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Mach 5 to 7 RBCC Propulsion System Testing at NASA-LeRC HTF

H. Douglas Perkins, Scott R. Thomas, and William D. Pack
Lewis Research Center
Cleveland, Ohio

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H. Douglas Perkins, Scott R. Thomas, and William D. Pack
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

A series of Mach 5 to 7 freejet tests of a Rocket Based Combined Cycle (RBCC) engine were conducted at the NASA Lewis Research Center (LeRC) Hypersonic Tunnel Facility (HTF). This paper describes the configuration and operation of the HTF and the RBCC engine during these tests. A number of facility support systems are described which were added or modified to enhance the HTF test capability for conducting this experiment. The unfueled aerodynamic performance of the RBCC engine flowpath is also presented and compared to sub-scale test results previously obtained in the NASA LeRC 1x1 Supersonic Wind Tunnel (SWT) and to Computational Fluid Dynamic (CFD) analysis results. This test program demonstrated a successful configuration of the HTF for facility starting and operation with a generic RBCC type engine and an increased range of facility operating conditions. The ability of sub-scale testing and CFD analysis to predict flowpath performance was also shown.

The HTF is a freejet, blowdown propulsion test facility that can simulate up to Mach 7 flight conditions with true air composition. Mach 5, 6, and 7 facility nozzles are available, each with an exit diameter of 42 in. This combination of clean air, large scale, and Mach 7 capabilities is unique to the HTF. This RBCC engine study is the first engine test program conducted at the HTF since 1974.

Introduction

Rocket Based Combined Cycle engines combine the high thrust-to-weight ratio of rockets with the high specific impulse of ramjets in a single integrated propulsion system that is capable of generating thrust from sea-level-static to high Mach number conditions. The "strutjet" tested at the NASA Lewis HTF is one example of this engine concept which is being developed cooperatively by a government and industry team.

The strutjet is an ejector ramjet engine in which small, fuel rich rocket chambers are embedded into the trailing edges of the inlet compression struts. The engine operates as an ejector ramjet from takeoff to about Mach 3. At low Mach numbers, entrained air is completely consumed by the fuel rich rocket exhaust. As freestream Mach number and air flow increase, additional fuel is introduced to maintain the stoichiometric combustion of all available oxygen. At approximately Mach 3 the strut rockets are turned off. Above Mach 3 the engine operates as a thermally choked ramjet, and then transitions to supersonic combustion (scramjet) mode. For space launch applications, the rockets are re-ignited at a Mach number beyond which airbreathing propulsion becomes impractical. Further details of this engine concept are available in Ref. 1.

The purpose of this paper is to show the successful integration of a generic RBCC type engine into the HTF, the increased operating range achieved by the HTF, and the high fidelity of previously completed subscale and CFD simulations of this engine configuration as demonstrated by the HTF unfueled engine data.

Facility Description

General

The HTF is a blowdown, non-vitiated freejet test facility capable of testing large scale propulsion systems at Mach numbers up to 7. Major features of the facility are shown in Fig. 1. Nitrogen from the GN_2 rail car is supplied at the desired test pressure to the magnetic induction graphite storage heater where it is heated to a temperature somewhat above the desired test total temperature. This GN_2 then passes out of the heater bed into the hot train section where ambient temperature GO_2 and GN_2 are added to bring the flow to true air composition and the desired test total temperature. This flow then goes through a converging-diverging facility nozzle which expands the flow to supersonic conditions. The test flow then passes through and around the engine mounted on the thrust stand in the test cabin and enters the diffuser. The test cabin and diffuser are kept at altitude through the use of a steam ejector mounted in the diffuser duct which exhausts all of the test flow to atmosphere. Additional facility description is contained in Refs. 2 and 3.

GN_2 Heater

Figure 2 is a cutaway of the graphite storage heater. The heater consists of a stack of 15 cylindrical graphite blocks 6 ft in diameter and 2 ft in height, with 1100 holes drilled through each block to distribute the GN_2 flow. Hexagonal graphite block keys assure the proper alignment of the drilled holes which increase in diameter from the bottom block to the top block to maintain a constant velocity and to minimize the pressure drop through the stack. Electric current from a 180 Hz, single phase, 750 V supply (3 MW) is passed through water cooled copper induction coils to induce a magnetically coupled current in the outer diameter of the graphite blocks to a depth of about 4 in. The graphite blocks are then heated as a result of their resistance to the induced current. The heat induced on the outer edge of the blocks then soaks by conduction to the center of the blocks. The blocks are heated at a maxi-mum rate of 50 °F/hr in order to reduce thermal stresses. The stack of blocks is insulated with a 7 in. thick layer of graphite felt and a 2 in. thick silicon carbide tile shell to reduce heat loss to the outer components and the water cooled pressure vessel. The heater core assembly is con-tained in a water cooled carbon steel pressure vessel rated for 1200 psig. The maximum heater outlet conditions are 4500 °F and 130 lb/s.

Hot Train Components

After the heated GN_2 exits the heater bed it enters what is referred to as the “hot train,” consisting of the hot tee, the radiation shutter valve, the diluent injection flange, the film cooling flange, the mixer and the facility nozzle. This assembly is shown in Fig. 3. These components up to the nozzle have an inside diameter of ~18 in. and are all water cooled. There are currently three water cooled facility nozzles which expand the flow to Mach 5, 6, or 7. Each nozzle has a 42 in. exit diameter.

Test Cabin/Thrust Stand

The test chamber is a domed cylindrical structure 25 ft in diameter and ~20 ft in height made of high carbon steel. The chamber is equipped with a 17 in. diameter vent valve used to bring the chamber quickly back to atmospheric pressure. The facility nozzle penetrates the test cabin wall ~8-1/2 ft and the supersonic diffuser penetrates the test cabin wall ~6-1/2 ft. Each penetration is sealed with an inflatable rubber seal. The engine is mounted on an overhead translating thrust stand. The engine can be translated up to 30 in. along the freejet axis and can be hydraulically pivoted to a 5° angle of attack. The engine can also be pivoted out of the flow stream in order to change out the facility nozzle. The thrust stand was designed to handle a test article of up to 16,000 lb weight and 8,500 lb thrust.

Diffuser/Steam Ejector System

The exhaust system consists of a water cooled supersonic diffuser, a heat sink subsonic diffuser, a spray cooler, and a single stage steam ejector. The supersonic diffuser consists of a translatable, water cooled, 55 in. diameter inlet collection cone followed by a constant diameter section 30 ft in length and 43 in. in diameter. The subsonic diffuser incorporates water spray nozzles designed to cool the exhaust gases to saturation temperature. The single stage steam ejector uses a coaxial nozzle and consumes 500 lb/s of steam at 130 psig. Steam is supplied to the ejector through a 30 in. pipe from five 500 psig steam accumulators with a combined useful capacity of 144,500 lbs of steam. The accumulators are located ~3,000 ft from the HTF. .

GN_2 Supply System

GN_2 is supplied to the heater bed, to the diluent mixing section, and for general facility use from a high pressure railroad tank car. This vessel has a capacity of 663,000 SCF at its rated pressure of 4500 psig. However, the system is currently operated at a maximum of 3300 psig due to limitations in the feed piping system to the facility. The GN_2 vessel is charged from a 66,000 SCFH LN_2 vaporizer located near the facility.

GO_2 Supply System

GO_2 is supplied to the diluent mixing section downstream of the heater from six high pressure bottles mounted next to the steam ejector/diffuser. These bottles have a combined capacity of 386,000 SCF at their rated pressure of 2212 psig. The GO_2 bottles are charged from a 20,000 SCFH LO_2 vaporizer located adjacent to the bottles.

JP-10 Supply System

JP-10 is supplied to the engine forward and aft fuel injection blocks from either of two 1500 psig GN_2 pressurized supply tanks. The first tank has a capacity of 20 gal and operates at ambient temperature, while the second tank has a capacity of 10 gal and operates at temperatures up to 450 °F. The JP-10 in the high temperature tank is heated using an electrical resistance immersion heater. A recirculation pump is used to keep the heated JP-10 from stratifying and to keep the engine feed lines at temperature. Heated JP-10 was not used in this phase of the RBCC test program. Fuel flow rate is measured using venturi flow-meters and is controlled using hydraulically operated globe valves. A simplified schematic of this system is shown in Fig. 4(a).

Silane Supply System

A pyrophoric mixture of 20 percent silane (SiH_4) and 80 percent H_2 by volume is supplied to the forward fuel injection block as an ignition source for the JP-10. The silane/H_2 mixture flow is controlled by a sonic venturi and flowrate is calculated based on upstream conditions. The silane/H_2 mixture is supplied from a pair of 250 SCF bottles located outside the test cabin. A simplified schematic of this system is shown in Fig. 4(b).

Engine Water Cooling Systems

The engine leading edges are water cooled using two 20 gal, 1000 psig pressurized supply tanks connected in parallel. The exit from the engine leading edges is throttled with a hand valve to maintain 250 psig backpressure during operation to help prevent boiling. The precompression plate in front of the engine inlet and the precompression plate support struts have water cooled leading edges which are supplied from a facility 400 psig centrifugal pump.

Data Systems

The HTF is equipped with 3 different data systems serving 3 different applications. The data recording and display system for all of the facility related data parameters is an ESCORT D system which scans a maximum of 527 channels at a rate of 1 sample/sec on all channels. Additionally, there is a 64 channel MassComp high speed data system capable of scanning at an aggregate rate of 330,000 samples/sec. This system was set to sample all 64 channels 20 times/sec for these tests. There is also a 192 channel Electrically Scanned Pressure (ESP) unit that is used at HTF which samples engine static pressures at a rate of ~17 samples/sec across all channels.

Test Article Description

General

The model is a heat sink type strutjet engine constructed primarily of 2 in. thick Oxygen Free Electronic (OFE) grade copper plates. The engine is shown schematically in Fig. 5. The inlet is a fixed geometry design which incorporates two windscreen/isolator struts that divide the inlet into 3 channels. Behind each windscreen/isolator strut is a forward fuel injection block followed by an aft fuel injection block which also houses 3 small rockets. The top surface of the diverging nozzle section is made up of hinged sections which allow the nozzle expansion angle to be changed between tests. All of the different sections used to construct the engine are sealed from leakage using red silicon o-rings compressed between the sections. A precompression plate is mounted in front of the inlet to partially simulate a vehicle forebody in order to give the proper engine inlet conditions. The leading edges of the inlet, struts, and precompression plate are all water cooled.

Precompression Plate

Prior to entering the engine, the freejet air flow encounters a forebody simulation precompression plate. This plate is 28 in. long, 25 in. wide at the upstream end and tapers back to a width of 9 in. at the engine inlet. The plate length was selected to place the plate bow shock at the engine cowl leading edge at Mach 6. The plate is at an 8° angle to the flow, matching the inlet top wall angle, and the trailing edge of the plate is in line with the inlet top wall. A gap of ~1/4 in. allows for thermal growth of the model and for deflection of thrust stand mounts. An interlocking, non-contacting seal was installed between the precompression plate and the inlet top wall to prevent excessive flow spillage. The precompression plate can be mounted with a 1 in. offset to the inlet top wall to provide boundary layer diversion, but this was not done in this test program. The precompression plate is constructed of 1 in. OFE copper and is supported by two carbon steel struts. The carbon steel support struts are constructed with removable water cooled copper leading edges.

Inlet

The freejet air flow, after passing through the precompression plate bow shock, passes into the engine inlet. The inlet consists of an 8° compressive top wall, 2 compressive struts, a flat bottom (cowl) surface, and 2 flat side walls. The cowl leading edge is located at the maximum thickness point along the inlet struts, 12.7 in. behind the top wall leading edge. The inlet flow is compressed by the 8° ramp of the precompression plate and inlet top wall, then by the strut leading edge sections. There is no internal contraction downstream of the cowl leading edge. Although the cross sectional geometry varies, the net cross sectional area is constant. The convergence between the cowl and top wall panels is compensated for by a reduction in strut thickness. This lack of internal contraction enables the inlet to self-start at a Mach number below Mach 4.

Leading Edges

The leading edges of the inlet (top wall, cowl, side walls, and struts) are water cooled using 1000 psig water supplied from two GN_2 pressurized tanks in parallel. The leading edges were formed by electron beam welding a 0.200 in. outside diameter, 0.070 in. wall thickness OFE copper tube into a recess machined into each leading edge. The weld areas were then finish machined to create a smooth, continuous surface. All of the engine leading edges are removable for repair or replacement. The leading edges of the precompression plate and the two precompression plate support struts are water cooled using 400 psig water from a facility water cooling supply pump. The leading edges of the two support struts for the precompression plate are water cooled through 0.25 in. inside diameter, 0.100 in. wall thickness passages drilled into the copper leading edge inserts.

Nozzle

The nozzle section is made up of three manually adjustable top wall sections along with the 2 flat side walls and the bottom (cowl) plate. The top wall is made up of two 12 in. long sections and one 19.65 in. section. These sections are adjustable through the use of jack screws located above the model. The first two sections were configured with an expansion angle of 6° for these tests. The last section was set at a expansion angle of 10.2° to give a 10 in. nozzle exit height.

Forward Fuel Blocks

The forward fuel blocks are constructed of stainless steel and are 3.75 in. long and 0.90 in. wide. There are three fuel manifolds drilled into each block for distributing the fuel into the center and side flow channels. The forward fuel manifold has two 0.040 in. diameter injection orifices on each side for a pyrophoric mixture of 20 percent silane (SiH_4) gas and 80 percent hydrogen gas used as the engine pilot. The second and third manifolds are configured with two 0.024 in. diameter injection orifices on each side for liquid JP-10 fuel. The JP-10 is vaporized and ignited by the flame from the silane/H_2 mixture. Only the first of the two JP-10 manifolds was used for these tests. The forward and aft fuel blocks are bolted together and inserted into the model from the top wall where they are held at the bottom in a machined slot and at the top by a clamp secured to the side walls. The fuel distribution can be changed by welding shut the existing orifices and redrilling new orifices. The fuel block assembly is shown in Fig. 6.

Aft Fuel Blocks

The aft fuel blocks are constructed of OFE copper and are 7.00 in. long and 0.90 in. wide. The aft fuel blocks contain three gelled propellant Mono-methyl-hydrazine/ Inhibited Red Fuming Nitric Acid (MMH/IRFNA) rocket chambers and two JP-10 injection “shower heads” per block. The platelet injector fed rocket chambers operate at 2500 psia and have a 0.33 in. diameter throat, generating 330 lb of thrust per chamber. The rocket chambers are water cooled from a 4000 psig supply. As the strut rockets were not used during this phase of the test program, two aft fuel blocks with the same outside dimensions but without the embedded rocket engines were used.

The JP-10 “shower heads” are trapezoidal stainless steel blocks mounted on the downstream face of the aft fuel blocks between the rocket nozzles. These injectors have two 0.024 in. diameter orifices on the top and bottom angled surfaces, and one 0.024 in. diameter orifice on each of the two side faces of the injector. These injectors are fed from fuel lines passing through the aft fuel block to the forward fuel block, where they are fed from a common supply manifold. The fuel distribution from the aft JP-10 injectors is also changed by welding shut the existing orifices and redrilling new orifices.

Instrumentation

The engine instrumentation consists primarily of 82 static pressure taps located along the top wall, side walls, and rear surfaces of the engine and along the top surface of the precompression plate. Additional static pressure taps are included in the engine shrouding to determine approximate thrust loads for those surfaces. Other measurements include the engine thrust and 5 combustor wall temperatures using chromel/alumel (type K) thermocouples.

Test Article Installation

Engine Mounting

The engine assembly is suspended from the overhead thrust stand using two 10 in. I-beams. The two support I-beams are in turn mounted to a box frame which is then bolted to the thrust stand. The forward I-beam is in the vertical position and mounts rigidly to the engine sidewalls near the rear of the inlet above the top wall. The rear I-beam angles back from approximately the midpoint of the engine up at the box frame to a hinged joint located half way along the nozzle section. The engine hangs ~3 ft below the bottom of the thrust stand assembly. An isometric view of the mounted engine is shown in Fig. 7.

Position in Facility Nozzle Flow

The inside diameter of the exit of each of the 3 HTF facility nozzles is ~42 in. Based on previous nozzle calibrations,[4] a uniform core flow of at least 30 in. exists for each nozzle used for this program. The engine is mounted such that the leading edge of the precompression plate is 5.8 in. above the nozzle centerline. In this position, the leading edge of the cowl is 6.2 in. below the nozzle center-line. With this geometry, a uniform core flow of 27.5 in. diameter is required, which is less than the uniform core available. Thus, boundary layer and nozzle distortion effects do not have to be considered when analyzing the test results.

Shrouding

To protect the instrumentation and equipment located immediately above the engine from heat and “wind” damage, shrouding was installed from the top of the engine up ~23 in. This shrouding is constructed of 1/4 in. copper plate in the front and 1/8 in. copper plate in the rear. The shrouding is tapered in the front and has a solid copper nose piece. At the rear of the engine the shrouding follows the contour of the engine. The shrouding is sealed to the top of the engine using 1/4 in. ceramic rope held in place by a thin strip of steel screwed into the top of the model. The shrouding assembly is visible in Fig. 8.

Facility Starting Appliances

To facilitate starting of both the tunnel and the engine, an aerodynamic starting "appliance" was installed. This hardware consists of upper and lower semicircular sections that act as an extension of the facility diffuser around the engine. The sections are constructed of 1/4 in. carbon steel plate rolled to match the diffuser entrance diameter. The lower section is a single piece 75 in. long mounted to a frame of structural steel which is in turn mounted to both the diffuser entrance and the floor. The upper section is cut into three pieces to facilitate disassembly for access to the engine. These 3 pieces are bolted to each other and to the lower section. When fully assembled, the "appliance" comes up from the diffuser to just behind the engine inlet as shown in Fig. 9. The installed engine, shrouding, and precompression plate flow blockage is ~28 percent.

Precompression Plate Mounting

The precompression plate support struts are mounted to a 1 in. thick carbon steel plate. This plate is then mounted to a support structure cantilevered from a non-metric section of the thrust stand assembly. Any loading applied to the precompression plate is not a part of the engine thrust measurement. A 1 in. thick carbon steel spacer is placed between the precompression plate mounting plate and the support structure to lower the plate in line with the inlet. This plate can be removed to divert the precompression plate boundary layer from the engine inlet.

Test Sequencing

Tunnel Operations

Prior to facility operation, the heater and supporting systems are energized and the heater is brought up to the required operating temperature. The steam plant is brought on line and all accumulators are charged to 500 psig. The cooling water system, main nitrogen and oxygen systems, hydraulic systems, control systems, and data systems are set up and calibrated. The steam line is preheated using steam supplied directly from the boilers. A 2.5 psig purge is present on the graphite heater at all times. Immediately prior to facility operation, the steam line is brought up to 200 psig at the ejector supply station. The chamber vent valve is then closed, the cooling water flow is established, a 2.5 psig purge is placed on the hot train components, and the radiation shutter valve is opened. The main steam supply valve is then opened and the ejector flow is established. When the test chamber pressure drops below 3 to 4 psia, the nozzle pressure is then slowly ramped up to the test operating point and the spray cooler is brought on line. The initial portion of the facility ramp is done without oxygen, using ambient temperature diluent nitrogen to control the nozzle temperature. Oxygen is then brought on during the final portion of the nozzle pressure ramp, at which time the ambient temperature nitrogen is reduced. The facility control system then balances hot nitrogen, ambient temperature nitrogen and oxygen flows to supply "air" at the appropriate test temperature, pressure, and composition. During the course of the test run the storage heater temperature drops several hundred degrees, requiring the controls to constantly adjust the flow mixture. At the end of the test, the oxygen flow is shut off and replaced with ambient temperature nitrogen flow as the nozzle pressure is slowly ramped back down to zero. The spray cooler is then shut off, the heater nitrogen purge is re-established, and the radiation shutter valve is closed. Finally, the steam ejector is shut off and chamber vent valve opened.

Engine Operations

After the facility has ramped up to the test condition, a dwell time of ~3 sec is allowed for the facility nozzle inlet pressure and temperature to steady out before beginning engine operations. The initial tests at each Mach Number were run without fuel to determine engine/tunnel starting characteristics and aerodynamic drag. The next series of tests were run with fuel injected from the forward fuel blocks only. In general, the Silane/H_2 mixture was introduced 1 sec prior to initiating the forward JP-10 flow. The JP-10 was started at a low flow rate, and then increased in 2.5 to 4 sec steps up to a point beyond the estimated unstart limit. After the unstart limit for the forward fueling stations was thus determined, a similar series of tests were run to determine the unstart limit of the engine with JP-10 flow from the aft fuel blocks. The forward JP-10/Silane/H_2 flow rates were set at 75 to 80 percent of their unstart limit and then aft JP-10 flow was initiated 2.5 to 4 sec later at a low level and increased in 2.5 to 4 sec steps up to a point beyond the estimated unstart point. The total fueled run time for the engine was set at 20 sec for Mach 6 conditions and 15 sec for Mach 7 conditions. The run times were limited by heat loads on the engine and on several facility components.

Test Results

Test Facility Conditions

The RBCC engine test plan called for the facility to be operated at a Mach 6 enthalpy (3000 °R) with the Mach 5 facility nozzle to simulate a Mach 6 flight condition. The lower engine inlet entrance Mach number was used to account for the bow shock of the vehicle on which the engine would be installed in flight. The test plan similarly called for the facility to be operated at a Mach 7 test gas enthalpy (3900 °R) with the Mach 6 facility nozzle to simulate a Mach 7 flight condition. The HTF as configured was able to achieve a test gas enthalpy equivalent to Mach 6.6 (3500 °R) at 1065 psia total pressure during this test series. The maximum test condition previously demonstrated since the HTF reactivation was completed in 1994 was 3000 °R total temperature at 1050 psia total pressure. Modifications to the facility will be required to achieve the full Mach 7 test condition.

Table I summarizes the tests run at HTF during this test program, including the engine fueling locations used for each run. Lower temperatures and pressures were used on initial runs to check out the facility and engine systems prior to full test condition operation. The majority of data was taken with the Mach 6 facility nozzle. Table I does not include aborted tests where no useful engine data was recorded.

Engine Aerodynamic Test Data and Comparison to Subscale Inlet Aerodynamic Test Data

A series of aerodynamic studies of a 40 percent scale model of the inlet region down to the end of the fuel blocks were conducted previous to the fabrication of this full scale RBCC engine to aid in the design and characterization of the inlet. These tests were conducted at NASA Lewis Research Center's 1x1 SWT over a test Mach number range of 4 to 6. Details of this test program are contained in Ref. 5. The test hardware configuration used for these subscale tests is shown schematically in Fig. 10. Figure 11(a) shows a plot of this data for the Mach 5 case overlaid upon a plot of the RBCC engine data for the same conditions. The Mach numbers listed throughout this section refer to the facility nozzle exit Mach number, as opposed to the simulated flight Mach number. All pressure distributions shown were measured along the top wall (body side) of the engine on the engine centerline. A scaled drawing of the HTF engine is included above the plot to help correlate the pressure distributions with the engine hardware. As shown, the zero position is referenced to the leading edge of the inlet top wall. Distances are shown linearly along the top wall of the engine uncorrected for angle. Figure 11(b) shows a similar plot for the Mach 6 case.The pressure spikes at 23 in. and 42 in. in the Mach 5 case are a result of the impingement on the top wall of the reflected precompression plate bow shock. The Mach 6 case does not indicate the second shock impingement in either data set. For both cases, the divergence between the subscale and full scale pressure distributions beyond the strut base is indicative of differences in geometry in that area. The good agreement of these results helped to validate the use of pitot survey data from the subscale tests in determining flow distribution within the RBCC engine and air capture by the inlet.

During the subscale inlet study, a series of tests were run with the inlet back-pressured by a flow plug in order to simulate the effect of high pressures in the combustor/nozzle region upon the inlet. Figure 12 shows a fueled static pressure distribution for the full scale RBCC engine overlaid with a plot of the subscale inlet back-pressured to the same combustor static pressure at the 38 in. location. As shown, the subscale testing accurately modeled the pressure profile in the inlet/isolator region. This result gives further confidence to the use of this subscale testing meth-odology for predicting combustor/inlet interaction.

Comparison to CFD Analysis Results

A CFD analysis of the HTF engine at Mach 5 and 6 without fuel was conducted in parallel with the freejet test activity. The details of this analysis are contained in Ref. 6. Figure 13(a) shows a plot of the CFD analysis results for the Mach 5 case overlaid with a plot of the HTF engine data for the same conditions. Figure 13(b) shows a similar plot for the Mach 6 case. The CFD results accurately predict the pressure distribution within the engine, capturing the position and magnitude of peaks and correctly predicting the changes shown between the Mach 5 and Mach 6 cases. This validation of the CFD analysis allows for the use of the computational model to determine flow field details not available from the subscale or full scale engine tests.

Summary

A series of 15 tests of an RBCC strutjet engine were conducted at the NASA LeRC HTF. These tests further demonstrated the operability of the HTF, including the achievement of test conditions above those previously demonstrated. These tests also demonstrated a successful aerodynamic configuration for the HTF with a representative RBCC class engine installed. The HTF was upgraded to include heated and ambient hydrocarbon fuel systems, a silane ignition system, a high pressure cooling water system, and a high speed data system. Mach 5 and 6 unfueled and liquid JP-10 fueled engine performance data was taken and shown to agree well with subscale test data and CFD analysis. Further testing should be conducted to optimize fueled engine performance with JP-10 and to demonstrate engine performance with rockets at sea-level-static conditions and at high Mach number.

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TABLE I.—FACILITY CONDITIONS SUMMARY

Run number	Data number	SiH_4/H_2 flow, Y/N	FOR. JP-10 flow, Y/N	AFT JP-10 flow, Y/N	Facility nozzle, Mach number	Average heater temperature, °R	Nozzle mass flow, lb/s	Nozzle inlet total temperature, °R	Nozzle inlet total pressure, psia	Steady state test time, sec	Facility nozzle exit static pressure, psia
1	8	N	N	N	5	3710	160	2440	365	9	0.72
2	10	Y	Y	N	5	4060	190	2770	515	16	0.71
3	14	Y	Y	N	6	4140	185	2950	1065	20	0.64
4	15	Y	Y	N	6	4080	185	2960	1065	20	0.64
5	17	Y	Y	Y	6	4090	190	2870	1065	15	0.63
6	18	Y	Y	Y	6	4120	185	2960	1065	20	0.64
7	25	Y	Y	N	6	4120	185	2960	1065	17	0.58
8	32	Y	Y	Y	6	4260	185	3025	1065	18	0.60
9	33	Y	Y	Y	6	4280	190	2850	1065	18	0.63
10	34	Y	Y	Y	6	4320	190	2905	1065	23	0.57
11	36	N	N	N	6	4690	165	3470	1075	3	0.55
12	38	Y	Y	N	6	4690	170	3500	1065	15	0.56
13	39	Y	Y	Y	6	4670	170	3450	1065	15	0.56
14	40	Y	Y	Y	6	4630	170	3475	1065	17	0.58
15	41	Y	Y	Y	6	4690	170	3500	1065	15	0.58

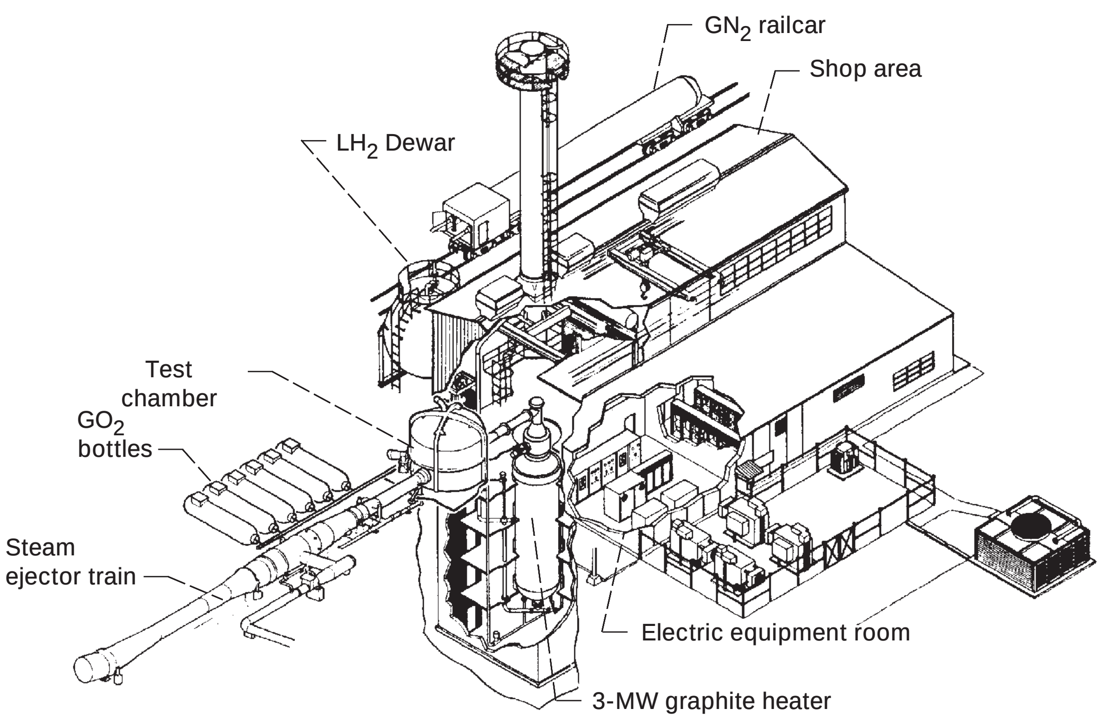

Figure 1.—Cutaway view of Hypersonic Tunnel Facility (HTF).

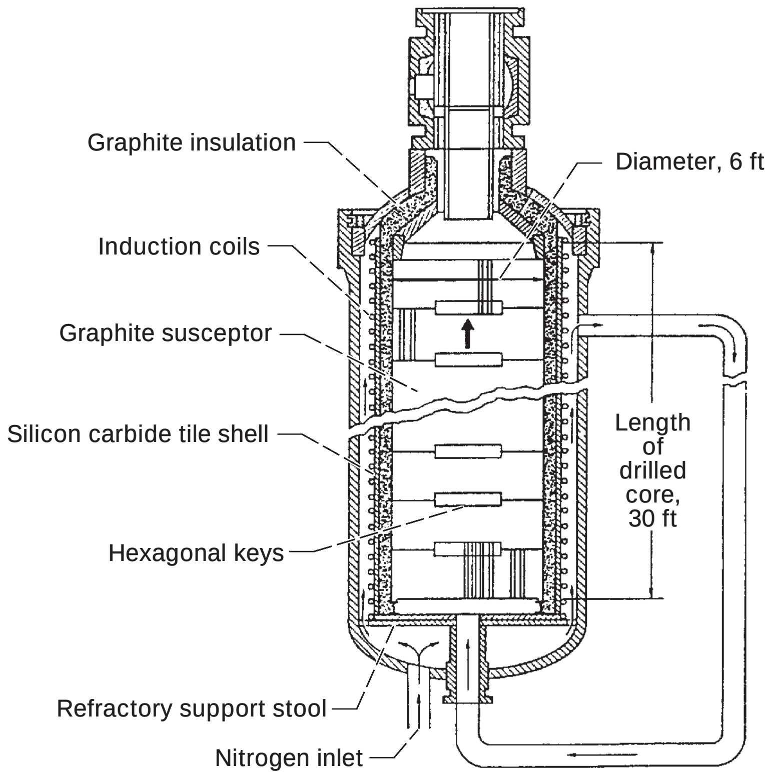

Figure 2.—Nitrogen induction storage heater.

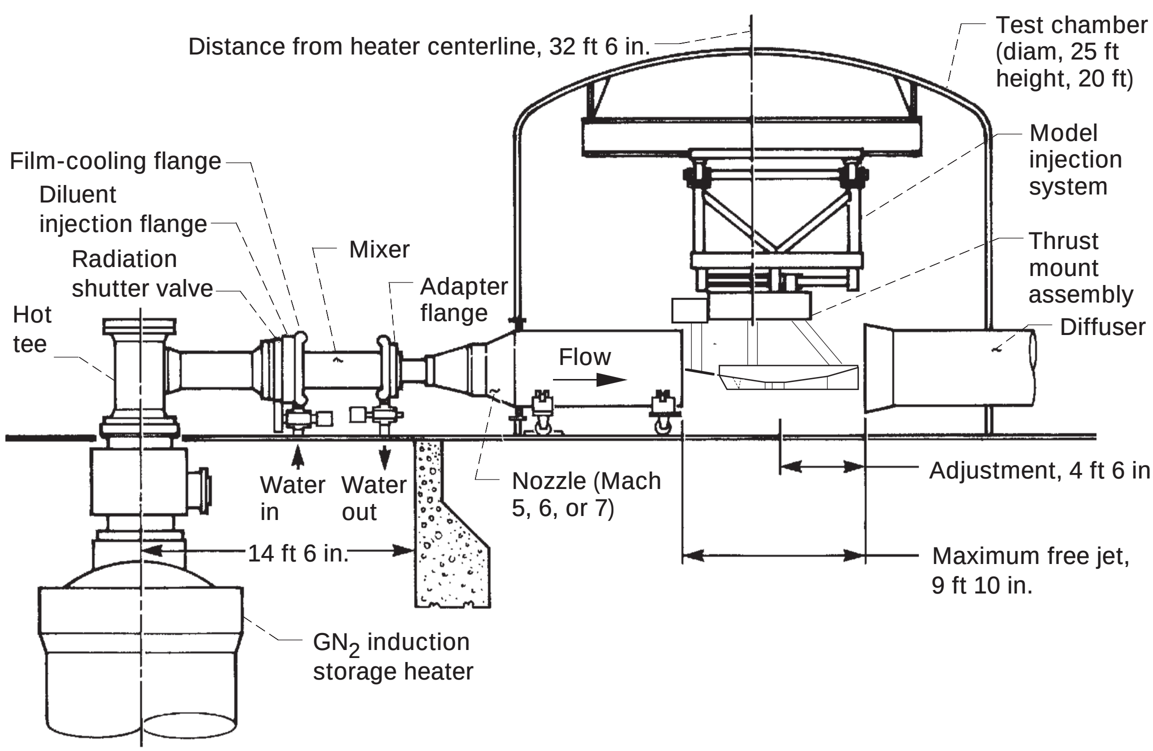

Figure 3.—Hypersonic tunnel facility (HTF) hot train and test chamber.

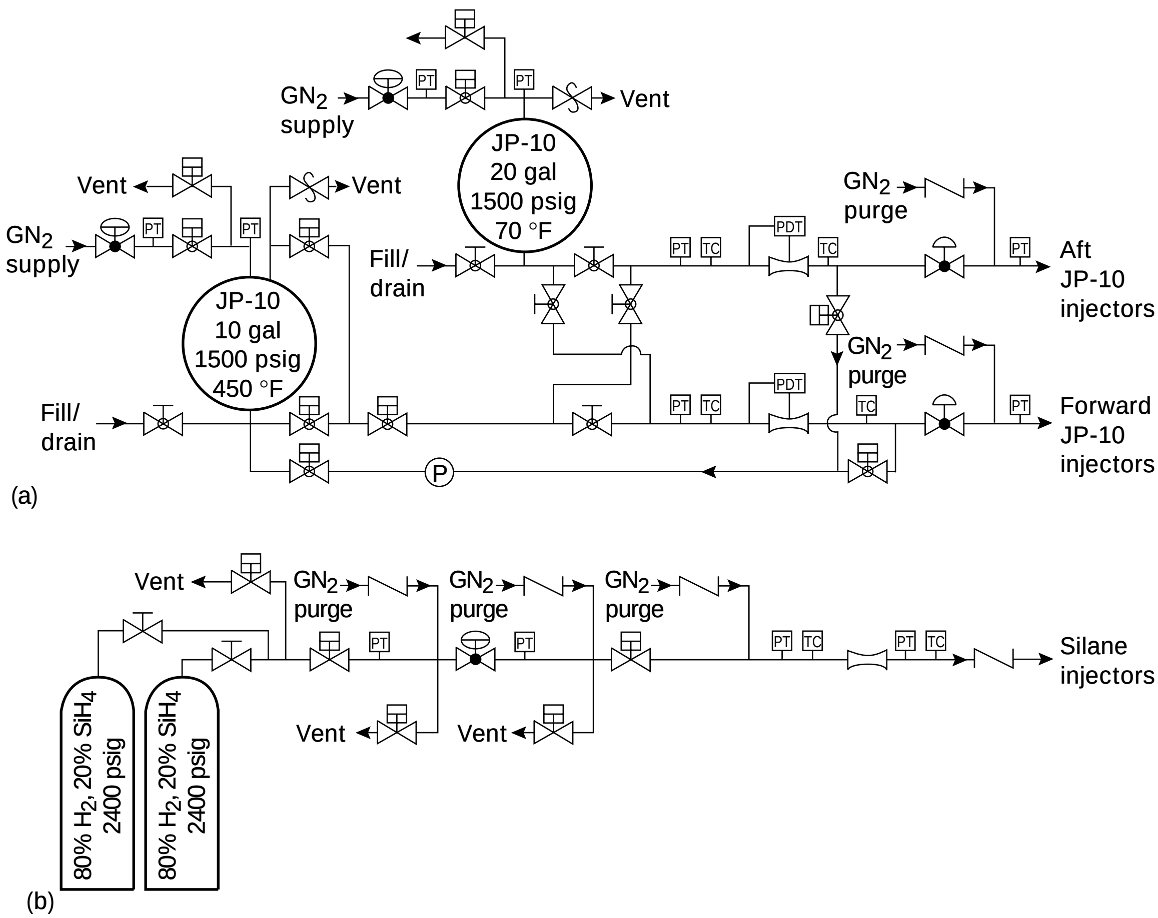

Figure 4.—Simplified HTF propellant system schematics. (a) JP-10. (b) Silane.

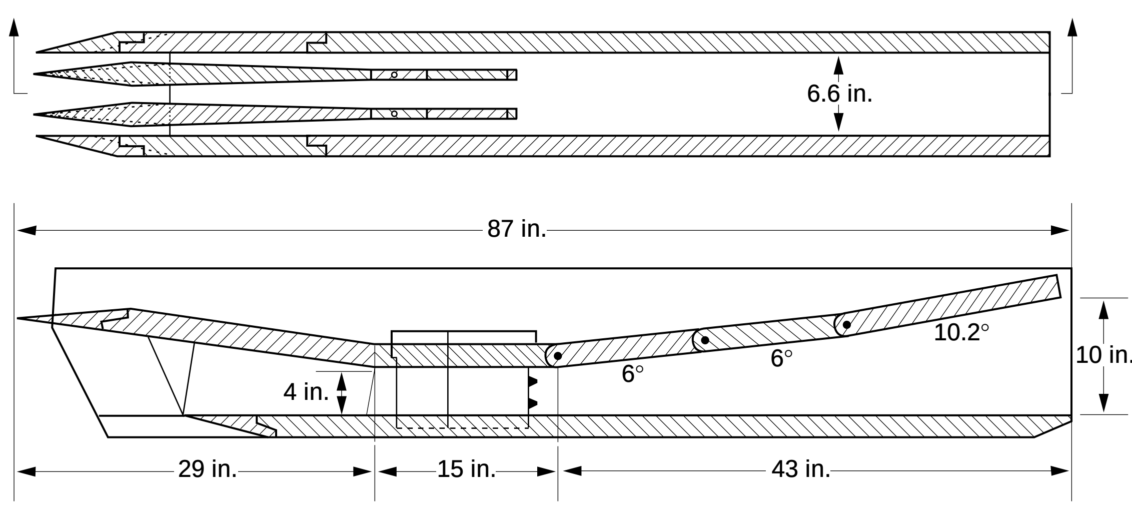

Figure 5.—Schematic of RBCC Strutjet engine with fuel injection blocks installed.

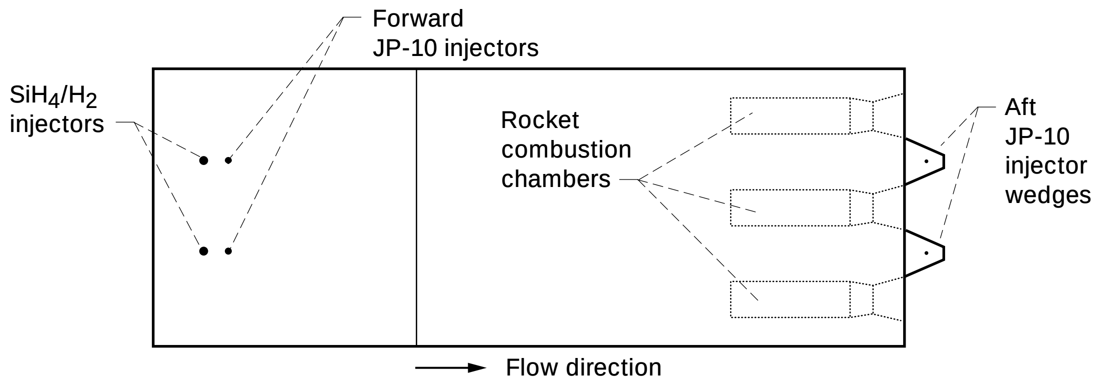

Figure 6.—Side view of forward and aft fuel injection blocks with rockets.

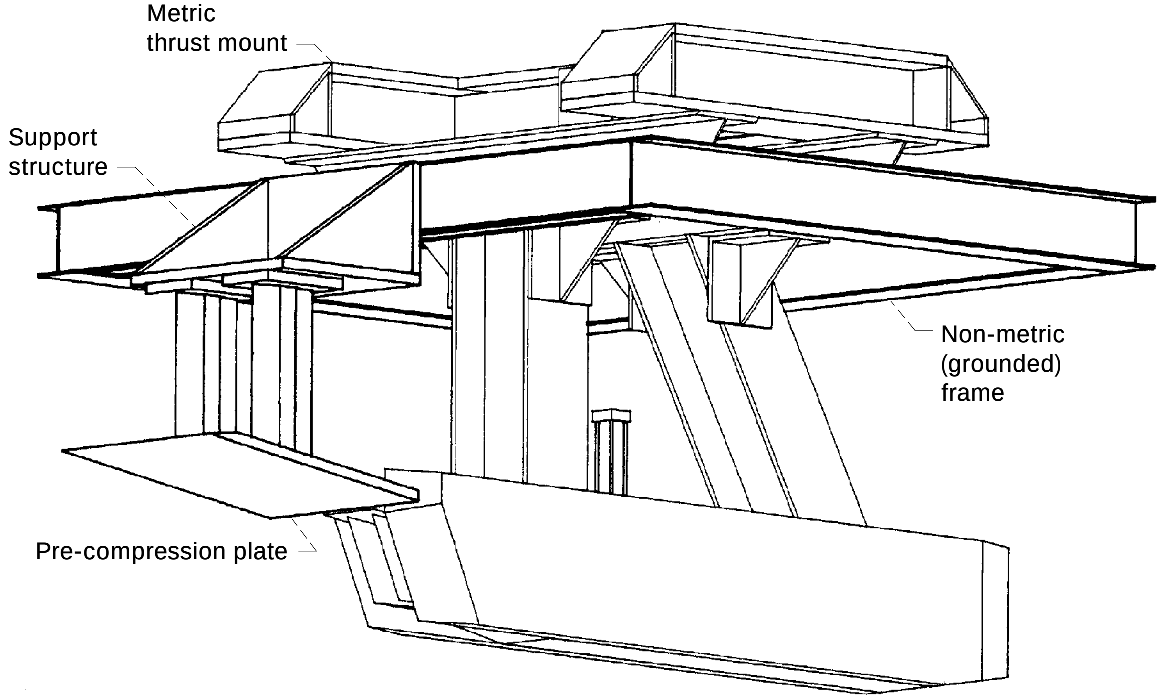

Figure 7.—Isometric sketch of RBCC Strutjet engine installation in the HTF without shrouding or facility starting appliance.

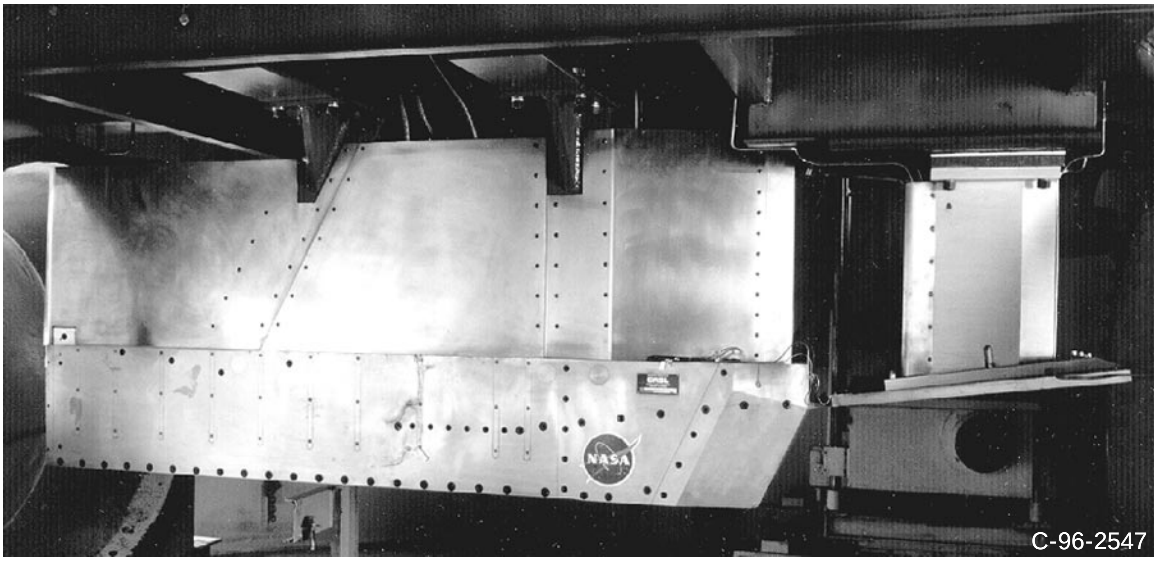

Figure 8.—RBCC Strutjet engine installed in the HTF.

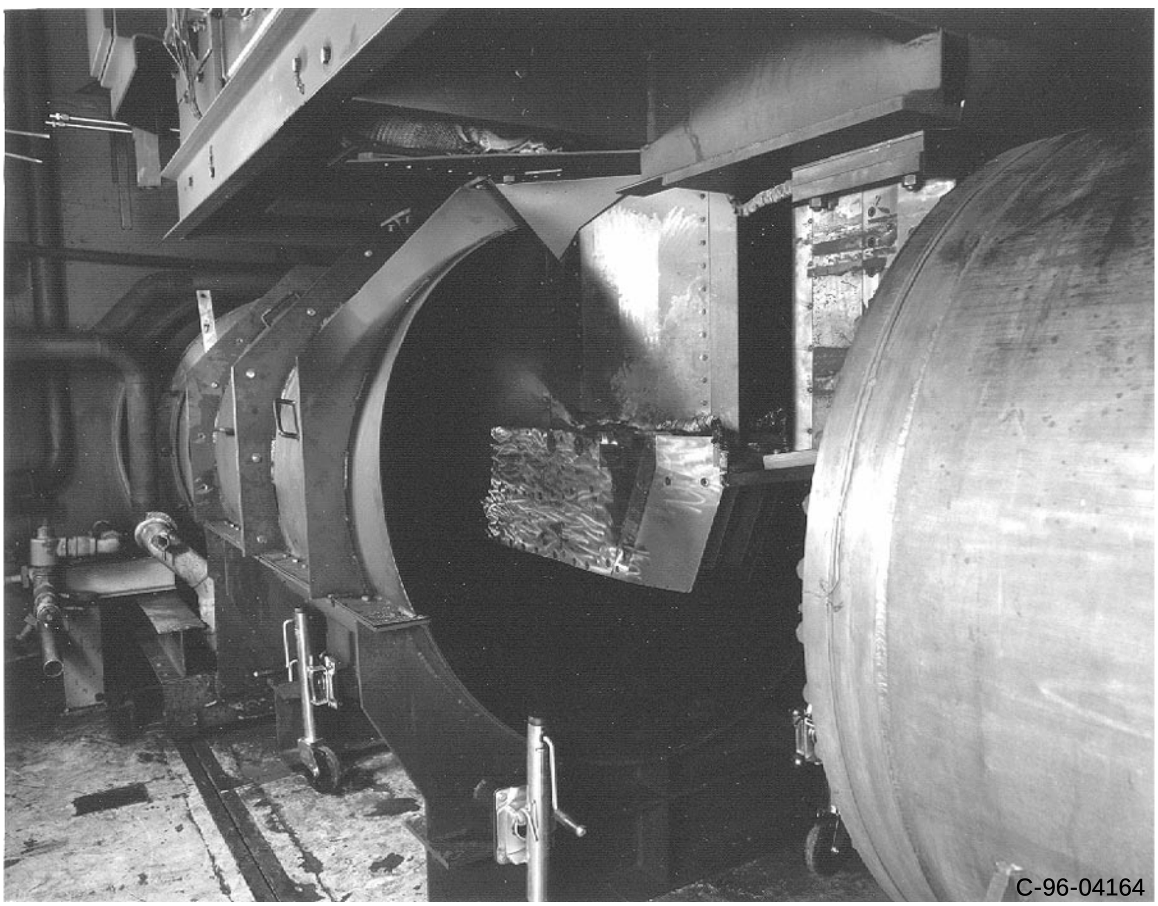

Figure 9.—RBCC Strutjet engine with facility starting appliance installed.

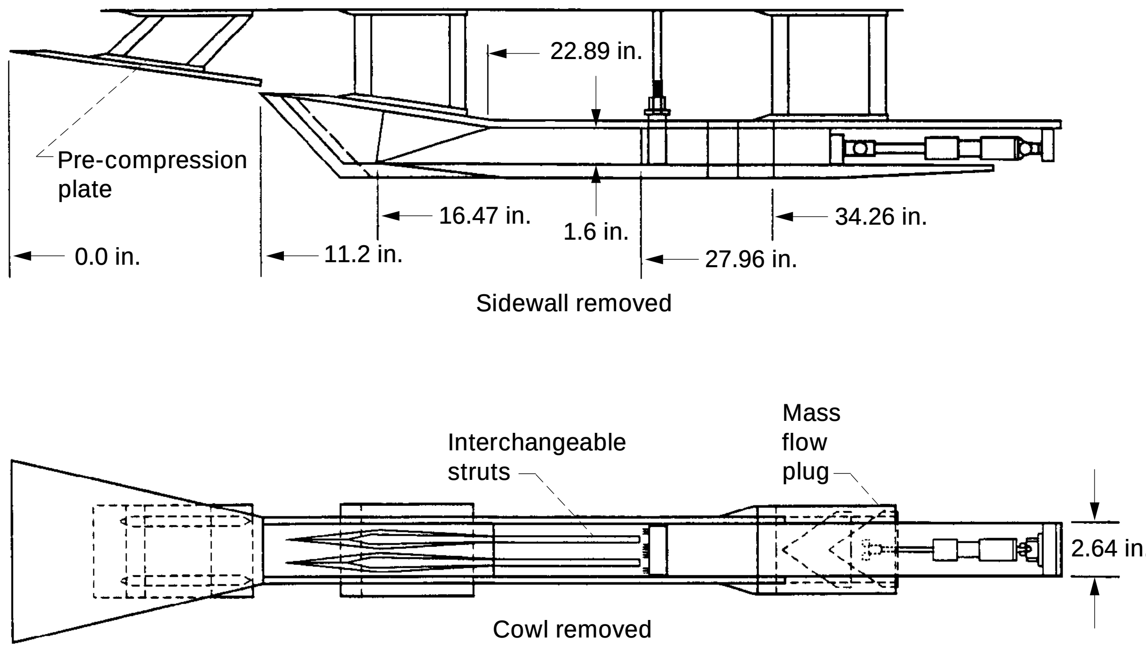

Figure 10.—40% scale RBCC Strutjet inlet model run in LeRC 1x1 SWT.

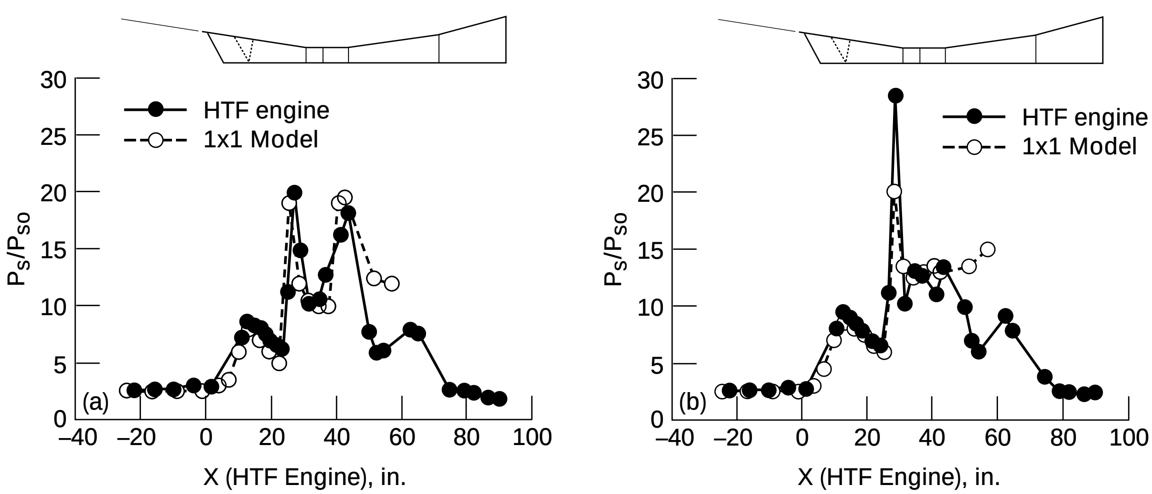

Figure 11.—Unfueled top wall centerline static pressure distributions of HTF full scale engine and 1x1 sub-scale inlet model with scaled engine schematic shown above. (a) Mach 5. (b) Mach 6.

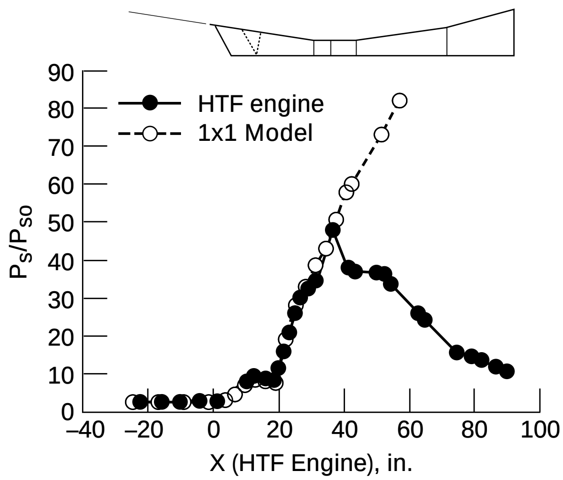

Figure 12.—Fueled top wall centerline pressure distribution of HTF full scale engine and mechanically backpressured 1x1 sub-scale inlet model with scaled engine schematic shown above.

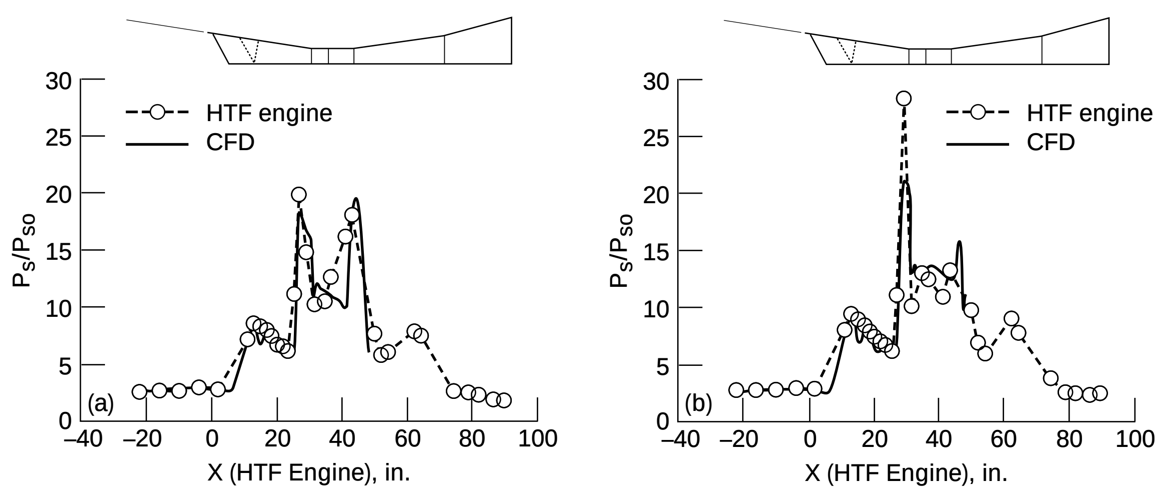

Figure 13.—Unfueled top wall centerline pressure distributions of HTF full scale engine and CFD analysis results with scaled engine schematic shown above. (a) Mach 5. (b) Mach 6.

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H. Douglas Perkins, Scott R. Thomas, and William D. Pack

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13. ABSTRACT ***(Maximum 200 words)***

A series of Mach 5 to 7 freejet tests of a Rocket Based Combined Cycle (RBCC) engine were conducted at the NASA Lewis Research Center (LeRC) Hypersonic Tunnel Facility (HTF). This paper describes the configuration and operation of the HTF and the RBCC engine during these tests. A number of facility support systems are described which were added or modified to enhance the HTF test capability for conducting this experiment. The unfueled aerodynamic performance of the RBCC engine flowpath is also presented and compared to sub-scale test results previously obtained in the NASA LeRC 1x1 Supersonic Wind Tunnel (SWT) and to Computational Fluid Dynamic (CFD) analysis results. This test program demonstrated a successful configuration of the HTF for facility starting and operation with a generic RBCC type engine and an increased range of facility operating conditions. The ability of sub-scale testing and CFD analysis to predict flowpath performance was also shown. The HTF is a freejet, blowdown propulsion test facility that can simulate up to Mach 7 flight conditions with true air composition. Mach 5, 6, and 7 facility nozzles are available, each with an exit diameter of 42 in. This combination of clean air, large scale, and Mach 7 capabilities is unique to the HTF. This RBCC engine study is the first engine test program conducted at the HTF since 1974.

14. SUBJECT TERMS

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