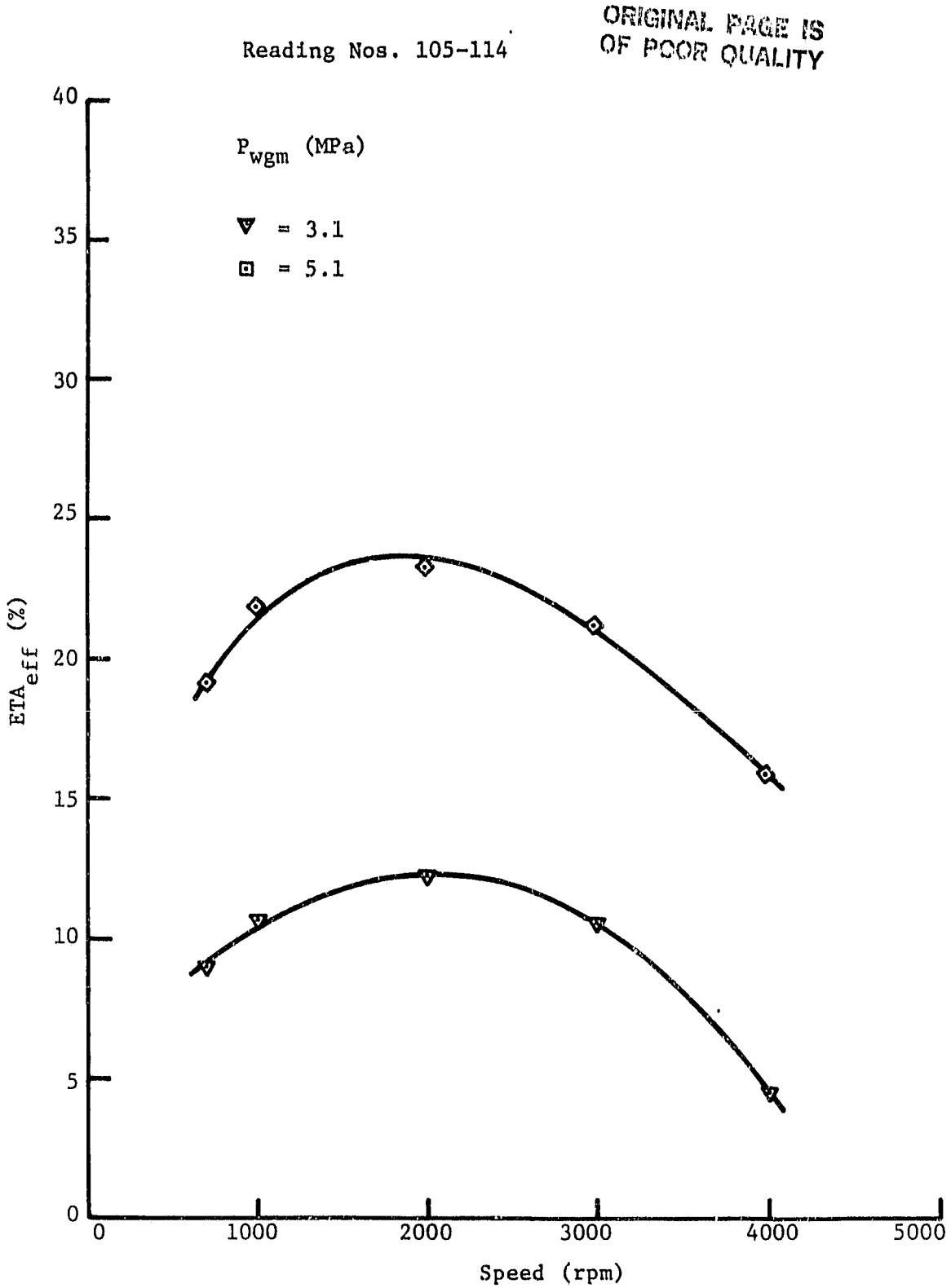

Figure 4.5-2 Mod I — Initial SES Performance Tests Measured Efficiency

R13362

The engine was dismantled in May and the following was noted:

- no damage on the gear wheels (after 13.96 hours);
- no dome-cylinder wall contact;
- ring 4-17103 on top of the regenerators was distorted;
- the regenerators were fairly hard to remove; and,
- the tubes used for the thermocouples on the front heater tube row had been burned out.

The distorted rings on top of the regenerators did not result in any changes in engine performance; however, the diameter of the regenerator housings had decreased somewhat during the test period. The thermocouple tube (TC) on Cylinder No. 2 was broken during engine disassembly. The three other heater section tubes were cracked due to the high operating temperature. The TC tube was insufficiently cooled between the heater tube and the insulation below the heater.

The engine was reassembled, and performance and emission tests were performed after 6.34 hours of running-in of the new components. After 33.54 hours of running-in, a new performance test was made at the same mean working gas pressures but with 200 rpm steps in engine speed. After 69.63 hours, the performance test was repeated. Between these performance tests, small adjustments were made to tune the SES for an optimal performance. Engine power and efficiency is shown in Figures 4.5-3 and 4.5-4.

During June, adjustments were made to improve engine performance at engine speeds below 1000 rpm. After the performance test in May, the burner blower was removed for a flat belt inspection. The belt had not been running on the central part of the pulleys, resulting in belt wear on one side. The alignment was checked and no failure was found. The pulleys were cleaned and the belt adjusted to the correct tension. Power Control Block No. 4 was replaced to cure the variator speed drop caused by a leaking valve in the hydraulic system. The atomizer air tubes were connected to a relief valve for controlling the atomizer air pressure. The following problems were encountered: the atomizer air pressure at low speeds was too low; the atomizer air pressure at high speeds was too high; the hydraulic pressure at low speeds was too low; the hydraulic oil temperatures at high speeds was high; and the burner blower airflow at very low speeds was too low.

The low atomizer air pressure (P_{aa}), hydraulic pressure (P_{hydr}), and burner blower airflow (M_a) were caused by too low a step-up on the variator, so a new bracket set was made that increased the step-up. After some modifications of the atomizer air system, sufficient values of P_{aa} and P_{hydr} at an engine speed of 600 rpm were obtained. The M_a problem was not completely solved. A new ratio variator belt drive (prime part) will be tested that will increase the value of M_a at an engine speed of 600 rpm so that $\leq$ 9 MPa mean working gas pressure can be run at 600 rpm.

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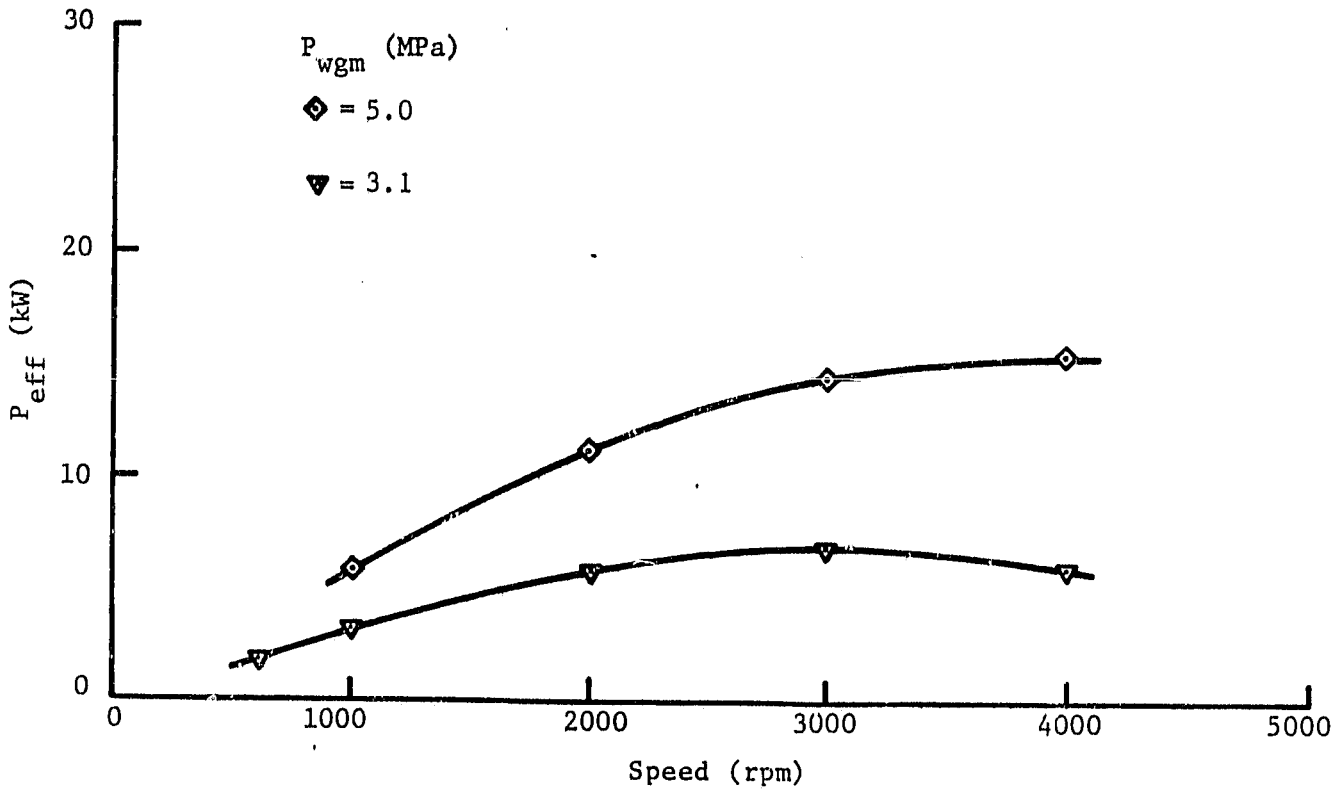

Figure 4.5-3 Mod I Engine No. 1 SES Performance Test After Rebuild — Measured Power

813363

A new high-tensile strength main drive shaft was mounted and tested together with the 0.8 module gear wheels. A new heater head was also tested. The clearance between the cylinder manifolds had to be adjusted before further testing could be resumed. Total hours on the Mod I BSE/SES at the end of this quarter were 172.1 hours; 101.1 hours were accumulated in the SES Configuration.

Motoring Test - Mod I No. 2

The motoring test of Mod I No. 2 was completed in April. Inspection after the motoring test showed one discrepancy from normal condition - the transmission gears had cracked teeth.

The assembly work of the BSE was started in May; however, assembly start was delayed about three weeks, with completion scheduled during the first week of June.

Motoring Test - Mod I No. 3

The motoring unit was assembled in April with spur gears. Breaking in of the motoring unit was started in April, and the motoring test was finished in May. The motoring unit was inspected and shipped to MTI in June. The motoring unit was tested with different cylinder liners of steel and nodular iron.

Mod I Mock-Up - SES No. 2

The mock-up of SES No. 2 was finished in April. All equipment was moved over to Engine No. 1. Buildup of a new SES for Engine No. 2 was also started. Hardware such as brackets and tube fittings were modified in May according to findings from the assembly work of SES No. 1.

Photos of the Mod I are contained in Figures 4.5-5 through 4.5-7.

Task 4.6 - Vehicle Test Program

Mod I Vehicle System Development

Based on Mod I system performance and fuel economy optimization studies, the following drivetrain components were selected in April for the first vehicle build:

- Chrysler wide-ratio, three-speed automatic transmission;
- 10 3/4"-high stall-torque converter with lockup; and,
- 2.73 : 1 rear axle ratio.

USSw, AMG, and MTI personnel attended a coordination meeting in June on the vehicle installation. The main topic was the final location of control system components. Control Blocks Number 1, 2, and 3 were mounted on the vehicle and connected to the engine through flexible-wire braid-covered lines. This will improve the ease of maintenance.

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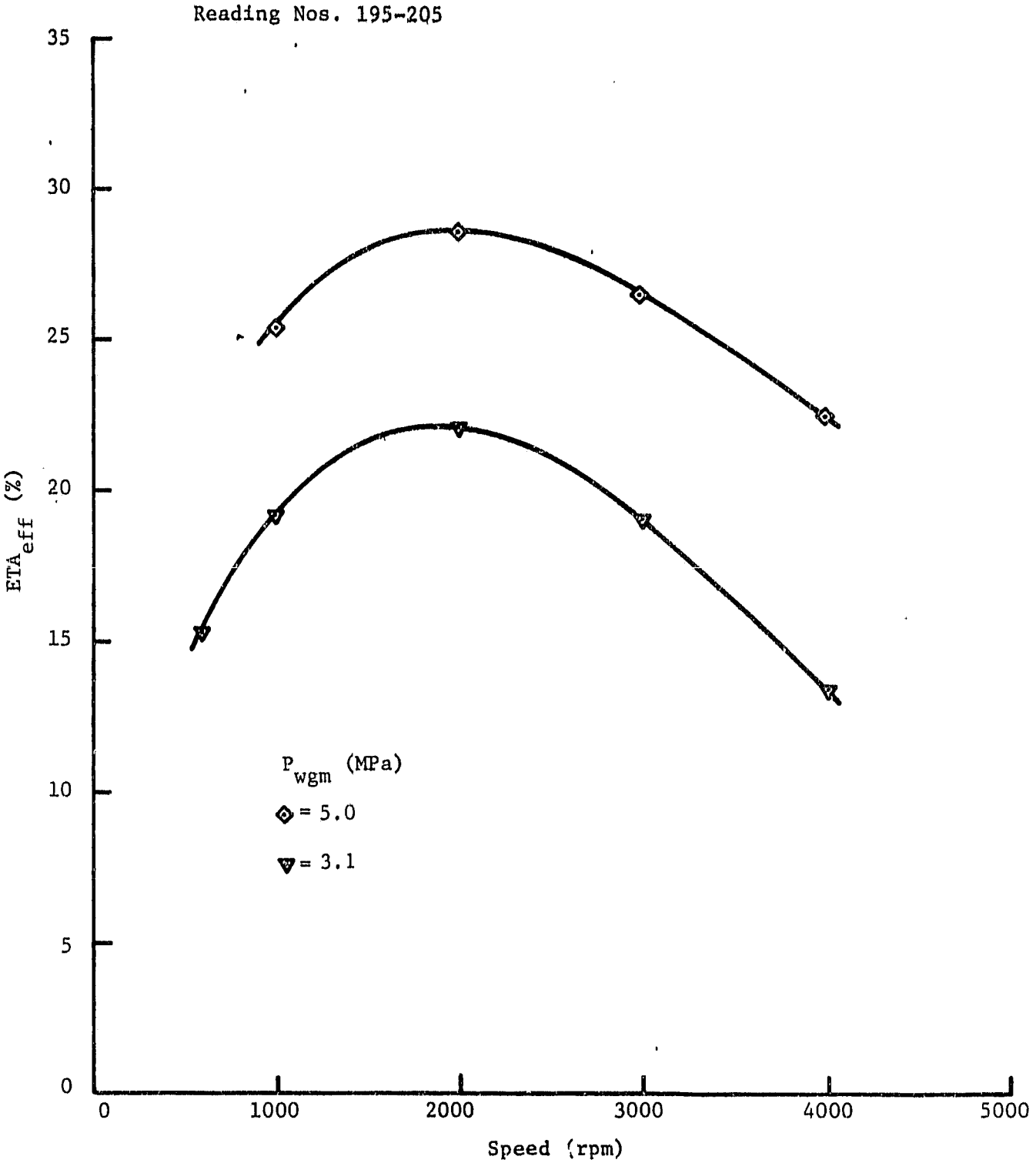

Figure 4.5-4 Mod I Engine No. 1 SES Performance Test After Rebuild — Measured Efficiency

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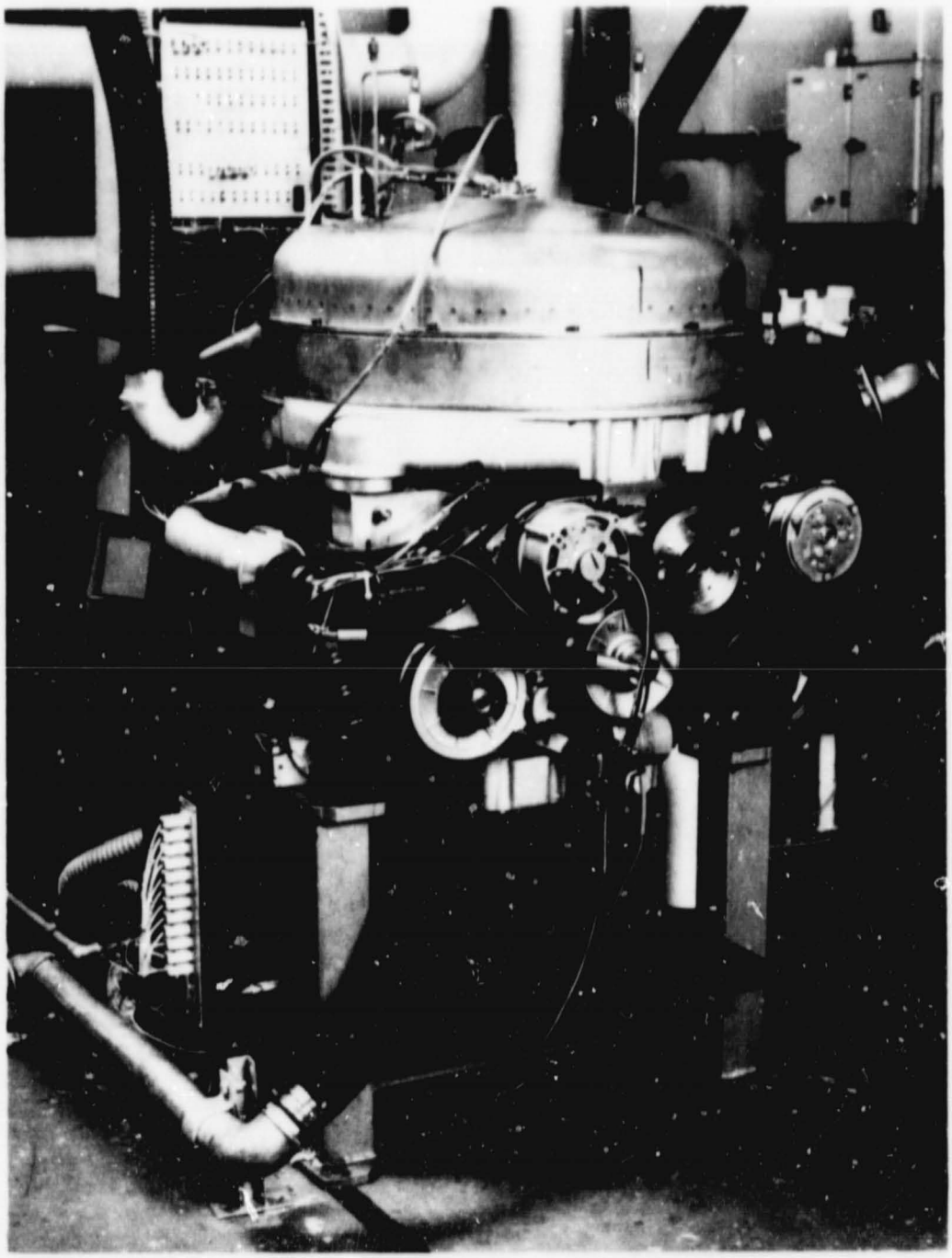

Figure 4.5-5 Mod I Basic Stirling Engine on Test Stand on USSw

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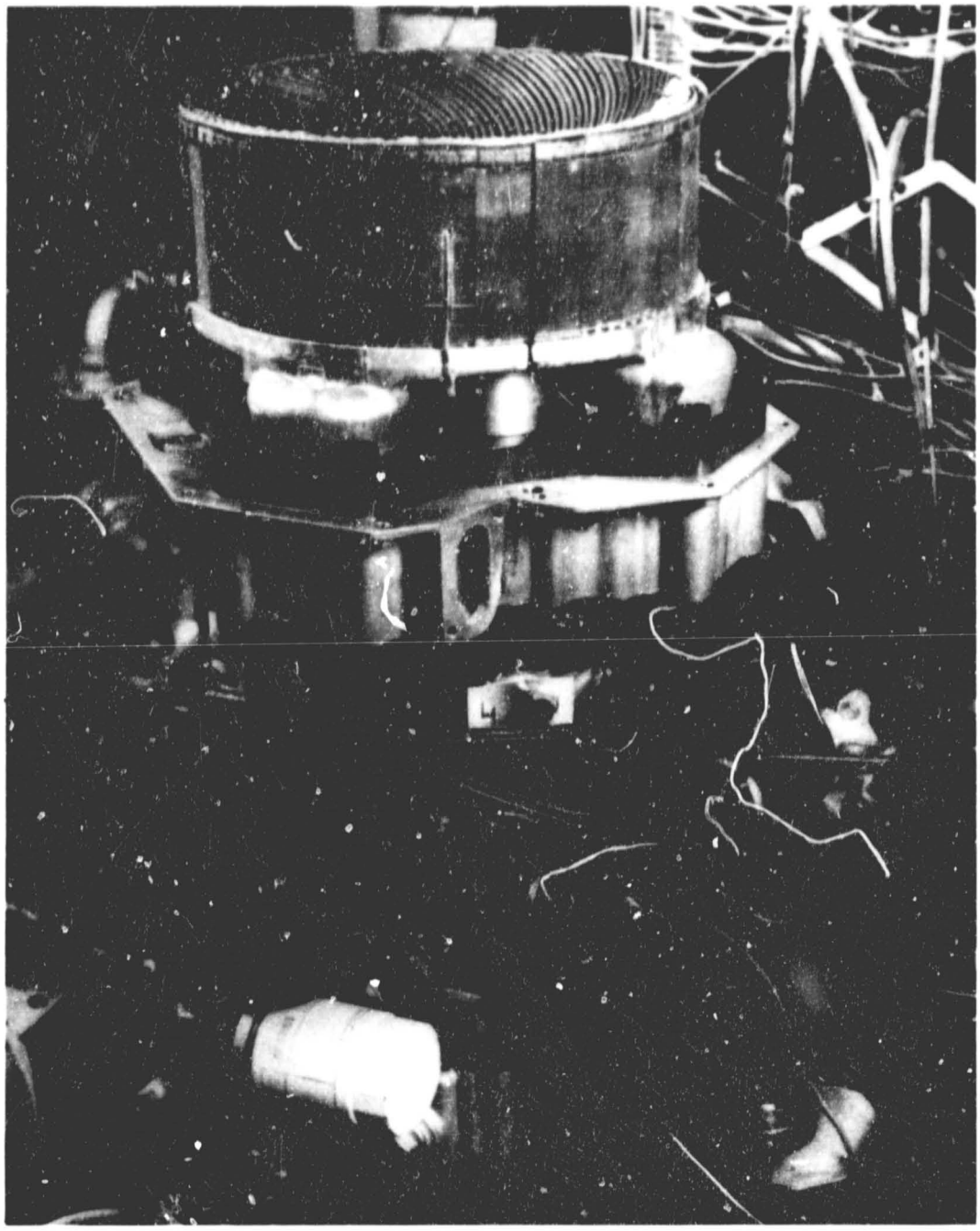

Figure 4.5-6 Mod I BSE with Combustor and Preheater Removed to Show Heater Head

C-2

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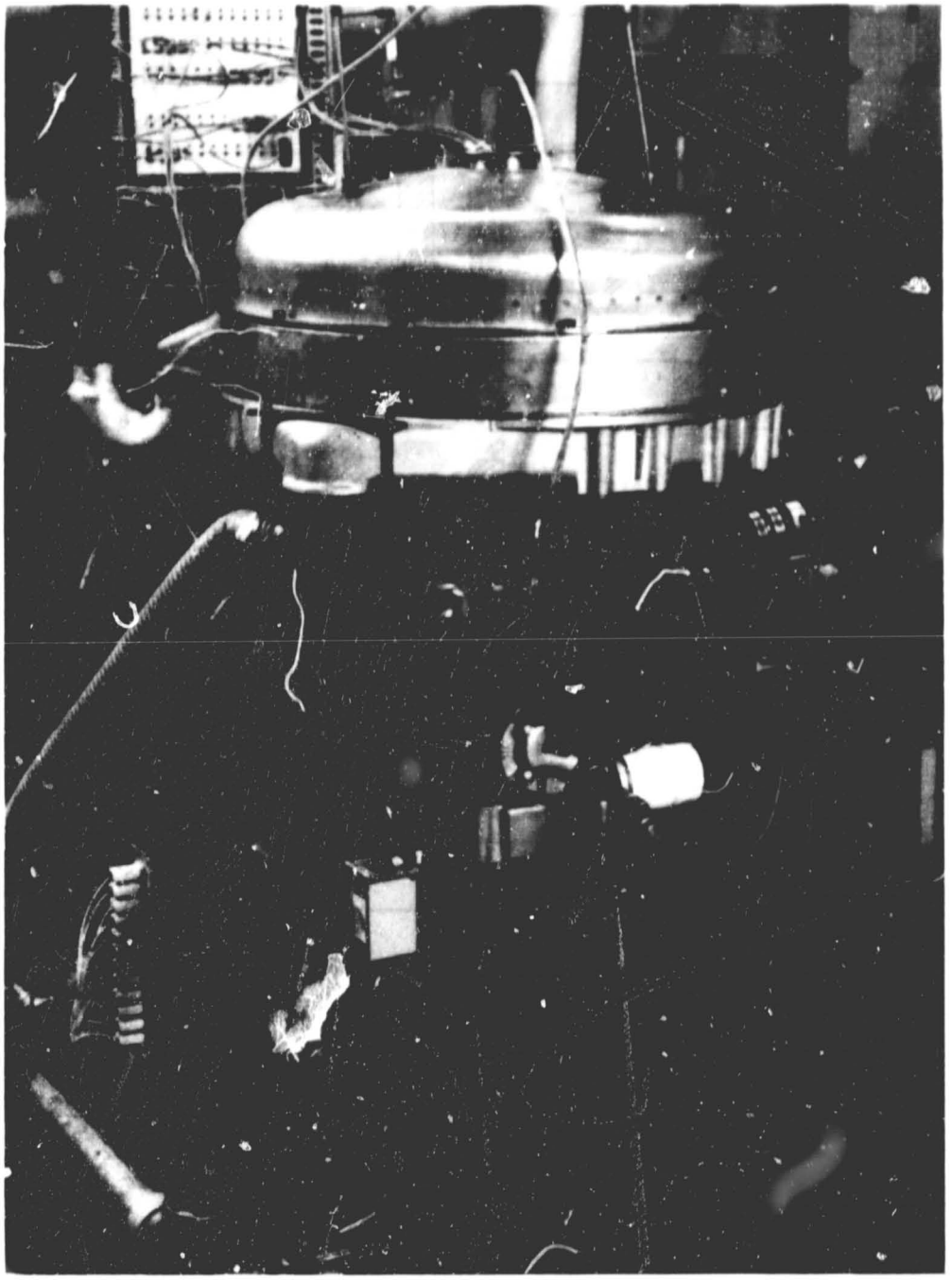

Figure 4.5-7 Mod I Complete Stirling Engine System on Test Stand at USSw

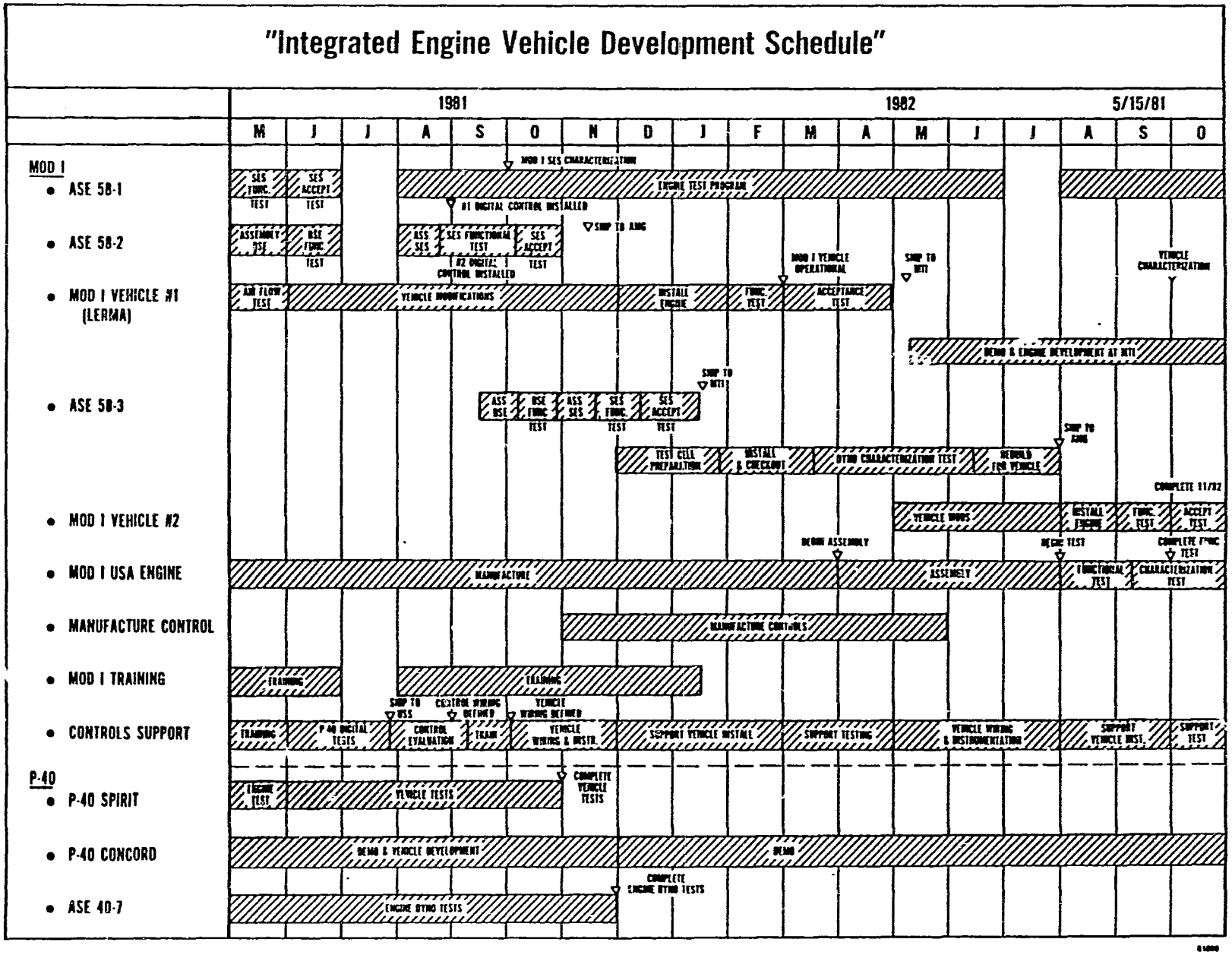
"Integrated Engine Vehicle Development Schedule"
1981
1982
5/15/81
M J J A S O N D J F M A M J J A S O
MOD I
ASE 58-1
ASE 58-2
MOD I VEHICLE #1 (LERMA)
ASE 58-3
MOD I VEHICLE #2
MOD I USA ENGINE
MANUFACTURE CONTROL
MOD I TRAINING
CONTROLS SUPPORT
P-40
P-40 SPIRIT
P-40 CONCORD
ASE 40-7
MOD I SES CHARACTERIZATION
ENGINE TEST PROGRAM
#1 DIGITAL CONTROL INSTALLED
SHIP TO AMG
#2 DIGITAL CONTROL INSTALLED
MOD I VEHICLE OPERATIONAL
SHIP TO NTI
VEHICLE CHARACTERIZATION
VEHICLE MODIFICATIONS
INSTALL ENGINE
ACCEPTANCE TEST
DEMO & ENGINE DEVELOPMENT AT NTI
TEST CELL PREPARATION
INSTALL & CHECKOUT
DYNO CHARACTERIZATION TEST
REBUILD FOR VEHICLE
COMPLETE 11/82
VEHICLE MODS
DEGRIF ASSEMBLY
MANUFACTURE
ASSEMBLY
FUNCTIONAL TEST
CHARACTERIZATION TEST
MANUFACTURE CONTROLS
TRAINING
SHIP TO USS
CONTROL WIRING DEFINED
VEHICLE WIRING DEFINED
P-40 DIGITAL TESTS
CONTROL EVALUATION
TRAIN
VEHICLE WIRING & INSTR.
SUPPORT VEHICLE INSTALL
SUPPORT TESTING
VEHICLE WIRING & INSTRUMENTATION
SUPPORT VEHICLE INST.
SUPPORT TEST
COMPLETE VEHICLE TESTS
VEHICLE TESTS
DEMO & VEHICLE DEVELOPMENT
DEMO
COMPLETE ENGINE DYNO TESTS
ENGINE DYNO TESTS

Figure 4.6-1

Wir g layout work was initiated at MTI in June, and will be coordinated with AMG, who will construct the actual wiring harnesses. Definition of the dashboard display and instrumentation requirements was also initiated.

Figure 4.6-1 shows the latest integrated engine/vehicle development schedule for the Mod I and P-40 engines.

Task 4.7 - U.S.A. Mod I Build

Drive Unit

A complete drive unit was scheduled for delivery to MTI by September 30, 1981.

Cold Engine System

The piston domes were received in April from C.B. Kaupp & Sons. The domes were EB-welded to the lower parts (on order from Centurian Industries). Delivery of the completed assemblies was expected in mid-November. Five domes were provided to United Stirling.

In May, the cylinder liner material selected was 410 SS with a nitrided inner diameter. This material was chosen over cast iron due to its anticorrosion properties. At the end of May, activity on pistons and rods was awaiting the receipt of the latest drawings from USSw.

External Heat System

In April, an investigation of ceramic preheaters was started at Corning Glass Works. Corning furnished heat transfer data on their matrix design, and also looked into a ceramic lower cone for the combustor.

The combustor was released for quotes in June, followed by the release of the remainder of the system in August.

Hot Engine System

By the end of May, Precision Castparts Corp. (PCC) had poured 20 cylinder housings. The first pour revealed some hot spots which resulted in shrinkage. This information was used to reconfigure the pouring of the regenerator housings in mid-June. Inconel 625 heater head tubes were also sent to the vendor for bending.

A second casting of the heater head cylinder and regenerator housings at PCC was scheduled for July. More ceramic cores were ordered in June to meet the casting schedule. Sample heater head fins were delivered and approved in June, completing the order. Heater tubes are due at MTI in July.

MAJOR TASK 7.0 - COMPUTER PROGRAM DEVELOPMENT

The interim version of STENSY was delivered to NASA/LeRC during the first week of April. The "User's Instructions" were also completed and released. The user's manual includes a complete listing of the current version of STENSY. Some modifications relative to the interim source code were made to correct a programming error and to improve the program output. The Mod I validation of the STENSY Code will continue in the next quarter.

MAJOR TASK 8.0 TECHNICAL ASSISTANCE

- Total Number of Technical Directives received to date: 81
- Number of active TD's: 3
- Summary of open/active TD's:

TD #74 - Routine Maintenance of Demonstration Vehicle

ASE 40-12 was rebuilt and the vehicle is now available for demonstrations.

The following demonstrations utilized the P-40 Concord Vehicle:

At MTI	Date
NASA and Senator D'Amato's staff	June 19, 1981
Channel 10 (Albany - TV)	June 24, 1981
Former Senator J. Durkin	June 26, 1981

MAJOR TASK 9.0 - PROGRAM MANAGEMENT

Product Assurance

The Pressure Test Rig was completed at MTI for P-40 heater head quadrants.

All equipment required to perform dye penetrant tests was received at MTI.

All heater head quadrants available at MTI were examined and pressure tested. The results are shown in Table 9.0-1.

A problem report closeout meeting (81-2) was held at NASA in May. The results were:

- 35 Failure Notices were closed;
- 117 Discrepancy Notices were closed;
- 3 Quality Assurance Reports were closed;
- 18 Failure Notices were deferred for further action;
- 14 Discrepancy notices were deferred for further action; and,
- 15 Quality Assurance reports were deferred for further action.

Table 9.0-2 summarizes the Failure, Discrepancy, and Quality Assurance Reports as of June 30, 1981.

Table 9.0-3 is a summary of operating times versus failures for all ASE Program engines.

PART NO.	SERIAL NO.	CYCLE LOCATION	HOURS ON QUAD.	ENGINE NO.	LOCATION OF OBSERVATION	PRESSURE TEST	PENETRANT INSPECTION	REPORT NO.	COMMENTS	REPAIR
12640	27	3	103.3	40-12	Tube failure. Cut adjacent tube. Two cracks outside each of 2 cyl. center holes(inside)	N/A	Indications 4/15/81	MQ-11		
12640	25	1	184	40-12	Joint at 9th tube from outside of cyl. manifold. Two cracks outside each of 2 cyl. center holes(inside)	Engine (Leak)	Indications 4/15/81	MQ-10 MQ- 2		
12640	5	1	245	40- 8	L.P.showed 2 cracks. Center ports cyl.(inside) Center port of end reg.	4/10/81 (TIGHT)	4/3/81	MQ-4LP		
12640	8	4	245	40- 8	L.P. showed 3 indications across center outside of 2 ports in cyl.	4/14/81 (TIGHT)	Indications 4/14/81	MQ- 9		
12640	7	3	245	40- 8	Joint @tube & reg. casting Last tube L.P.showed crack @inside of cyl.@center port	4/13/8 (Leak)	Indications 4/3/81	MQ- 8PT MQ- 3LP		
12640	6	2	245	40- 8	Crack in manifold	Engine (Leak)	Indications on Outside	Met. Report #6 3/18/81	Cut up for analysis	
12909	1	1	35	40- 7		4/10/81 (TIGHT)	No Indic. 4/14/81			NASA Tube Repair
12640	26	2	184	40-12	Crack inside of cyl. hsg. between 2 ctr holes	On Engine (TIGHT)	Indications 4/13/81	MQ- 5LP		
12640	28	4	184	40-12	Two cracks inside cyl. hsg. -between center holes -outside of 1 of 2 ctr hls.	On Engine (TIGHT)	Indications 4/13/81	MQ- 7LP		
12640	19	3	70.9	40-12	Two cracks inside of cyl. hsg. cracks on outside of each of 2 center holes	On Engine (TIGHT)	Indications 4/13/81	MQ- 6LP		
12640	20	-	0.0	-		4/15 OK	4/15 NONE	-		
12640	57	-	0.0	-		4/15 OK	4/15 NONE	-		
12640	49	1	10.5	8		Tight	No Indication	-		
12640	51	2	10.5	8		Tight	No Indication	-		
12640	53	3	10.5	8		Tight	No Indication	-		
12640	54	4	10.5	8		Tight	No Indication	-		

Table 9.0-1 Heater Head Status

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Summary of Failure Notices/Quality Assurance Reports

Open Failure Notices	26
New Failure Notices since May 31, 1981	0
Failure Notices closed since May 31, 1981	0
Closed Failure Notices (total to date)	205
Total Failure Notices in System	231
P-40 Failure Notices	198
Mod I Failure Notices	33

Summary of Discrepancy Notices/Quality Assurance Reports

Open Discrepancy Notices	48
New Discrepancy Notices since May 31, 1981	0
Discrepancy Notices closed since May 31, 1981	0
Closed Discrepancy Notices (total to date)	218
Total Discrepancy Notices in System	266
P-40 Discrepancy Notices	145
Mod I Discrepancy Notices	121

Summary of Quality Assurance Reports

Open Quality Assurance Reports	61
New Quality Assurance Reports since May 31, 1981	31
Quality Assurance Reports closed since May 31, 1981	0
Closed Quality Assurance Reports (total to date)	3
Total Quality Assurance Reports in System	64
P-40 Quality Assurance Reports	45
Mod I Quality Assurance Reports	19

Table 9.0-2 Summary of Failure, Discrepancy and Quality Assurance Reports as of June 30, 1981

Engine	Operation Time	Mean Operating Time to Failure (hrs)*
ASE 40-1 (NASA)	238.0	6.43
ASE 40-7 (MTI)	206.0	7.95
ASE 40-8 (Spirit)	292.44	3.75
ASE 40-12 (Concord)	140.4	14.04
ASE 40-4 (USSw)	6134.46	91.56
ASE 58-1 (USSw)	172.06	15.64

Table 9.0-3 Summary of Accumulated Operation Time for ASE Engines and Mean Operating Time to Failure

*All classes of failures, since initial start of the engine, are included in the calculation of mean time to failure. This includes, for example, replacement of components due to residual core particles in engine due to improper cleaning, burner blower belt failure, cracked spark plug, etc.

4.0 REFERENCES

1. "Assessment of the State of Technology of Automotive Stirling Engines." MTI Report No. 79ASE77RE2 (available as Government Report DOE/NASA/0032-79/4 or NASA CR-159631 from NTIS).

2. "Compact Heat Exchangers," Kays, William and London, A.C. Second Edition New York: McGraw Hill, 1955.

3. "The Heat Transfer and Friction Flow Characteristics of Regenerator Matrices of Steady Cycle Machine." V. Vashista's Masters thesis, University of Calgary.

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0  0  0    0     ON 4-123 STIRLING ENGINES (MOD 1)    Table    #
0  0   0    0    DURING ACCEPTANCE TESTS              Document #
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NAME	EXPLANATION
Pvgm	* MEAN VALUE OF THE MEAN PRESSURES IN THE CYLINDERS (MPa)
SPEED	ENGINE SPEED (rpm)
B-SPEED	Burner blower speed
Ttubm	* MEAN VALUE OF THE HEATER TEMPERATURES, 2nd TUBE ROW
Twgbm	* MEAN VALUE OF THE WORKING GAS TEMPERATURES, 2nd TUBE ROW
Twein	COOLING WATER TEMPERATURE, INLET OF ENGINE
Ttuf1	HEATER TEMPERATURE, 1st TUBE ROW, SECTOR No 1
Ttuf2	HEATER TEMPERATURE, 1st TUBE ROW, SECTOR No 2
Ttuf3	HEATER TEMPERATURE, 1st TUBE ROW, SECTOR No 3
Ttuf4	HEATER TEMPERATURE, 1st TUBE ROW, SECTOR No 4
Ttufm	* MEAN VALUE OF HEATER TEMPERATURE, 1st TUBE ROW
Ttub1	HEATER TEMPERATURE 2nd TUBE ROW SECTOR NO. 1
Ttub2	HEATER TEMPERATURE 2nd TUBE ROW SECTOR NO. 2
Ttub3	HEATER TEMPERATURE 2nd TUBE ROW SECTOR NO. 3
Ttub4	HEATER TEMPERATURE 2nd TUBE ROW SECTOR NO. 4
Twgb1	WORKING GAS TEMPERATURE, 2nd TUBE ROW, CYCLE No 1
Twgb2	WORKING GAS TEMPERATURE, 2nd TUBE ROW, CYCLE No 2
Twgb3	WORKING GAS TEMPERATURE, 2nd TUBE ROW, CYCLE No 3
Twgb4	WORKING GAS TEMPERATURE, 2nd TUBE ROW, CYCLE No 4
Tegat1m	*COMBUSTION GAS TEMPERATURE, AFTER TUBES, SECTOR No 1
Tegat2m	*COMBUSTION GAS TEMPERATURE, AFTER TUBES, SECTOR No 2
Tegat3m	*COMBUSTION GAS TEMPERATURE, AFTER TUBES, SECTOR No 3
Tegat4m	*COMBUSTION GAS TEMPERATURE, AFTER TUBES, SECTOR No 4
Tegatm	* MEAN VALUE OF THE COMBUSTION GAS TEMP, AFTER TUBES
Tamb	AMBIENT AIR TEMPERATURE
Taaf	AIR TEMPERATURE AFTER FAN
Tweout	COOLING WATER TEMPERATURE, OUTLET OF ENGINE
Tweoo	COOLING WATER TEMPERATURE, OIL COOLER OUTLET
Tweoin	COOLING WATER TEMPERATURE, OIL COOLER INLET
Toilae	OIL TEMPERATURE AFTER ENGINE
Taa	ATOMIZER AIR TEMPERATURE
Tegm	* MEAN COMBUSTION GAS TEMPERATURES, EXHAUST GAS PIPES
dTwe	COOLING WATER DIFFERENCE TEMPERATURE, ENGINE
dTweo	COOLING WATER DIFFERENCE TEMPERATURE, OIL COOLER
dTtuf	* MAX DIFFERENCE TEMPERATURE HEATER, 1st TUBE ROW
dTtub	* MAX DIFFERENCE TEMPERATURE HEATER, 2nd TUBE ROW
Pwgmax	MAX WORKING GAS PRESSURE (MPa)
Pwgmin	MIN WORKING GAS PRESSURE (MPa)
Pratio	* Pwgmax/Pwgmin
Pwgfil	WORKING GAS PRESSURE FILTER (MPa)
Pwgm1	MEAN WORKING GAS PRESSURE, CYCLE No 1 (MPa)
Pwgm2	MEAN WORKING GAS PRESSURE, CYCLE No 2 (MPa)
Pwgm3	MEAN WORKING GAS PRESSURE, CYCLE No 3 (MPa)
Pwgm4	MEAN WORKING GAS PRESSURE, CYCLE No 4 (MPa)
TORQUE	ENGINE TORQUE (Nm)
Paa	ATOMIZER AIR PRESSURE (KPa)
Paaf	AIR PRESSURE AFTER FAN (KPa)
Pfu	FUEL PRESSURE (KPa)
Pfur	FUEL REGULATING PRESSURE (KPa)
Poil	OIL PRESSURE (KPa)
Pcomps	COMPRESSOR GAS PRESSURE, SUCTION SIDE (MPa)
Ptank	STORAGE TANK PRESSURE (MPa)
LAMDAI	* CALCULATED AIR FUEL RATIO (Ma+Maa)/(14.5*Mfu)
O2	OXYGEN CONCENTR. IN THE COMBUSTION GAS, EXHAUST PIPES
LAMDAo	* AIR FUEL RATIO MEASURED FROM THE OXYGEN CONCENTRATION
Ma	AIR MASS FLOW RATE (g/s)
Maa	* ATOMIZER AIR FLOW RATE (g/s)
Mwe	COOLING WATER MASS FLOW RATE (Kg/S)
Mweo	COOLING WATER, OIL COOLER, MASS FLOW RATE (Kg/s)
Mfu	FUEL MASS FLOW RATE FROM TURBINE FLOW METER (g/s)
Mfuaes	* FUEL MASS FLOW RATE FROM THE FUEL WEIGHT DEVICE (g/s)

Engine Instrumentation Listing

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Qfu     * SUPPLIED FUEL HEAT FLOW RATE (kW)
Qa      * SUPPLIED AIR HEAT FLOW RATE (kW)
Qaa       SUPPLIED ATOMIZER AIR HEAT FLOW RATE (kW)
Qcg     * REJECTED COMBUSTION GAS HEAT FLOW RATE (kW)

Peff    * EFFECTIVE SHAFT POWER (kW)

QRADp   * HEAT REJECTED BY RADIATION AND CONVECTION, PREHEATER (kW)
Qwc     * REJECTED WATER HEAT FLOW RATE (kW)
Qwoc    * REJECTED WATER,OIL COOLER,HEAT FLOW RATE (kW)
QRADcr    HEAT REJECTED BY RADIATION AND CONVECTION, CRANKCASE (kW)

ETAeff  * EFFECTIVE ENGINE EFFICIENCY (%)

dQ      * DIFFERENCE IN HEATBALANCE (kW)
dQ%     * DIFFERENCE IN HEATBALANCE (%)

Qe      * Qfu+Qa+Qaa-QRADp-Qcg (kW)


ETAb    * HEATING SYSTEM EFFICIENCY (%)

Tcgat11   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 1
Tcgat12   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 1
Tcgat21   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 2
Tcgat22   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 2
Tcgat31   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 3
Tcgat32   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 3
Tcgat41   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 4
Tcgat42   COMBUSTION GAS TEMP, AFTER TUBES, SECTOR No 4

TcgL      COMBUSTION GAS TEMPERATURE, LEFT EXHAUST GAS PIPE
TcgR      COMBUSTION GAS TEMPERATURE, RIGH EXHAUST GAS PIPE

          * = CALCULATED VARIABLES FROM MEASURED VARIABLES.
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Engine Instrumentation Listing (Cont'd)