GARRETT

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STRUCTURES AND COOLING DEVELOPMENT
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Prepared by Engineering Staff

Edited by L. F. Jilly

Approved by E N Harris
Edward N. Harris
HRE Program Manager

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FOREWORD

This interim technical data report is submitted to the NASA-Langley Research Center by the AiResearch Manufacturing Company, Los Angeles, California. The document was prepared in accordance with the guidelines established by paragraph 5.7.3.2.2 of NASA Statement of Work L-4947-B (Revised).

Interim technical data reports are generated on a quarterly basis for major program tasks under the Hypersonic Research Engine Project. Upon completion of a given task effort, a final technical data report will be submitted.

The document in hand presents a detailed technical discussion of the structures and cooling development for the period of 3 August through 2 November 1970.

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TABLES

1. SUMMARY OF STATUS

The Structures Assembly Model (SAM) arrived at the NASA-Langley 8-Foot High-Temperature Structures Tunnel on 31 July 1970. Preparations for installation in the wind tunnel were started 3 August 1970. Following installation, the SAM and tunnel systems were checked out. The first run, with hydrogen cooling and the SAM inserted in the tunnel stream ($M = 7.7$, $P_{TOTAL} = 900$ psia, $T_{TOTAL} = 2500^{o}R$), was accomplished on 20 October 1970. The condition of the SAM after the run was satisfactory, with no visible signs or data indications of overheating or overloading.

2. PROBLEM STATEMENT

The objective of the structures and cooling development program is to analyze, design, and fabricate the regeneratively cooled surfaces and their associated structures and to verify the performance of these surfaces and structures at conditions that simulate the operating conditions expected in the flight test engine.

The Hypersonic Research Engine requires regenerative cooling on all surfaces that contact the engine airstream. The use of ablative coating on the engine aerodynamic surfaces is barred by the Statement of Work to minimize extraneous effects on engine performance. No such restriction is imposed on the engine cowl; therefore, ablative protection is used for this component.

The characteristic design problem in regeneratively cooled structures for this type of application is associated with the large heat fluxes encountered over major portions of the engine surfaces. These heat fluxes range from values of approximately 10 Btu/sec-ft^2 to 1800 Btu/sec-ft^2 on the stagnation line of the support strut leading edge. The conservation of fuel requires that these heat fluxes be accommodated at temperature differences across the regeneratively cooled surfaces which range up to approximately 800°F in flat surfaces and 1200°F in leading-edge areas. These temperature differences in turn, result in strains that cause plastic deformation of the hot surfaces. Design, therefore, is governed by low-cycle fatigue conditions. Uncertainties associated with the prediction of low-cycle fatigue performance have led to heavy emphasis, in the experimental portion of the program, on the evaluation of the low-cycle fatigue performance of the engine components.

The general performance objectives set for the cooled structures are as follows:

<u>Design life</u> - 10 hr of hot operation of which 3 hr are to be taken at Mach 7 to 8 flight conditions

<u>Cycle life</u> - 100 cycles, at conditions which produce the highest plastic strain

3. TOPICAL BACKGROUND

The cooled structures, which are being designed, fabricated, and tested as part of this task, and the associated connecting structures constitute the basic structural elements of the engine. The cooled surfaces of these structures form the aerodynamic surfaces of the engine, as shown in Figure 3-1.

3.1 GENERAL DESIGN GUIDELINES

The regeneratively cooled surfaces must be designed and fabricated to minimize engine performance losses. In addition to providing the basic contours, the cooled surfaces must be fabricated and assembled in a way that avoids discontinuities; leading edges must use the minimum radius compatible with reliable structural design.

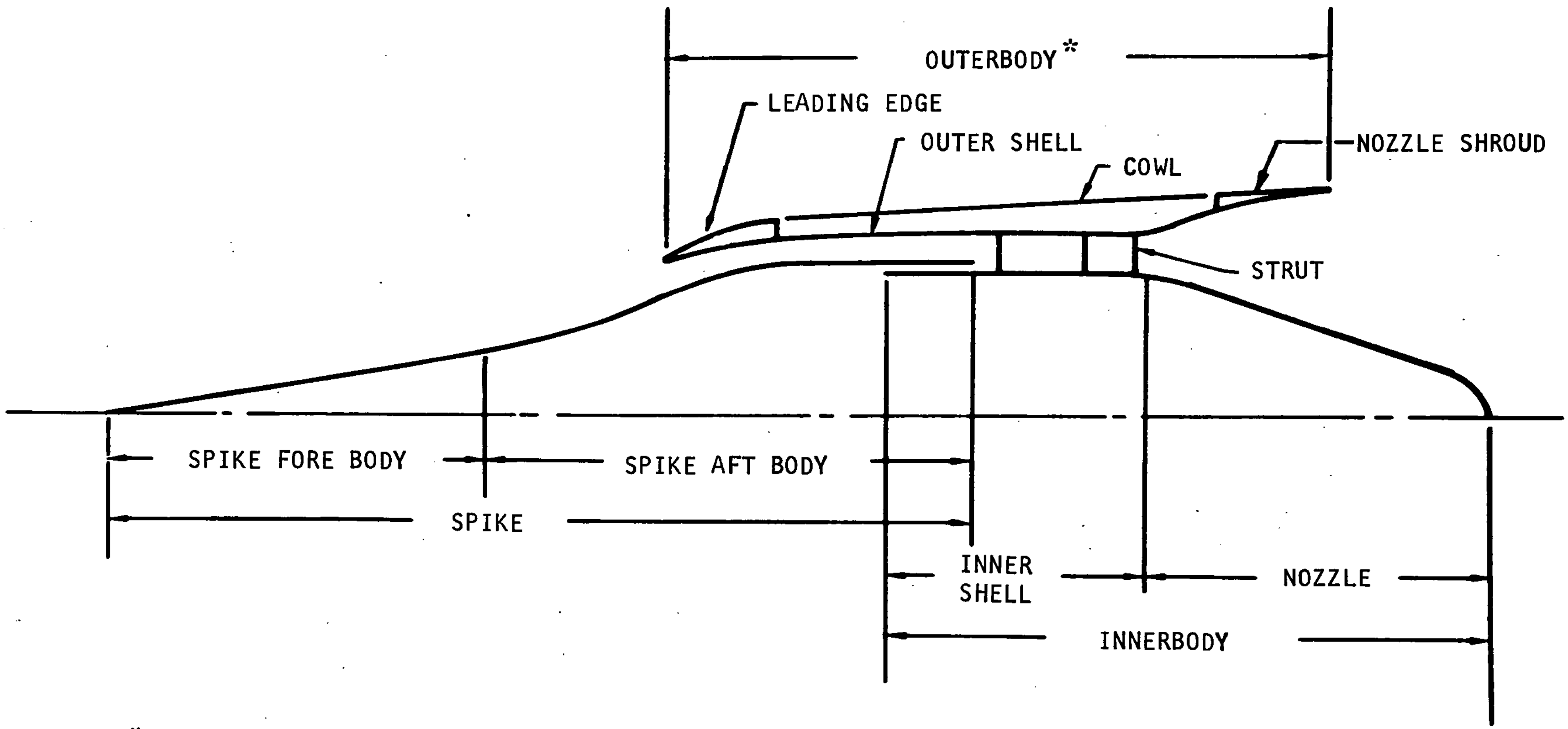
Because of the research nature of the HRE program, temperatures and pressures will be measured throughout the engine. Consequently, the engine structures must accommodate static pressure taps and metal temperature thermocouples.

The total amount of fuel available to the engine in flight and for cooling of its structure must be limited to the storage capabilities of the aircraft to which it is attached. Consequently, in cooling the structure, fuel usage in excess of combustion requirements must be minimized. To accomplish this goal, the cooled surfaces must function at maximum metal temperatures and temperature differences compatible with sound structural design.

Engine internal structures and plumbing must be designed to allow space for installing fuel system components, engine controls, instrumentation transducers, and signal conditioning equipment. Because of operating limitations, electronic equipment must be installed in locations having the least severe environment.

To permit the engine to operate over the flight Mach number range from 3 to 8, the inlet spike must be translated to various positions. To conserve coolant prior to and after engine operation, the inlet spike must be translated to a position nearly in contact with the outerbody leading edge. Consequently, it is necessary to have a spike actuation system capable of the desired positioning accuracy, with control provided by the control system computer.

Engine fuel pressurization is provided by a hydrogen turbopump. Therefore, the total pressure drop in the regeneratively cooled surfaces, manifolds, and associated plumbing must be compatible with the pressure output of the turbopump.



*OUTER BODY - LEADING EDGE + OUTER SHELL + NOZZLE SHROUD + COWL

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Figure 3-1. Cooled Structures Nomenclature

In addition to control of temperatures and temperature differences, the integrity of the coolant structures requires that the flow routes within the engine be matched in such a way as to minimize temperature differences at axial stations for innerbody and outerbody surfaces. This will minimize distortion of the engine internal passages. Axial temperature discontinuities as produced, for example, by the termination of two flow routes that differ greatly in temperature at the same station, are objectionable because of the severe thermal strains that result.

Measurement of engine internal thrust during operation is required. Consequently, external loads (drag and lift) that are transmitted directly to the thrust measuring device must be minimized. Specifically the engine cowl has drag loads that are of the same order of magnitude as the engine thrust. Mounting of the cowl in such a way as to minimize this external drag load, and thus the uncertainties in calculation of thrust, is therefore required.

A basic engine design requirement is that malfunction of the engine in flight would not endanger the safety of the aircraft to which it is attached or the life of its pilot. Therefore, provision must be made to jettison the engine. Because of probable hydrogen leakage to the engine cavities, the innerbody engine cavity must either be inerted or must be capable of containing an explosive mixture of hot hydrogen and air. To accomplish this, the engine cavity will be vented to near nozzle base pressure and provisions will be made for explosion containment. During ground checkout, the engine cavity will be inerted with nitrogen.

The weight of cooled structures, inlet spike actuation system internal supporting structures, and plumbing is most of the total engine weight. Although optimization of the structures and structural components for minimum weight is not an objective, the specified weight limitation requires careful consideration of structural weight.

The instrumentation, controls, and fuel subsystems contained in the engine cavity will require servicing prior to and after each test. Consequently, the mechanical assembly of the engine cooled structure components must provide easy access to subsystem components for replacement in the field.

3.2 OPERATIONAL BOUNDARIES

3.2.1 General Design Ground Rules

The maximum dynamic pressure specified for the current phase of the program is 2000 psfa. This compares with the specified dynamic pressure of 2500 psfa, specified for the HRE Phase I program. Consequently, the minimum altitude at Mach 8, during which cooling must be provided, is 85,000 ft, as compared to the Phase I minimum altitude of 81,000 ft. The minimum design altitude for the current program is 88,000 ft. The increased altitude results in a reduction of heat flux throughout the engine, but this reduction is offset in part by an increase in engine contraction ratio from 10 in Phase I to 14.6 in Phase IIA. In summary, the operating envelope for the engine is as follows:

Engine Structural Design - With engine either lit or not lit, dynamic pressure (q) = 2000 psfa

Engine Cooling Design

Normal design, engine lit: q = 1750 psfa, h = 88,000 ft minimum

Emergency design, engine lit: q = 2000 psfa h = 85,000 ft minimum

For the emergency design, engine lit conditions all of the pump output pressure is available for coolant pressure drop. The dump valve opens and fuel injection valves close as the aircraft approaches these conditions from the normal operating line.

3.2.2 Engine Operating Cycles

A qualitative definition of the engine operating cycles has been formed for the purpose of providing a basis for analyzing heat transfer transients evaluating the structural effect of transient temperature differences, establishing general control requirements and typical environmental conditions, and for defining acceptable operating cycles. The types of missions or conditions the engine must survive are as follows:

Case I - Constant M, with aircraft power on, at a constant high q

Case II - Constant M, with aircraft power off, aircraft diving

Case III - Variable M, expected to involve a change in M of 0.5 during 20-sec engine operating cycle

Case IV - Subsonic-supersonic combustion transition at M = 6

Case V - Inlet unstart, with shock expelled

Figure 3-2 is a qualitative representation of the critical cases. The common features, typical for all simulated missions, are numbered on the figure and are as follows:

1. Launch to M = 3+, during which the engine structure is assumed to go from a soak at -65°F to a soak at 1140°F. No cooling is required. At the end of this period, the helium purge is performed and coolant flow started through all portions of the cooled structure.

2. Approach to test Mach number, inlet closed (leakage flow only), during which coolant flow is increased to maintain maximum structure temperature (cold surface) at 1140°F.

3. Time for retraction of inlet spike to desired position. The solid lines assume programmed cooling flow; the dashed line assumes controlled cooling flow based on temperature sensing. The approach selected will be a function of control system response and actuating system response. Controlled cooling is preferred.

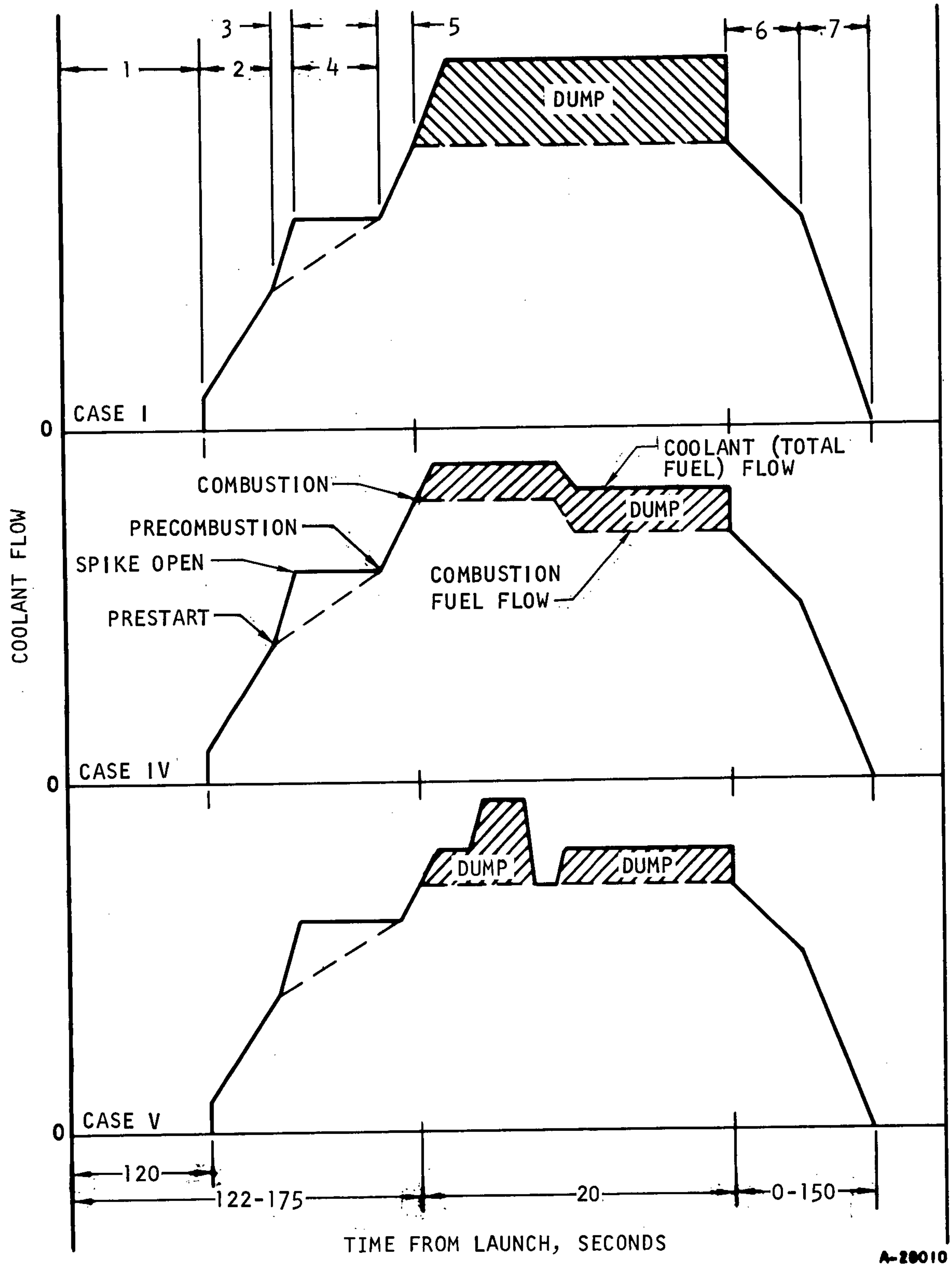

Figure 3-2. Typical Engine Operating Cycles

4. Inlet spike in starting position, full airflow through the engine, no combustion.

5. Programmed increase in cooling flow to starting combustion equivalence ratio (ϕ). This ϕ will be less than the test ϕ. Combustion ϕ will ramp to test ϕ (not shown).

6. Combustion terminated and inlet spike being extended to closed position.

7. Inlet closed (leakage flow only), deceleration to M = 4 +, with coolant flow decreased to maintain maximum structure temperature at 1140°F. Helium purge.

As combustion starts, the cooling ϕ must be controlled to accommodate increasing heat fluxes. The variations among missions occurring during the compustion phase are as follows:

Case I - Shown in Figure 3-2. Cooling ϕ is in excess of combustion ϕ. Combustion ϕ will ramp at beginning and end of test. Ramps of 5-sec duration to and from ϕ = 1 may be assumed at beginning and end of test.

Case II - Not shown. Represents a gradual change in conditions shown for Case I and will involve less severe transients. Not considered a design point.

Case III - Same comments as Case II, but may become a design point at lower Mach numbers because of potential for increased test time and wider Mach number range.

Case IV - Shown in Figure 3-2. Involves a near-step change in gas-side engine conditions during test run.

Case V - Shown in Figure 3-2. The general rise in pressure would be expected to cause a step-change type increase in heat flux. Spike will extend and close, then retract to operating position for second attempt at starting. At this point, either normal operation or a second unstart is possible.

4. OVERALL APPROACH

The diverse requirements imposed on the cooled structures require iteration of the cooled structural design with (1) the engine aerodynamic design; (2) the instrumentation, control, and fuel subsystems designs; and (3) the airplane interface design. Internal constraints on cooled structural design are imposed by the close coordination required in thermal design, structural design, mechanical design, and manufacturing. It is generally not possible to treat any one of these areas independently of the others. During Phase I of the program, the basic design concepts for the engine were defined and are basically feasible in terms of the constraints imposed on the design. These concepts and the design data generated during Phase I are being used as the starting point for design of the Phase IIA cooled structures. Component layout drawings of acceptable mechanical design and with acceptable manufacturing features form the initial step in the iteration. These layout drawings have been evaluated to establish the required thermal and structural design features. Based on these inputs, layout drawings are revised to incorporate the required features, followed by substantiation of thermal and structural performance of the revised design.

Although the Phase I design is being used as the starting point of Phase IIA cooled structure design, each of the components is being reviewed with the objective of simplification in terms of mechanical design and manufacturing features. The interfaces between two or more components, in particular, will be reevaluated. The interfaces include engine-to-airplane mounting, outer-shell-to-innerbody mounting by means of the support struts, nozzle-to-inner-shell assembly, inlet spike-to-innerbody assembly, inlet spike actuator-to-inlet spike and innerbody mounting, leading edge-to-outer shell mounting, and cowl-to-outer shell support.

The general approach to cooled structures development places heavy emphasis on fabrication and testing of the full-scale components. A limited number of types of cooled structural elements and models is being fabricated and tested to evaluate the problems which are basic to the overall engine design, or which are sufficiently localized in nature to permit use of subscale evaluation. All significant manufacturing development and evaluation is being accomplished using the full-scale components. The nature of the required manufacturing operations for the components is such that use of subscale components would be expected to lead to only limited information on the adequacy of manufacturing techniques and processes.

4.1 THERMAL DESIGN

The overall thermal design approach is by analyses based on experimental data obtained from tests on similar geometric configurations and heat transfer situations. These experiment-based analyses, in turn, will be verified by experiments where the geometry or fluid conditions, or both, will be like those existing for the flight engine.

Where the discrepancy between calculated and experimental heat flux values is large, steps are being taken to improve the analytical techniques so that the correlation between calculated and experimental results can be improved.

The basic goals of all thermal analyses and designs are (1) limiting temperature and temperature differences to structurally acceptable values, while keeping hydrogen cooling flow equal to or less than hydrogen flow required for combustion, and (2) at the same time maintaining hydrogen pressure drop compatible with cooling jacket pressure containment and pump outlet pressure capabilities. The limiting values being used at present are (1) a maximum gas side metal temperature of 1700°F (2160°R), (2) a maximum primary structure temperature of 1140°F (1600°R), and (3) a hydrogen pump outlet pressure of 1100 psia.

The thermal design procedure involves separate calculation of aerodynamic heating and cooling jacket performance. The aerodynamic heating conditions are calculated (as during Phase I) primarily by use of the computer program H1940. Special aerodynamic heating conditions, such as shock wave/boundary layer interaction, are computed separately. Cooling jacket fin performance is calculated (as in Phase I) by use of computer program H1930. Special conditions, such as pressure and flow distributions for inlet, outlets, and bolted flange/manifolds, require separate calculations. Verification of aerodynamic and cooling jacket heat transfer and pressure drop calculations will be accomplished by actual tests. Specifically, aerodynamic heat transfer calculations will be verified by tests of engine component models, such as the combustor, and with the boilerplate engines. Calculated performance of cooled structures will be verified by full-scale component and some subscale component testing at heat flux levels and distributions comparable to those calculated for the flight engine components. The primary areas requiring verification in the cooled structures performance are flow distribution and associated temperature distribution and its effects on structural performance in terms of life and contour.

4.2 STRUCTURAL DESIGN

The structural design approach utilizes a combination of analytical and experimental methods. Experimental verification of detailed parts, such as short-term burst, creep-rupture, and thermal fatigue tests on sandwich plate-fin elements, will be employed wherever necessary. Generally, the structural tests will be performed on composite structural elements, such as the inlet spike and the innerbody assembly.

The bulk of the HRE structures consists of ring-stiffened orthotropic shell structures of variable thicknesses and contours. The ring stiffeners are also used for coolant flow manifolding and fuel injection rings for the engine combustor section. The structural loadings will produce axisymmetric and asymmetric forces and moments due to static normal pressures, acceleration, vibrational inputs, and aerodynamic flutter and buffeting effects.

Fully operational computer solutions are available to analyze axisymmetric isotropic thin shells of variable thicknesses and contours for stresses due to axisymmetric loads and temperature profiles. In addition, the isotropic shell analysis had been extended to treat orthotropic cylindrical shells with axisymmetric loads. Two MIT finite difference nodal circle solutions (SABOR III and DASHER I), which have been adapted for use on the AiResearch computer system (IBM-360/50), are available for use.

The SABOR III program is applicable for axisymmetric isotropic shells (local departures from ideal isotropy can be treated) that may be subjected to nonsymmetrical static forces. The SABOR III program may also be used to obtain the stiffness and mass matrixes for direct input into the DASHER I program to obtain dynamic response.

It would have required an extensive programming effort to modify the SABOR III and DASHER I programs to treat accurately many of the problems that will be encountered in the HRE. Rather than attempt this approach, a further survey of existing shell programs was carried out, and it was determined that an extremely applicable program had been developed under the auspices of the Analysis Group of the Theoretical Mechanics Branch, Structures Division of the Wright Patterson Air Force Base, Dayton, Ohio. This program is based upon the very recent improvement in matrix shell solutions generated by A. Kalnins (Department of Mechanics, Lehigh University). It solves the general axisymmetric orthotropic thin shell problem for symmetric and nonsymmetric loads due to static as well as dynamic inputs. The program has been successfully adapted for use on the AiResearch computer system. Although the program has been debugged, the final report describing the usability limitations, and methods of data input has not been completed, and will not be released by the Wright Patterson Air Force Base for at least twelve months. Until a program of this magnitude has been completely checked out by trying numerous test cases, a note of caution must be exercised regarding its capabilities. Another important point is the fact that the problem inputs and the data reduction of the outputs require considerable effort on the part of the user. The existence of the program also does not eliminate or substantially reduce the work needed to generate a sound design; however, it is the objective of careful analysis to discover design inadequacies that would otherwise not be recognized.

The eventual objective of the test program is to verify the actual performance capabilities of the structures as fabricated. Although it will not be possible to predict analytically the influence of realistic fabrication restrictions and limitations on the end product, the initial analysis will identify the serious design problem areas. Results of the test program will be used to assess the extent of the changes required to achieve the structural integrity goals.

4.3 MECHANICAL DESIGN

The guidelines used in mechanical design of the cooled structures components and assembly of the components into the engine require the use of known materials and joining techniques. Standard fasteners and seals are used to the greatest extent possible. Design for brazing is aimed at minimizing the total numberof braze cycles to which a given part must be subjected. In some cases, this is done by redesigning the parts to allow use of prebrazed subassemblies, substitution of machined or welded subassemblies, or substitution of bolted interfaces for brazed or welded interfaces. Also, as a general rule, all welding into or close to braze joints is being avoided, although in certain cases, such a procedure may be acceptable.

The mechanical design effort will be supported by experimental verification in selected areas. In particular, selected configurations that present analytical problems and raise questions as to manufacturing feasibility will be fabricated and tested on a subscale basis. The purpose of such tests will be to provide design data and guidance for possible design revision. Currently planned tests, which are in support of mechanical design, rather than thermal or structural design, include the following:

Test specimen to evaluate feasibility of bolting the nozzle flange manifold to the inner shell through the removable nozzle cap

Fabrication of a section of the inlet spike near the spike tip to help resolve questions regarding the best manufacturing approach, and hence, the best design for this portion of the inlet spike

Fabrication of the spike-to-innerbody seal to evaluate the adequacy of the design solution

Fabrication of a straight section of the bolted nozzle manifold to verify both the manufacturing aspects and structural integrity of the design solution

Fabrication and evaluation of the various mechanical seals used in the components to verify the adequacy of the design solution

Fabrication of flat panels using the various instrumentation and fuel injector fittings that penetrate the regeneratively cooled surfaces to verify manufacturing feasibility and structural integrity of the design. Tests results will be used to select the final configuration used in the engine.

4.4 MANUFACTURING

The manufacturing approach being used on this program has two aspects: (1) that dealing with the approach to development of manufacturing techniques and processes, and (2) that dealing with the specific manufacturing processes planned for use.

4.4.1 Development Approach

The development of the manufacturing techniques and processes will rely primarily on full-scale components. Except where isolated problems or basic data must be obtained, the use of subscale components represents a duplication of development effort. The compound forming of the shell-face sheets in half-scale, for example, results in working with radii of curvature which are half those encountered in the full-scale part. Use of lighter-gauge material to facilitate forming, on the other hand, is impractical. In addition, the size of the full-scale tooling, the machines required to use this tooling, and the unique problems associated with the forming of large thin wall shells cannot be duplicated in half-scale. As a result, a half-scale compound-curved model of the isentropic surface of the inlet spike is the only subscale component on which fabrication development work is being done. This part is being used to establish forming characteristics, evaluate electrohydraulic forming parameters, and investigate brazing problems.

4.4.2 Fabrication Approach

The most critical area of cooled structures fabrication is in the cooled surface shell face sheets. The starting point for these shells can either be rolled-and-welded-cone sections or flat sheets. The rolled-and-welded cones are bulge-formed, then final-sized, using electrohydraulic forming. Using flat sheets as a starting point, the shells must be deep drawn in about three stages. Final sizing of the shells occurs as for the welded cones. Of the two approaches, the one using the seam-welded cone has been selected. The weld seam is not considered structurally objectionable and the approach involves fewer steps than are required for deep drawing.

To ensure adequate braze fitup, forming accuracy for the shells must be high. Specifically, it is expected that the clearance between shells must be maintained within a tolerance of approximately ±0.001 in. Given this accuracy, the brazing of the fins between the face shape still requires special attention. To ensure sound braze joints, pressure must be exerted on the shells in such a way as to provide a crushing load on the fins. The methods available for providing this braze fixturing load include the following, as a function of the component being brazed:

> Graphite fixtures, with an external piece containing the assembly and an internal piece using expanding segments to exert pressure.
>
> Steel bags placed inside the shell and pressurized to a level sufficient to deform the shell with which the bag is in contact. Containment on the external face sheet may or may not be required with this approach.
>
> Evacuation and backfilling of the space between the two shell face sheets, using atmospheric pressure to provide the load.

Integrity of the shell joining will be experimentally evaluated and adjustments in shell forming tools and brazing procedures and fixtures made to correct problems that appear.

4.4.3 Nondestructive Testing

The critical area in fabrication of the full-scale components involves the shells themselves, as discussed in the two previous paragraphs. For structural integrity of the shells, only very limited areas of unbrazed joint areas are tolerable. These joints are detectable by proof pressure testing at sufficiently high pressure levels. Only in exceptional cases, however, will a defect that is revealed by proof pressure test be repairable. In general, a nondestructive test capable of revealing braze voids is preferable and offers better opportunity for subsequent repair. The two techniques available are radiographic inspection of the entire shell surface and the use of temperature-sensitive paint on one of the face sheets with a heating transient imposed on the other face sheet. These methods will show a braze void; that is, an unbonded joint. Weak joints are not discernable as such. In general, however, the existence of a brazed joint is reasonable assurance that adequate joint strength can be achieved. Verification of the result of radiographic or thermal inspection of the shells will be done by proof-pressure testing.

The repair techniques available for unbonded joints in the shells would generally be the following:

> Recycling of the complete shell to a slightly higher temperature than used during the first braze cycle. In this way, remelt and flow of the braze alloy is obtained with the objective of filling the void. Orientation of the shell in the brazing furnace can be used to assist the process.
>
> Removal of a portion of the face sheet in the unbrazed area, addition of filler alloy and closeout using a patch, with the entire shell recycled in the brazing furnace. The applicability of this repair procedure will be a function of the location of the affected shell area in the engine gas stream.

5. ANALYTICAL DESIGN

All analytical design was completed during the previous reporting period.

6. DESIGN EFFORT

All design activity was completed during the previous reporting period.

7. MANUFACTURING

All manufacturing effort was completed during the previous reporting period.

8. TESTING

Following installation of the SAM in the wind tunnel test section, checkout/calibration and performance tests were run, as summarized below. Figure 8-1 shows the SAM at the tunnel prior to installation in the test section. Figures 8-2 and 8-3 show the SAM installed in the wind tunnel test section with the elevator carriage in the running position.

8.1 CHECKOUT AND CALIBRATION TESTS

These tests were aimed at verifying the functioning of the SAM subsystems and establishing the operating conditions of the subsystems when connected to the wind tunnel interfaces. The subsystems are:

(a) Hydrogen fuel/coolant system, including the flightweight, cooled engine structure, and the external valves and manifolding.

(b) Water systems for the water-cooled cowl/pylon, the support wedge, and various components associated with the final assembly.

(c) Nitrogen systems required for (1) purging and pressurization of the engine and cowl/pylon cavity, (2) purging of an inner shell support manifold, and (3) valve actuation.

(d) Temperature control system (TCS).

(e) Pressure control system (PCS).

(f) Inlet spike actuation and control system.

Tests were performed under both static conditions and with the tunnel operating (hypersonic flow, with and without combustor lit) but with the SAM not inserted into the stream (the model is inserted vertically by means of an elevator following establishment of tunnel flow).

8.1.1 Hydrogen Fuel/Coolant System

8.1.1.1 Leak Tests

The installed system was leak tested by measurement of gas pressure decay. Results were comparable to those obtained during pre-installation calibrations.

8.1.1.2 Flow Tests

Flow tests using both nitrogen and hydrogen were run to verify operation

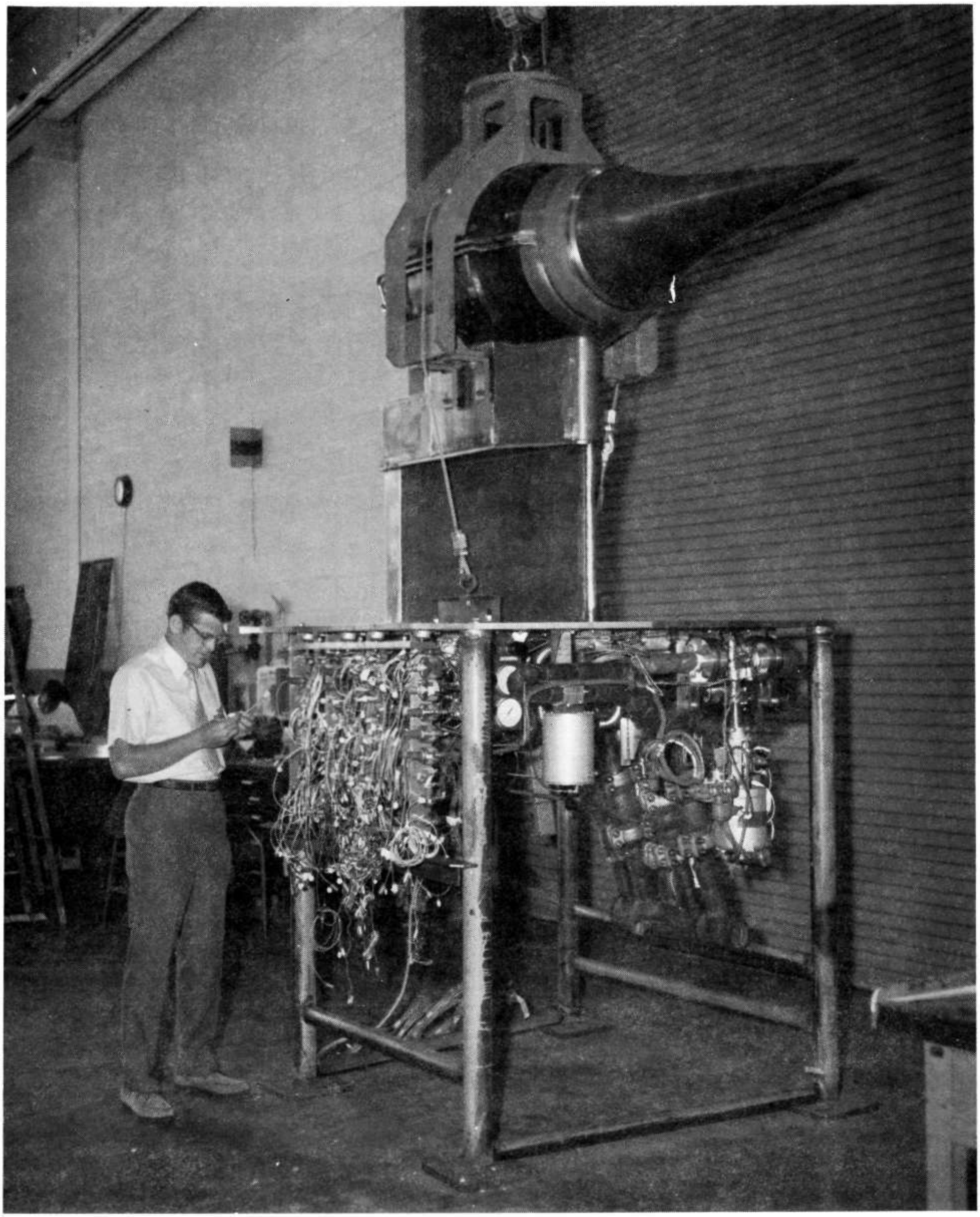

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Figure 8-1. SAM at Wind Tunnel Prior to Installation in Test Section of 8-Foot High-Temperature Structures Tunnel

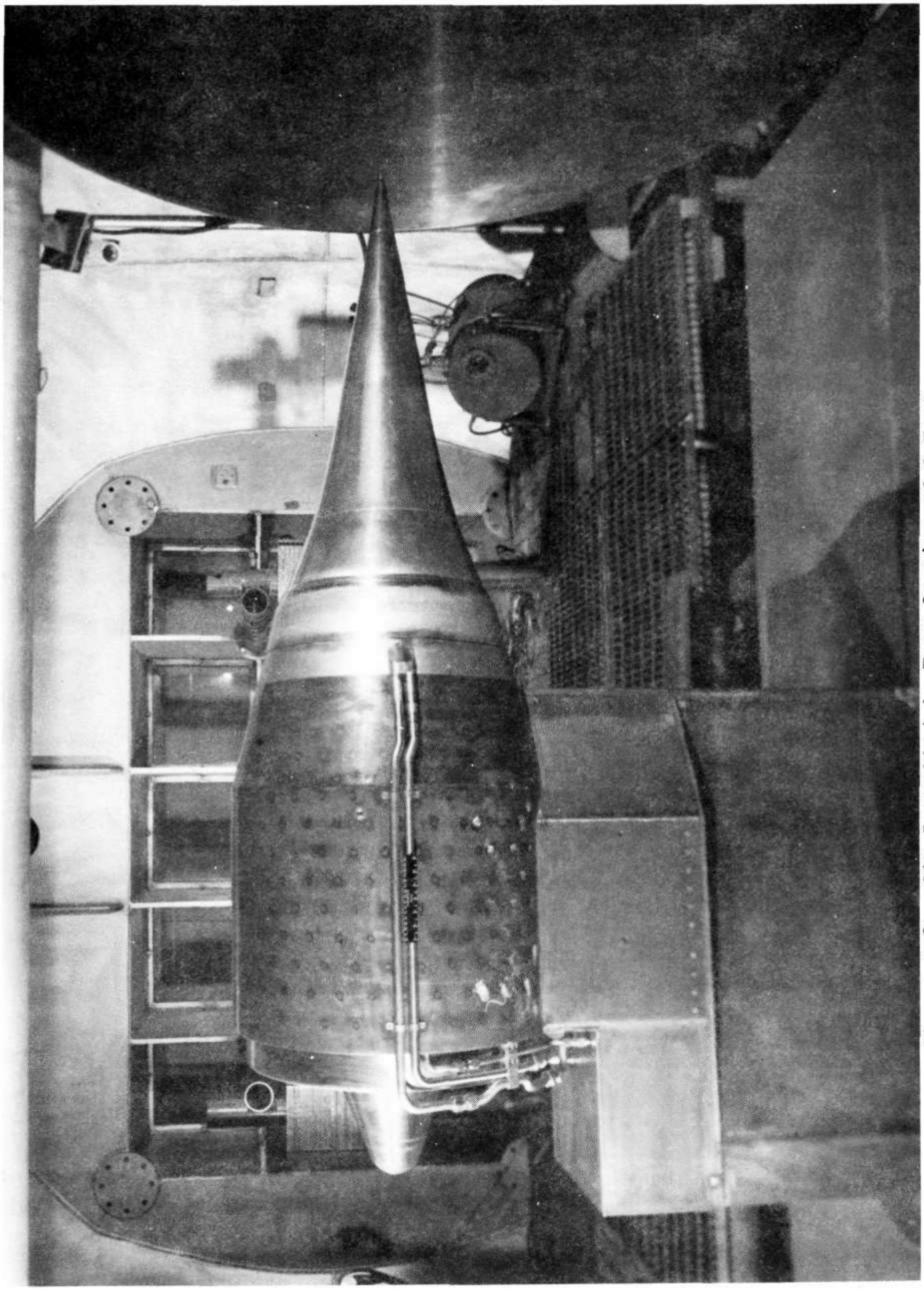

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Figure 8-2. SAM Installed in Test Section of 8-Foot High-Temperature Structures Tunnel (Side View)

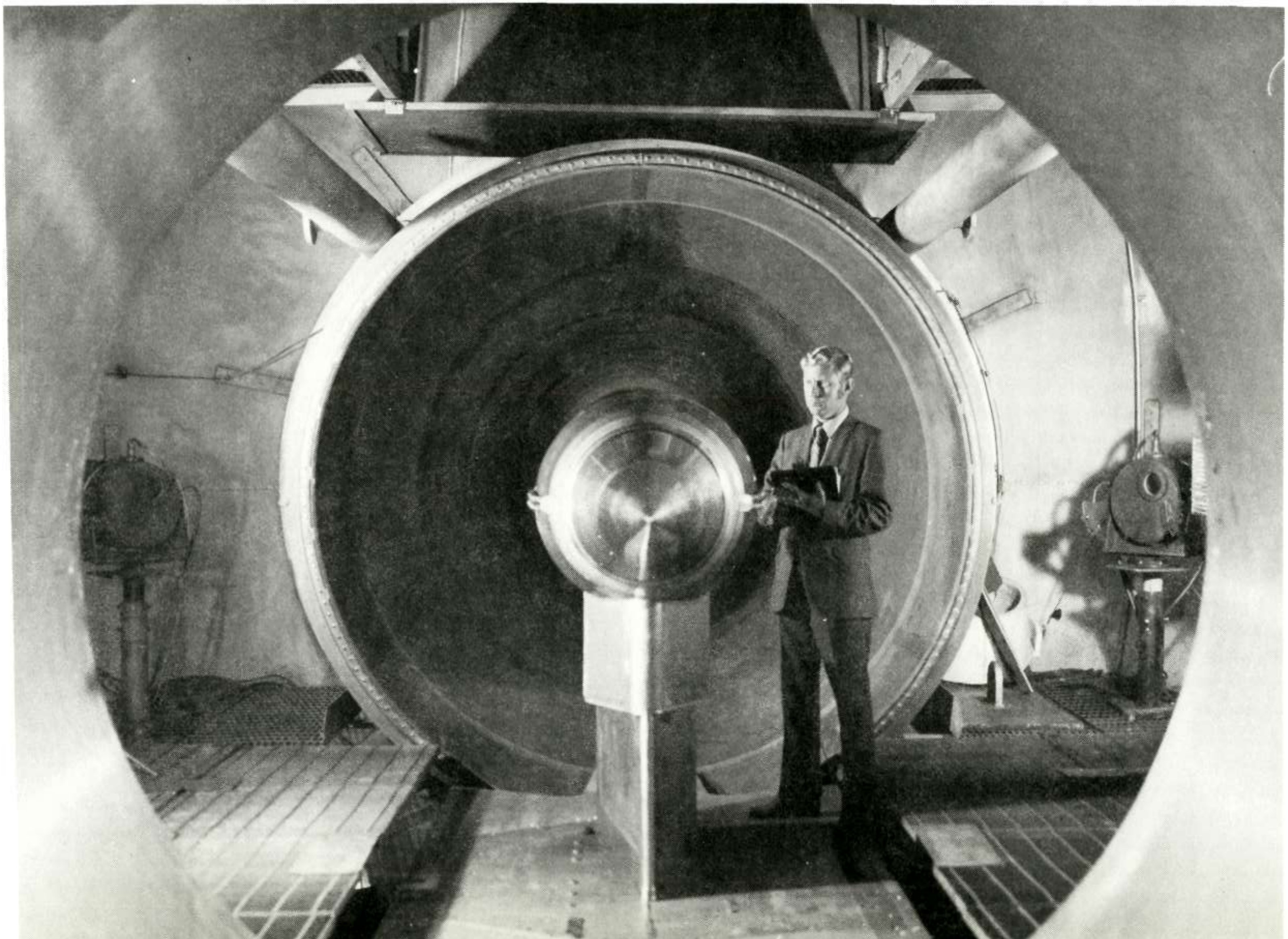

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Figure 8-3. SAM Installed in Test Section of 8-Foot High-Temperature Structures Tunnel (Front View) of the pressure and temperature control systems and establish settings for the coolant regulating valves, the fuel-dump valves, and the pressure control valve. Since all flows were isothermal, dynamic testing of the temperature control function is not possible. During all runs with hydrogen, the tunnel is operating. This is a requirement imposed by safety considerations. Operation of the tunnel during checkout and calibration was desirable and necessary in any event. By this means, the various subsystems could be evaluated in a dynamic environment approaching that encountered when the model is in the stream.

Results of these runs indicated satisfactory operation of model and tunnel systems. At the conclusion of these tests, performance tests, with the model inserted in the stream, were started.

8.1.2 Water Systems

Tests were performed, aimed at establishing the installed characteristics of the two water systems required to supply the five water-flow routes. Table 8-1 shows the selected operating and design conditions for the low and high pressure systems. Operation of the two flow routes of the low pressure system is essentially at design point and needs no further comment.

The flow-pressure drop characteristics of the three flow routes of the high pressure system require deviations from the original design operating conditions. Inlet pressure will be at 205 psig compared to 180 psig design. This increase still results in acceptable margin relative to a proof pressure of 285 psig. At the same time, however, the flow rates are reduced by approximately 10 to 15 percent below the design flow rates. The latter are based on the most severe operating point and are required for two of the planned tunnel runs. Modifications of plumbing are, therefore, being deferred pending availability of test data on water heat loads. Margins used in the original design are likely to be sufficient to accommodate the reduced flow rates without overloading of the structures.

8.1.3 Nitrogen Systems

The critical nitrogen system is the one involved in pressurization and purging of the engine and cowl/pylon cavity. Figure 8-4 shows the calibration of this system for the SAM, as installed. The inlet was throttled in such a way as to result in a pressure of 10 psia at tunnel static conditions of 0.1 to 0.2 psia. Calibration is accomplished at sea-level static pressure (14.7 psia) based on the results shown in Figure 8-4. Specifically, the flow is throttled to give a cavity pressure of 19.7 psia at sea-level ambient. Data taken during tunnel operation confirm the adequacy of the valve settings.

8.1.4 Control Systems

The temperature and pressure control systems were checked out and calibrated based on the procedures outlined in the operating instructions for the equipment. The adequacy of system operation was partly verified in conjunction with the flow tests summarized elsewhere.

TABLE 8-1

WATER SYSTEM PERFORMANCE

Water System and Flow Route	Operation			Design			Flow Rate Ratio*
	Inlet Pressure, psig	ΔP, psi	Flow Rate, gpm	Inlet Pressure, psig	ΔP, psi	Flow Rate, gpm	
Low pressure:							
Route 1	96	47	36	90	45	35	1.0
Route 2	96	64	127	90	62	125	1.0
Total	-	-	163	-	-	160	1.0
High pressure:							
Route 3	205	162	39	180	160	45	0.87
Route 4	205	162	12.7	180	140	15	0.85
Route 5	205	152	66	180	170	70	0.94
Total	-	-	117.7	-	-	130	0.90

*Ratio of "Operating" to "Design" value.

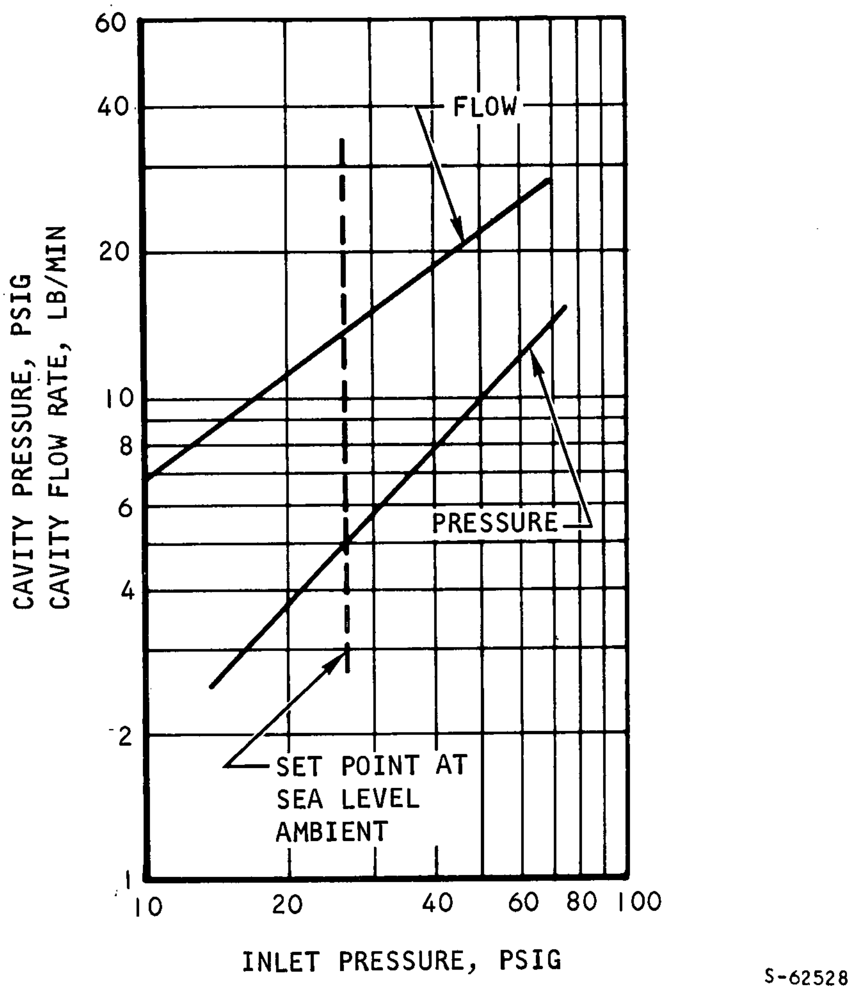

Figure 8-4. Nitrogen Purge Flow Calibration

8.1.5 Inlet Spike Actuation and Control System

The spike actuator hydraulics was connected to the wind tunnel hydraulic system following a cleanliness test of the Houghto-Safe 1010 fluid. Particle counts were better than considered necessary for satisfactory operation of the actuator hydraulic system. Operation of the actuator from the wind tunnel control room was verified as part of the basic checkout.

Using a special fixture, a calibration of the installed system in terms of spike position was performed. Figure 8-5 shows the results of this calibration. The LVDT output is used in the data reduction to establish spike position. The slopes of these two curves are the same, while the zero point is slightly shifted. During initial runs, calibrations will be repeated. Subsequently, it is expected that determination of zero points using the calibration fixture will be sufficient to define spike position.

8.2 PERFORMANCE TESTS

Table 8-2 summarizes the important parameters for the first two runs.

TABLE 8-2

PERFORMANCE TEST CONDITIONS

Parameter	Run 5	Run 7
Mach	7.7	7.8
Total temp, ^{o}R	2600	2600
Total pressure, psia	975	960
Spike retraction, in.	2.33	2.20
H_2 flow rate, lb/min.	0.36	0.20
H_2 inlet temp, ^{o}R	540	540
H_2 outlet temp, ^{o}R	1050	1130
H_2 pressure, psia	280 to 500	100 to 440
Time in stream, sec.	45	31

Following the second run, it was determined that the pressure control system was not functioning properly during the second run and, probably, during the first run. During both runs, outlet pressure was not maintained at the setpoint value of 525 psia, but declined through the range indicated in the table. The condition causing this has been corrected.

The first run was performed with the spike extended sufficiently to insure

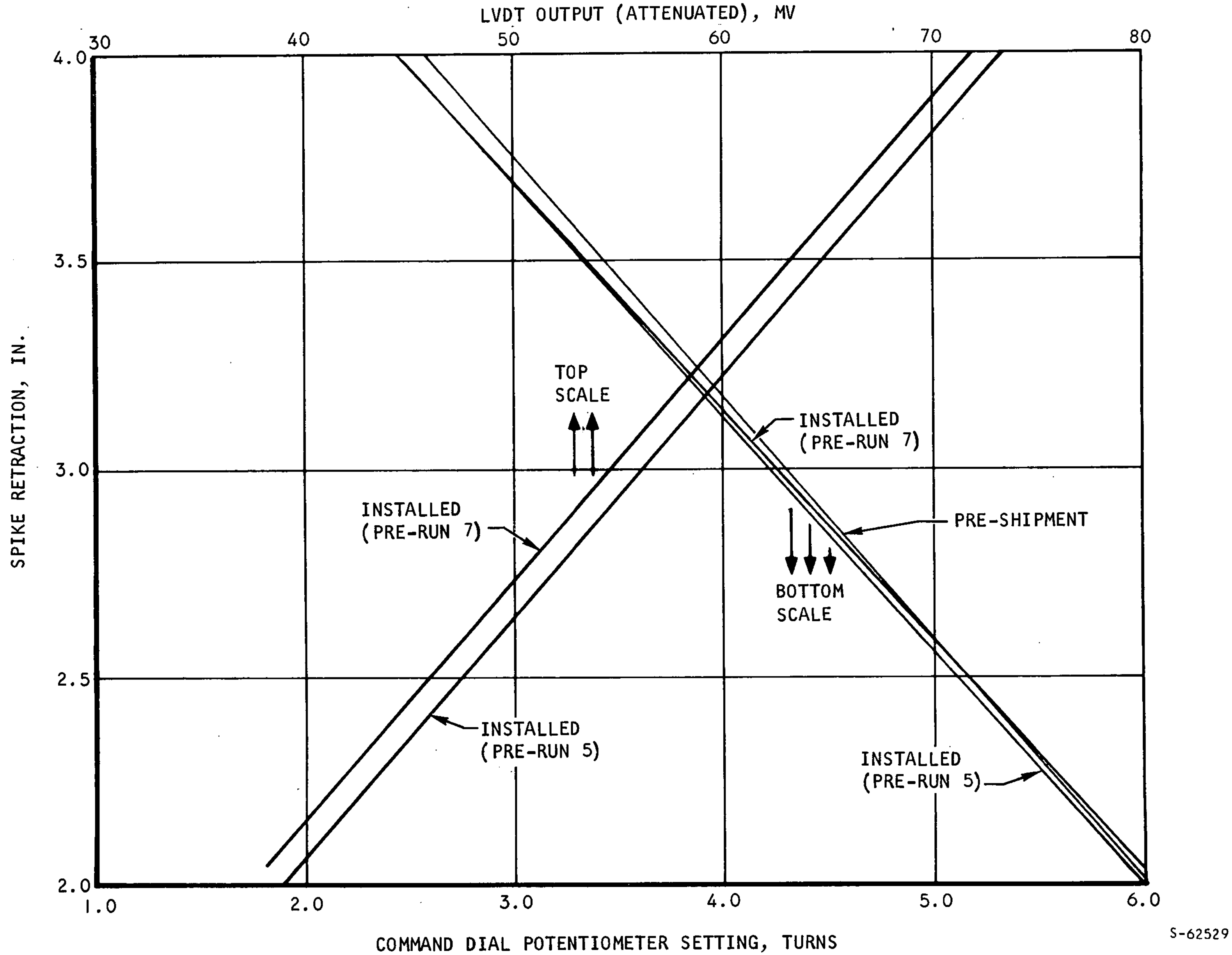

Figure 8-5. Spike Position Calibration

that the spike shock would be significantly outside the leading edge. The resulting flow spillage resulted in a significant redistribution of heat loads relative to the design condition. Valve settings were readjusted for the second run and a better balance obtained. Table 8-3 shows the flow rate and heat load distributions. The disparity between flow rate and heat load in Run 7 is the result of neglecting gas temperature changes and gas-to-wall temperature-difference changes in the predictions. Interpretation of certain of the data, made necessary by saturation of some of the data channels, contributed to this disparity.

Malfunction of the pressure control system during the second run resulted in retraction of the model by the temperature control system because of high temperature in the leading edge flow route. Since the model was being operated overcooled, design temperatures were not exceeded. This is further assured by the fail-safe procedures used: At the setpoint limit for any of the flow routes, both the pressure control valve and the fuel dump valve are bypassed to insure maximum cooling for all routes. Visual inspection of the SAM following these tests showed no evidence of overheating or overloading.

Data obtained from these tests is being analyzed. Periods of steady-state operation were achieved for most parameters during both runs, as determined from the raw data printouts. Results from the initial runs have provided the basis for setups used in subsequent tests and for evaluation of data reduction procedures and programs.

TABLE 8-3

FLOW RATE AND HEAT LOAD DISTRIBUTION

Flow Route	Condition				
	100-Percent-Capture Flow and Heat Load, percent	Run 5		Run 7	
		Flow, percent	Heat Load, percent*	Flow, percent	Heat Load, percent*
Spike	33	32	52	57	57
Innerbody	12	13	8	11	4
Leading edge and forward outer shell	31	31	25	20	32
Aft outer shell	19	20	14	10	6
Struts	5	5	1	2	1
Total	100	100	100	100	100

*Heat load between outer body control thermocouples and outlet manifold set to zero

9. FUTURE ACTION

Scheduled activities for the next reporting period are all related to the testing of the SAM in the NASA Langley 8-Ft High-Temperature Structures Tunnel. These include support of the testing and data reduction. The planned tests are with hydrogen cooling, progressing in severity from tunnel-total conditions of 900 psia and 2500°R to 3300 psia and 3600°R. In addition, the SAM will be subjected to repeated operating cycles at tunnel conditions of 1350 psia and 2640°R total pressure and temperature. These cycles will be used to evaluate the performance of the cooled structure under realistic thermal loading.