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EXPERIMENTAL FLOW MODELS FOR SSME FLOWFIELD CHARACTERIZATION*

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ABSTRACT

Full scale flow models with extensive instrumentation have been designed and manufactured to provide data necessary for flowfield characterization in rocket engines of the Space Shuttle Main Engine (SSME) type. These models include accurate flow path geometries from the pre-burner outlet through the throat of the main combustion chamber. The turbines are simulated with static models designed to provide the correct pressure drop and swirl for specific power levels. The correct turbopump-hot gas manifold interfaces have been designed into the flow models to permit parametric/integration studies for new turbine designs. These experimental flow models provide a vehicle for understanding the fluid dynamics associated with specific engine issues and also fill the more general need for establishing a more detailed fluid dynamic data base to support development and verification of advanced math models.

INTRODUCTION

The Marshall Space Flight Center (MSFC) Aerophysics Division has been very active in experimental testing of rocket propulsion systems over the past several years. Expanded capabilities are being established for full scale turbine air flow testing, turbopump component air and water flow testing, and full scale SSME air and water flow testing. These testing capabilities are needed to support MSFC engine projects which include: flight engines, advanced engines, the Alternate Turbopump Design (ATD) program, and the Technology Test Bed program. Experimental testing is needed to achieve an understanding of the significant gas flow non-uniformities which have been observed in the present SSME Hot Gas Manifold (HGM) design. Future generations of engines of this type must include optimized hot gas flow paths. Design optimization for this type of system requires analytical tools for quantitatively characterizing the highly three-dimensional, turbulent swirling flows. The MSFC experimental capabilities will permit establishing a detailed fluid dynamic data base for verification of computational math models developed for analyzing these types of flowfields.

The scope of this paper is limited to a discussion of the design and features of the full scale SSME air flow models. These models accurately simulate the hot gas flow path through a powerhead (see Fig. 1). The SSME powerhead is a structural arrangement consisting of eight

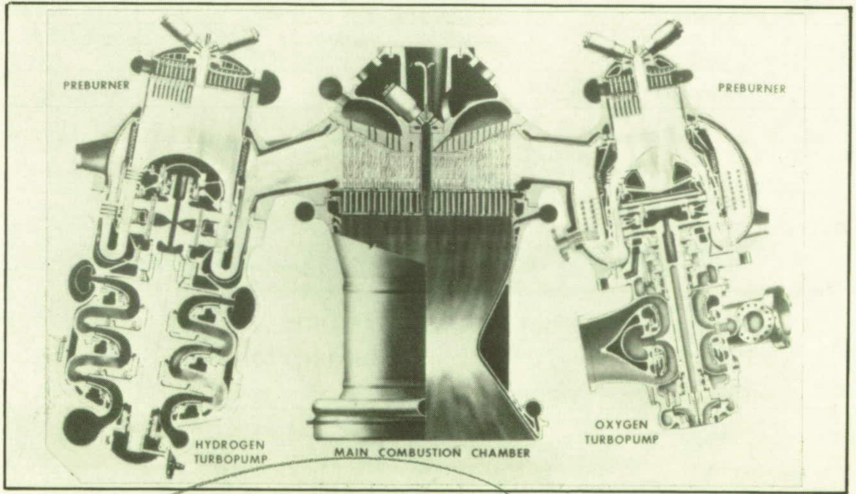

Fig 1 SSME Powerhead Assembly

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major engine components: preburners, turbopumps, HGM, main injector, heat exchanger and Main Combustion Chamber (MCC). The hot gas manifold serves as the structural base for the powerhead and ducts the turbine exhaust gases to the main injector. The preburners are close-coupled to these turbines for minimum length ducting, and the turbopumps are mounted to the hot gas manifold to provide a compact package.

FLOW MODEL CONFIGURATIONS

Two SSME flow model configurations, the Phase II and Phase II+, have been designed and fabricated to date. Drawings of the engine components were reviewed in order to define the gas flow path for the test articles. The dimensions are based on assembled components at ambient temperatures. Flow path definition dimensions have been consolidated onto a single drawing for each configuration (see Table I).

Table I Configurations

Geometry Drawing	Configuration	Comments
80M51756	Phase II Flight Engine	● Technology Test Bed Engine ● Three Fuel Transfer Ducts ● Small Diameter Center Duct ● Doubler And Welds Included
80M57701	Phase II+ Prototype Engine	● Increased Volume Fuel Bowl ● Increased Volume Main Injector Bowl ● Two Eliptical Fuel Transfer Ducts ● Larger Diameter LOX Transfer Ducts

Air flow approaches the model on the fuel and oxidizer sides through ASME flow nozzles designed with an outlet diameter equal to the preburner-liner diameter for each side of the model. The model entrance is located 1.5 preburner-liner diameters downstream of the flow nozzle throat. The hot gas flow path is accurately modeled through the HGM to the throat of the MCC. Exceptions are the flow paths through the turbines, which are simulated with perforated ΔP plates located at the turbine entrance plane, followed by 3-D swirl vanes which continue to the turbine exit plane. Simulator assemblies have been manufactured for 65% and 109% power levels. In the area of the main injector, the oxidizer flow path through the LOX posts is retained but oxidizer flow is not simulated. The hydrogen cavity between the primary and secondary plates is retained but coolant flow is not simulated. The baffle elements (hydrogen cavity outlet) have been modeled to include their geometry effects but are not functional as flow elements.

FACILITY CONSIDERATIONS

The models are designed for testing in the MSFC Air Flow Dual Leg Facility (AFD). This blow down facility provides the conditions shown in Table II.

Table II AFD Conditions

- Pressure: Internal Air, 420 psia max
- Temperature: -70 to 70°F airstream total
- Mass Flow Rates:

	Minimum	Maximum
Fuel Side	50 lbm/sec	170 lbm/sec
Oxidizer Side	20 lbm/sec	73 lbm/sec

As a safety measure, the components are designed as pressure vessels using the ASME Pressure Vessel and Boiler Code, Section VIII, Division 1. The design pressure for the models is 420 psia and the hydrostatic test pressure is 630 psia. Both maximum and minimum mass flow rates are important design considerations because the momentum loads associated with the turnaround ducts (TAD) are in the opposite direction of the thermal loads, which are a result of supply piping contractions. The maximum momentum loads occur with the maximum flow rates, while thermal loads are maximized with the longer duration, minimum flow rates. The test article thrust load must be reacted completely by the facility thrust stand since there is an O-ring slip joint in the exhaust piping. The design loads are shown in Fig. 2.

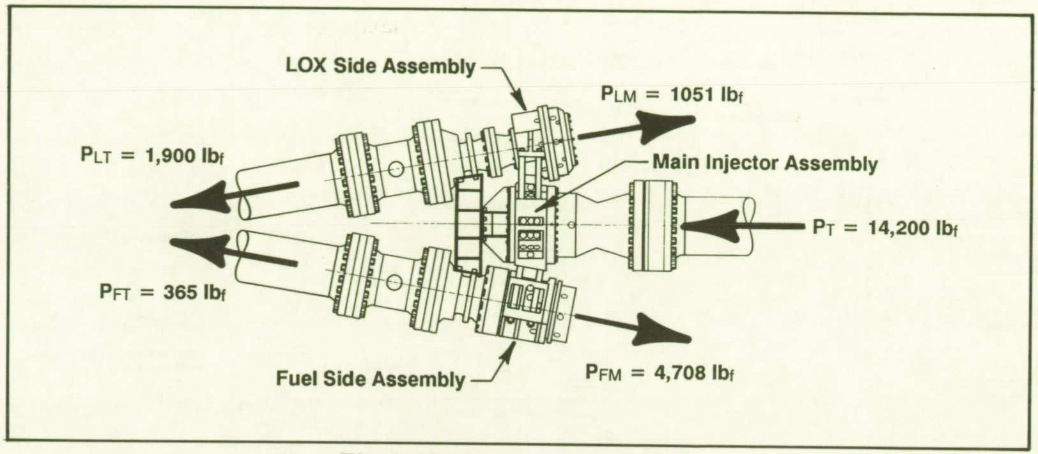

Fig 2 Model Design Loads

The application of these loads as a function of time is also of interest. Upon opening the flow control valves, the momentum and thrust loads are experienced almost immediately; however, thermal loads have yet to develop. Near the end of the test, all loads are applied simultaneously since the piping has undergone thermal contraction. When the control valve closes due to pressure decay in the blow down system, the momentum and thrust loads diminish, yet the thermal loads increase due to cold soaking of the supply piping. These considerations were drivers in establishing the final model design.

DESIGN CONCEPT

The considerations of the aerodynamic and thermal loading environments, combined with the extensive instrumentation requirements, led to the development of the modular construction concept for these models. See Fig. 3.

The modular concept provides direct load paths to the facility thrust stand by positioning the fuel and oxidizer housings of the test article relative to the main injector bowl with sleeved studs. The transfer ducts are entrapped between the housings and the main injector bowl with sliding seals at each end. This arrangement prevents the generation of significant thermal loads within the model and provides sufficient flexibility, as compared to the facility thrust stand, to prevent loading the transfer ducts in bending. This non-structural transfer duct concept was developed to minimize ductwall thickness in order to simplify the manufacture and instrumentation of this complex area of the HGM.

This modular concept also provides important assembly and handling benefits. The fuel side, the oxidizer side, and the main injector assembly may be built up in parallel to expedite model assembly. The completed fuel and LOX sides of the model are installed simply by sliding these component assemblies onto the four studs on either side of the main injector bowl and affixing the four retaining nuts, while the transfer ducts are held in the proper positions.

The goal of long term hardware value through testing flexibility led to the incorporation of flight article interfaces in the test article where appropriate. Flight turbopumps could be installed in the full scale HGM air flow models should the need arise. An immediate benefit of the interface feature has been realized in support of Pratt & Whitney and the ATD program. Full scale, thoroughly instrumented ATD turbine simulators have been designed and manufactured for integration testing in both the Phase II+ and current flight HGM.

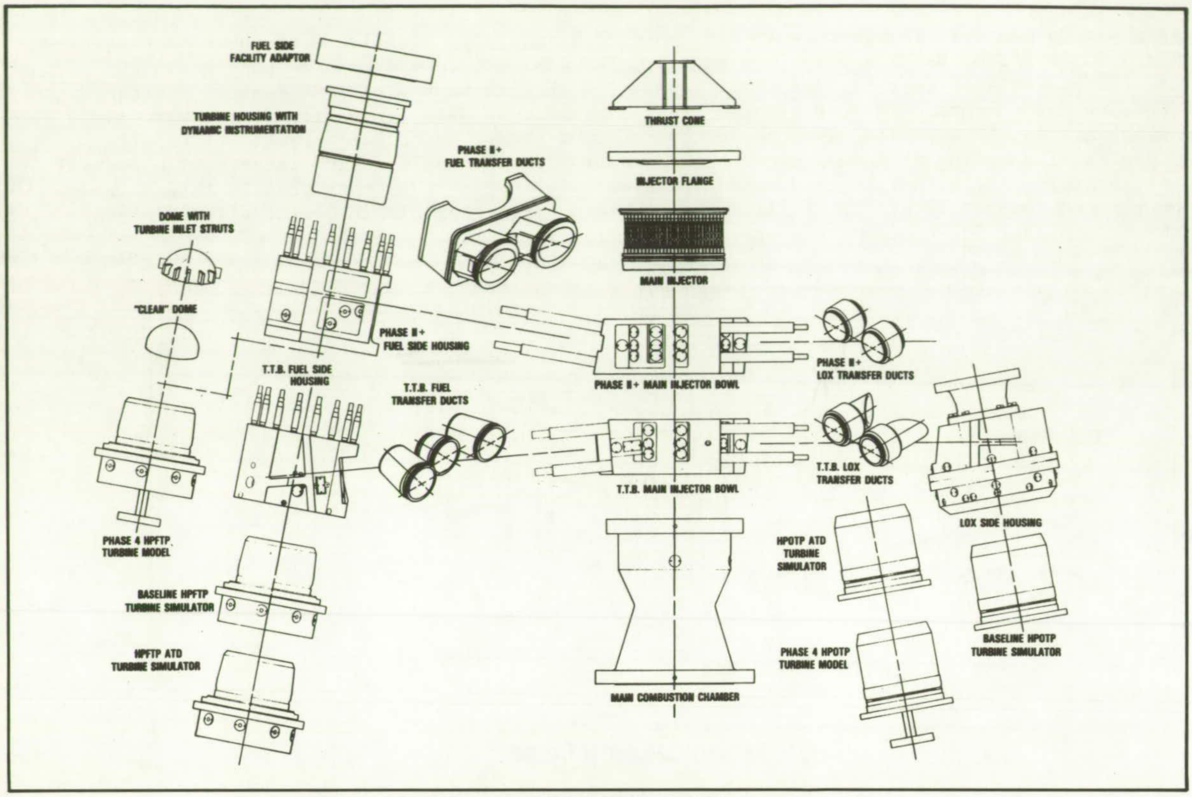

Fig 3 Full Scale SSME Model Components

The design effort for the prototype Phase II+ air flow model was initiated in April 1985, and the model was delivered ready for testing in November 1987. The current flight engine, Phase II, design started in November 1986, and the model was delivered in March 1988. The fifteen month reduction in the design/fab cycle for the second HGM model is a result of the modular construction approach to this hardware. The Phase II model uses many components from the Phase II+ air flow model. These common components are: HPFTP and HPOTP turbine simulators, main injector, main combustion chamber, and LOX side housing.

Both flow model configurations include a number of flow path components which are removable. This feature will aid in achieving an understanding of their influence on HGM flowfields. These removable components include: Turbine Inlet Struts, HPFTP Turbine Exit Guide Vanes, Fuel Side Struts and Posts, LOX Side Turning Vane, LOX Side Heat Exchanger, and LOX Post Flow Shields.

Flight components have been modified for use in the flow models when appropriate. Considerations include availability, ability to accomplish instrumentation requirements, and cost of flight hardware modification compared to cost of manufacturing a simulated component. Flight articles which have been modified for flow model use include the turning vane and heat exchanger for the LOX side, and the 600 element LOX post bundle for the main injector assembly. The modification of the injector required removal of the LOX dome and "hot dog" to provide access to the face plate for instrumentation (see Figs. 4 and 5). Three main injectors have been modified and instrumented for flow model use. One of these injectors is the super-post configuration which is scheduled for testing in July 1989. The other two injectors include pressure instrumentation and can also be used in the full scale SSME water flow models. These injectors may be tested with or without flow shields. Both models include the flow shields required for either the Phase II+ or Phase II configuration.

MATERIAL SELECTION

Material choices were limited to those listed in the ASME Pressure Vessel and Boiler Code, Section VIII, Division 1. The primary material is aluminum 6061-T6, selected for machinability and availability in relatively large forgings. The forgings required for major components exceed the size limitations of the material specifications. Procurement specifications for these forgings required mechanical properties in accordance with the appropriate ASME specification. Rough machining of large bores through these forgings was specified prior to tempering and aging; this increases the probability of uniform thermal treatments. After aging, samples were machined from the core of the forgings for Brinell hardness testing. The correlation between hardness and tensile strength was used to indicate that thermal treatments resulted in acceptable properties. The forgings were ultrasonically inspected to demonstrate the material contained no inclusions or discontinuities. Stainless steels are also used where appropriate, such as TP 347 for the main injector flange, selected for thermal expansion compatibility with the Inconel flight component. The highly three-dimensional swirl vanes are molded graphite-epoxy composite. A number of instrumentation potting techniques have been developed using a variety of adhesives and epoxies. The 630 psi hydro test requirements have been met satisfactorily.

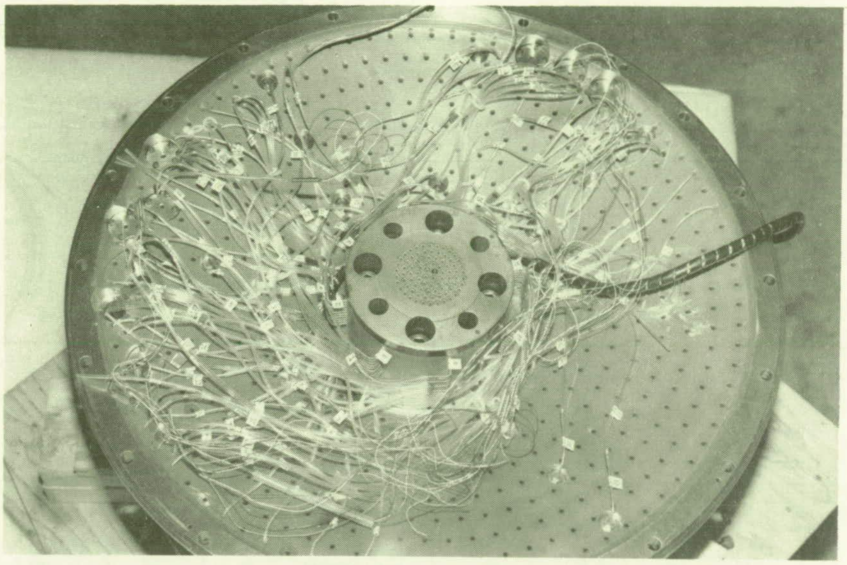
Fig 4 Injector Face Plate Instrumentation

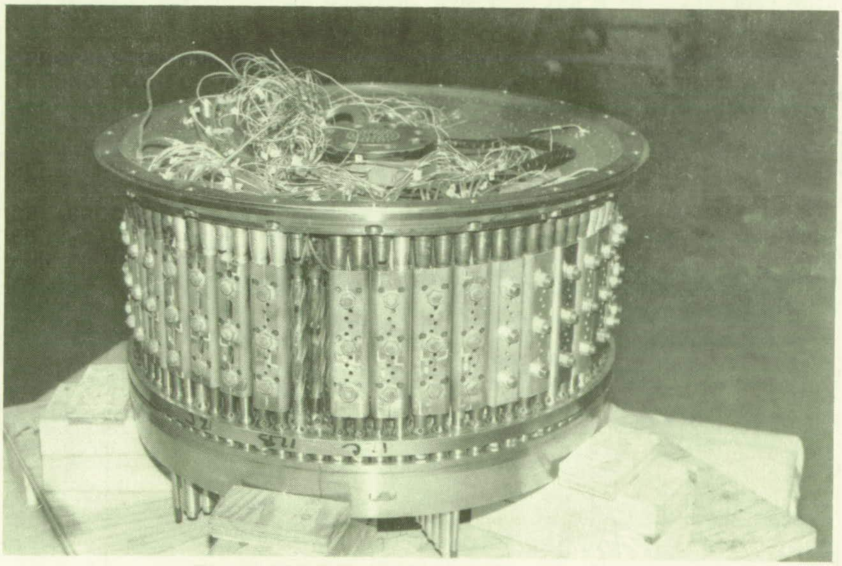
Fig 5 Modified Main Injector

INSTRUMENTATION

The instrumentation for the full scale air flow models was specified to address specific component problems, to understand issues associated with engine programs, and to provide a detailed fluid dynamic data base to support CFD developments. Where practical, the instrumentation locations correspond to locations for which hot fire and/or flight data are available.

PRESSURE INSTRUMENTATION

The flow models include provisions throughout the flow path for static pressure orifices, traversable pitot tubes, traversable kiel probes, traversable 3-D flow angularity probes, dynamic pressure transducers, and in select locations, total pressure rakes. The design permits these devices to be used interchangeably to provide data at the same location in the flow path. The requirements for the Phase II+ and the Phase II flow models are shown in Tables III and IV.

Table III Phase II+ Instrumentation

Measurement / Location	Static Orifices	Probes / Orifices	Dynamic Pressure Measuring Points	Rakes
Fuel Side				
Turbine Entrance	47		35	
Turbine Exit	24	8/40	16	8
Tad	8	8/40	8	
Tad Exit	56	8/40	16	
Fuel Bowl	66	7/35	46	
Transfer Ducts	151	4/20	35	8
Lox Side				
Turbine Entrance	1			
Turbine Exit	32	8/40	12	
Tad	8		8	
Tad Exit	8	8/40	12	
Lox Bowl	32	8/40	12	
Transfer Ducts	80	4/20	24	4
Main Injector				
Race Track	28	26/130	24	
Face Plate	24		24	
Lox Posts				
Lox Post Shields	60		11	
MCC	4			2
Totals	629	89/445	283	22

Table IV Phase II Instrumentation

Measurement / Location	Static Orifices	Probes / Orifices	Dynamic Presssure Measuring Points	Rakes
Fuel Side				
Turbine Entrance	47		35	
Turbine Exit	24	8/40	16	8
Tad	8	8/40	8	
Tad Exit	56	8/40	16	
Fuel Bowl	66	7/35	46	
Transfer Ducts	250	12/60	40	12
Hot Fire Probe		2		
Lox Side				
Turbine Entrance	1			
Turbine Exit	32	8/40	12	
Tad	8		8	
Tad Exit	8	8/40	12	
Lox Bowl	32	8/40	12	
Transfer Ducts	80	4/20	24	4
Main Injector				
Race Track	28	26/130	24	
Face Plate	24		24	
Lox Posts				
Lox Post Shields	60		11	
MCC	4			2
Totals	728	99/485	288	26

The requirement for interchanging a variety of devices at a common location was accomplished with the port and plug concept. The model hardware included standardized ports at the specified measurement locations. Plugs for each of the required devices were manufactured as shown in Fig. 6. The final machining of the flow surface of each plug was performed with the plug

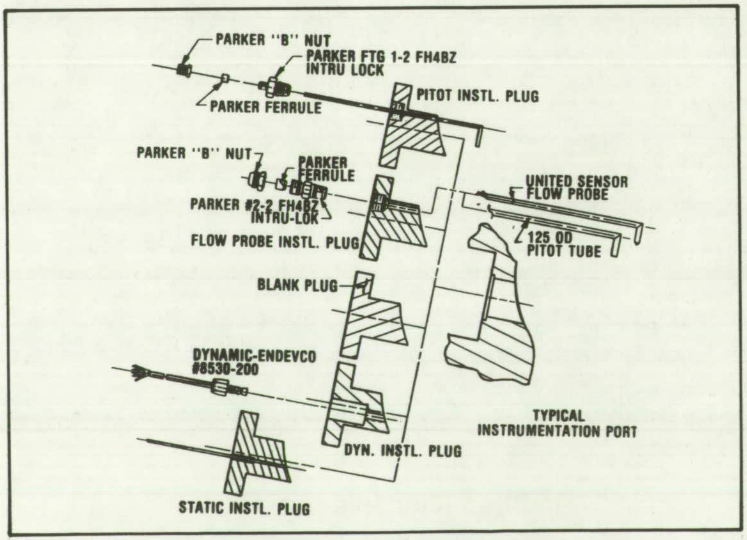

Fig 6 Port and Plug Concept

installed in the appropriate port. This technique insured that there were no discontinuities in the flow surface which could affect the measurements. The locations of the instrumentation planes for the fuel and LOX sides of the models are shown in Figs. 7 and 8. The main injector race track planes are shown in Fig. 9.

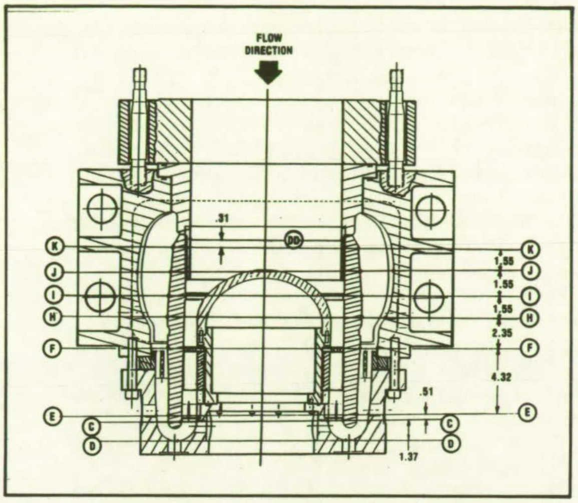

Fig 7 Fuel Side Instrumentation Planes

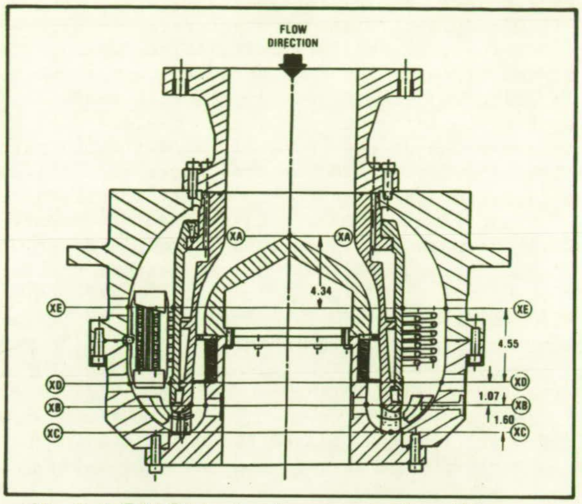

Fig 8 LOX Side Instrumentation Planes

Other Instrumentation. The main injector includes strain gaged LOX posts and four-component LOX post balances. Strain gages are installed on 23 of the row 13 posts and on 5 of the row 12 posts. The output of these gages will be analyzed to gain insight into the vibrational characteristics of the posts. Fluid dynamic loads on the posts will be measured with LOX post balances. It was necessary that the bridged beams be contained within the geometry of the heat shield retainers. This requirement precluded the cantilevered beam approach because the design loads would foul a cantilevered post against adjacent posts. This was experimentally verified when the primary and secondary Regi-Mesh plates were removed from the injector. The solution involved the use of a second bridged beam at the bottom of the post as shown in Fig. 10. The end of the post is supported with a spherical silicone bronze bushing that permits translation and rotation with negligible friction. A dead weight calibration fixture was fabricated and repeatable calibrations have been provided for the balances with and without the flow shields installed. The bridge outputs required non-linear data reduction techniques. Two LOX post balances have been manufactured. The injector includes provisions to install these balances at ten optional locations.

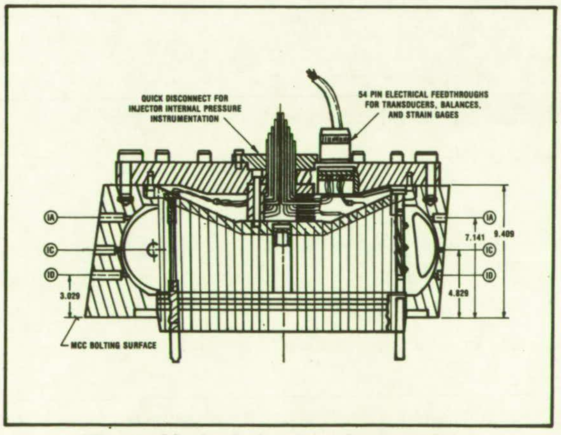

Fig 9 Main Injector Assembly Instrumentation Planes

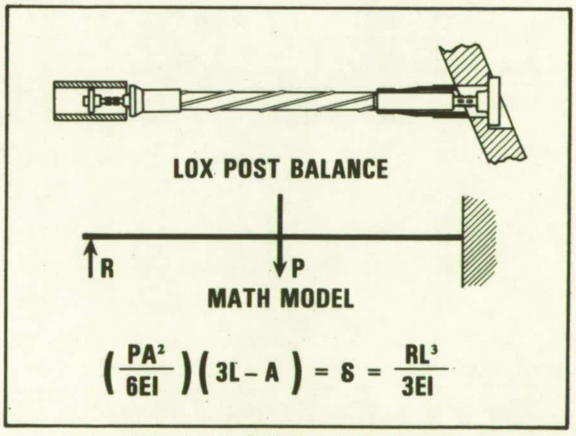

Fig 10 LOX Post Balance

CONCLUSION

The modular construction approach described herein has proven to be an effective means of providing extensively instrumented, accurate flow models for SSME flowfield characterization. Both models have been hydrostatically tested to 630 psi with no failures or unacceptable leaks. These flow models have been installed in the MSFC AFD and tested over the complete range of the design envelope. A facility malfunction has resulted in the flow control valves instantaneously opening and exposing the test articles to maximum momentum and pressure loadings. No failures were experienced. The Phase II+ HGM with baseline turbine simulators (see Fig. 11) completed a series of tests in August 1988. The desired data was obtained. These tests were followed by a very creative use of the Phase II+ hardware by Pratt & Whitney to verify the design of injector simulators for use in ATD hot fire testing. Additional hardware was designed and fabricated to permit fuel-side-only, or LOX-side-only operation. The LOX post bundle was replaced with the simulator and flow was exhausted through the passive side of the model into a spool which replaces the MCC. This test was successfully completed in October 1988 and program goals were achieved with minimal hardware expense due to maximum use of existing components. The flow model of the flight engine is scheduled to complete a series of tests in June 1989. This model is shown installed in the MSFC AFD facility in Fig. 12. The complexity of this flow model is shown in Fig. 13. The fuel side is shown in half section, and the other major elements are shown with a quarter section removed. Details, such as the turbine simulator swirl vanes, and flow path discontinuities, such as the doubler and welds, are shown; however, much of the instrumentation detail has been omitted from this illustration for simplicity. A third full scale SSME air flow model, the pilot model, is scheduled for design and fabrication in early 1990. This model will include simplified geometries and serve primarily as a CFD validation tool.

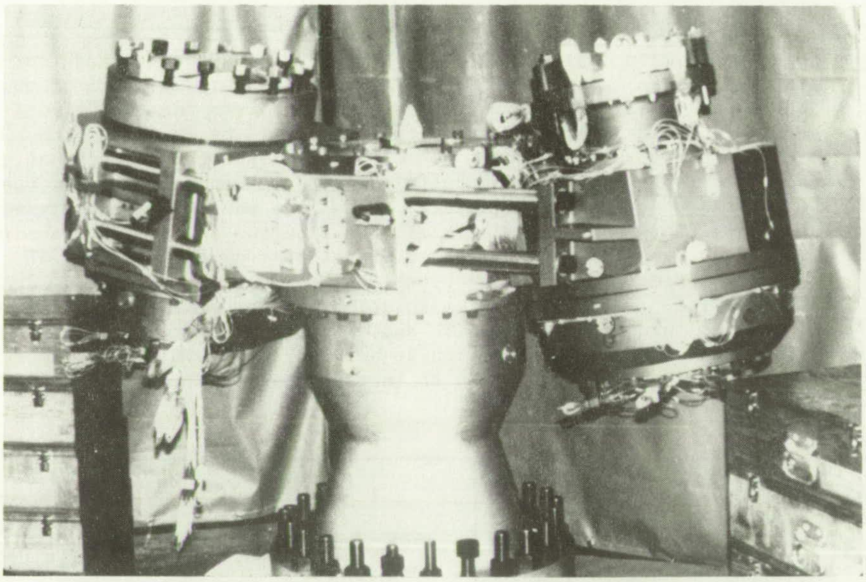

Fig 11 Phase II + Air Flow Model

ACKNOWLEDGEMENTS

The contributions of the following individuals have been invaluable throughout the design and fabrication cycles for these flow models:

Mr. Tim Hall, Designer, Micro Craft, Inc. - Mr. Hall established the flow path dimensions for the Phase II model and provided design details for both models.

Mr. Mike Richardson, Senior Modelmaker, Micro Craft, Inc. - As manufacturing team leader, Mr. Richardson provided manufacturing expertise and project coordination for both flow models.

Mr. E. K. Wood, Senior Modelmaker, Micro Craft, Inc. - Mr. Wood contributed project leadership and machining expertise for both flow models.

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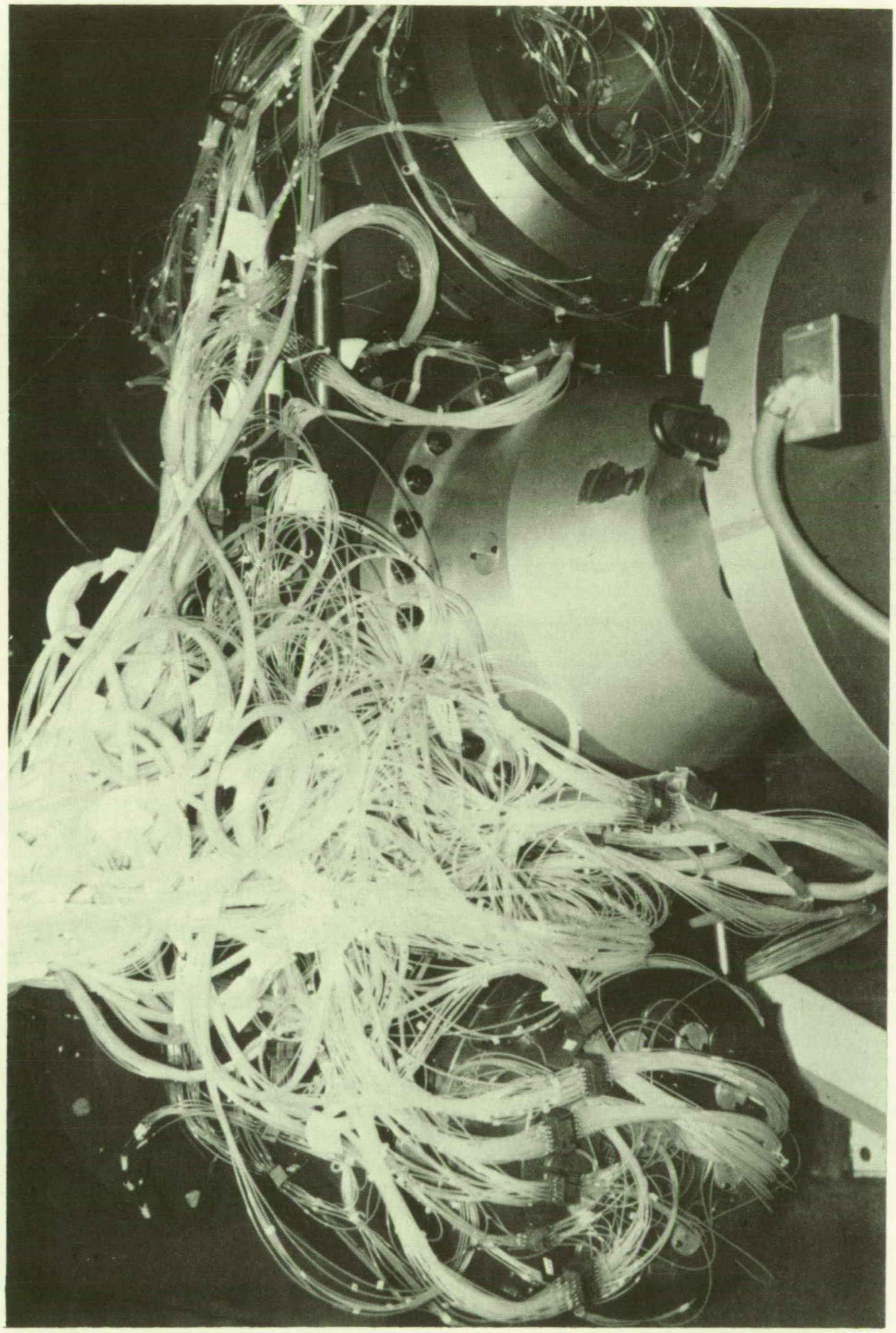

Fig 12 Flight Engine Flow Model in AFD

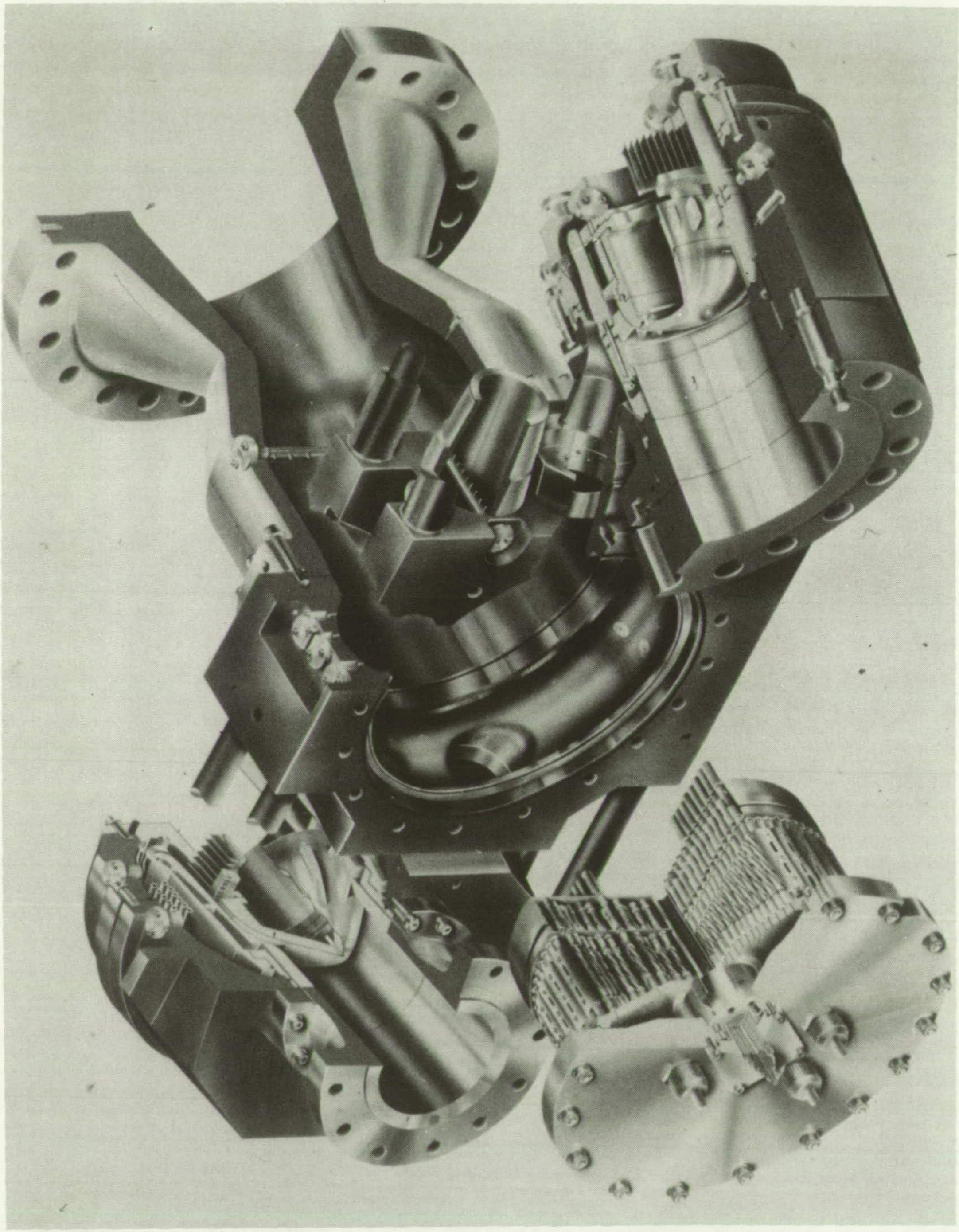

Fig 13 Cut-Away of Flight Engine Flow Model