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Chapter 16 - The NASA Glenn Research Center's Hypersonic Tunnel Facility

Mark R. Woike and Brian P. Willis

National Aeronautics and Space Administration

Glenn Research Center, Plum Brook Station

Sandusky, Ohio 44870

Abstract

The NASA Glenn Research Center's Hypersonic Tunnel Facility (HTF) is a blow-down, freejet wind tunnel that provides true enthalpy flight conditions for Mach numbers of 5, 6, and 7. The Hypersonic Tunnel Facility is unique due to its large scale and use of non-vitiated (clean air) flow. A 3MW graphite core storage heater is used to heat the test medium of gaseous nitrogen to the high stagnation temperatures required to produce true enthalpy conditions. Gaseous oxygen is mixed into the heated test flow to generate the true air simulation. The freejet test section is 1.07m (42 in.) in diameter and 4.3m (14 ft) in length. The facility is well suited for the testing of large scale airbreathing propulsion systems. In this chapter, a brief history and detailed description of the facility are presented along with a discussion of the facility's application towards hypersonic airbreathing propulsion testing.

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Introduction

The NASA Glenn Research Center's Hypersonic Tunnel Facility (HTF) is a blow-down, freejet wind tunnel that is capable of simulating Mach 5, Mach 6 and Mach 7 true enthalpy flight conditions. The Hypersonic Tunnel Facility is unique due to its use of non-vitiated (clean air) flow. The high stagnation temperatures required for simulating true enthalpy conditions are produced by flowing clean nitrogen gas through a 3MW graphite core storage heater. Clean gaseous oxygen is mixed with the heated gaseous nitrogen to yield the test medium of simulated air. Stagnation temperature, stagnation pressure and altitude are controlled during tunnel operation to generate the desired test conditions. Three discrete hypersonic nozzles, each with a 1.07m (42 in.) exit diameter, are used to set the facility Mach number conditions of 5, 6 and 7.

The facility's operation envelope is shown in Figure 1. The facility operation spans from 20.7 to 36.6 km (68,000 to 120,000 ft) altitude, 0.48 to 8.27 MPa (70 to 1200 psia) nozzle inlet stagnation pressure, and 1220 to 2335 K (2200 to 4200 degrees R) nozzle inlet stagnation temperature¹. Table 1 outlines the operating ranges and maximum run times for each Mach number condition. The facility's size and run duration allow for component and full systems testing of flight rated structures and air breathing propulsion systems. The use of non-vitiated flow for propulsion testing most closely represents actual flight conditions and minimizes potential errors between ground testing and true flight performance. In this light, the Hypersonic Tunnel Facility provides a critical capability for the research and development of hypersonic airbreathing propulsion systems. The remainder of this chapter will describe the facility in detail

and discuss its testing capabilities and how they apply to the needs of the hypersonic research community.

Facility History

The Hypersonic Tunnel Facility (HTF) was originally built in 1966 as the Hydrogen Heat Transfer Facility (HHTF). The facility was to be used for the development of nuclear rocket engines. The facility heater simulated a nuclear reactor heat source where gaseous hydrogen could be heated to temperatures approaching 2755 K (4500 degrees F).

In 1969, an effort was undertaken to convert the facility into a hypersonic wind tunnel for airbreathing propulsion testing. This entailed the conversion of the facility heater from a pebble bed to a graphite core design and the installation of a test chamber, steam ejector, and other support systems. The facility reconfiguration was completed in 1971. From June to December of 1971 test runs for the purposes of calibrating the facility were accomplished. The facility nozzles were calibrated over a range of stagnation pressures and temperatures. Vertical and horizontal surveys of Mach number were made for each nozzle. The results of this calibration are discussed in reference 2.

In 1972 the Hypersonic Research Engine (HRE) Test Program began at HTF. The HRE test program was initiated for the purposes of advancing hypersonic propulsion technology³. The program involved the testing of a full scale, water cooled, and gaseous hydrogen fueled version of the HRE called the Aerothermodynamic Integration Model (AIM). The purpose of the

program was to integrate the engine components (inlet, combustor, and nozzle) and to assess the engine performance at Mach numbers of 5, 6 and 7. The HRE test program was conducted from October of 1973 to May of 1974.

Following the completion of the test program the facility was placed in a stand-by condition. The facility remained in a stand-by condition from 1974 to 1986 when a study was performed to address the requirements to rehabilitate the HTF and bring it back to a fully operational conditional⁴. Work on the rehabilitation began in 1990 and was completed in 1994. In 1995, a series of Integrated Systems Tests were undertaken to validate the facility⁵. These tests were successful and demonstrated the operational readiness of the HTF.

In 1996, testing of the Aerojet Strut Jet Rocket Based Combined Cycle (RBCC) Engine began at HTF. The purpose of the test program was to demonstrate the engine performance in a freejet configuration and to also demonstrate the HTF's capability for testing an RBCC type engine⁶. Over 40 test runs up to Mach 6.6 were conducted for this test program.

In September of 1996, during a test run for the RBCC test program, a failure occurred with a facility component resulting in damage to facility systems. In 1997, a project was undertaken to repair the damaged facility components and restore the facility to its full operational capabilities⁷. The restoration work was completed in 1999. A series of Integrated Systems Tests were successfully completed in 2000, validating the full operational capability of the Hypersonic Tunnel Facility⁸.

Facility Description

Major features of the facility are shown in figure #2. The driving fluid for the tunnel is pressurized gaseous nitrogen. Gaseous nitrogen from a rail car tank is supplied at the desired test pressure to the 3MW graphite storage heater where it is heated to a temperature above the desired test temperature. This heated nitrogen gas passes out of the heater into the facility “hot train” section where ambient temperature gaseous oxygen is added to bring the flow to the composition of air. In addition to the oxygen, ambient temperature gaseous nitrogen is added to the flow to set the desired total temperature at the nozzle inlet. The test flow goes through a converging-diverging nozzle that expands the flow to hypersonic conditions. The flow then passes over and through the test article 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 single stage steam ejector connected to the facility diffuser duct. All of the test flow is exhausted to atmosphere. The major facility components and systems are described in the following sections.

Graphite Storage Heater

The heart of the facility is an induction type graphite core storage heater. This heater is used to heat gaseous nitrogen to temperatures approaching 2755 K (4500 degrees F). The heater vessel is approximately 12.2m (40 ft) in height and 3.0m (10 ft) in diameter. Figure #3 is a cutaway view of the storage heater. The heater consists of 15 cylindrical graphite blocks stacked

on top of each other. Each block is 1.8m (6 ft) in diameter and 0.6m (2 ft) in height, with 1,945 holes, ranging between 19mm (0.75 in.) to 29mm (1.125 in.) in diameter, drilled axially through the block to distribute the gaseous nitrogen flow. Hexagonal graphite block keys in each block 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 pressure drop through the heater stack.

The stack of graphite blocks is insulated with a 254mm (10 in.) thick layer of graphite felt insulation and a 51mm (2 in.) thick silicon carbide tile shell to reduce heat loss to the outer heater components. A 4-piece, water cooled, helical copper coil surrounds the graphite block / graphite insulation core. Electric current from an 180HZ, 750V single phase, 3MW supply is passed through these coils to induce a magnetically coupled current in the outer diameter of the graphite blocks to a depth of approximately 102mm (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 conducts radially through the rest of the block towards the centerline of the heater.

Heating of the 27,200 kg (60,000 pounds) of graphite must be done slowly to minimize thermal stresses within the blocks. The blocks are heated at a maximum rate of 28 K (50 degrees F) an hour. Consequently, heating of the graphite core from ambient temperature up to 2755 K (4500 degrees F) can take up to 100 hours. Each of the 4 sections of the induction coil can be independently controlled to accomplish the setting of the desired temperature throughout the heater. Graphite block temperatures are measured optically at scheduled time intervals during heater operation with portable pyrometers.

During tunnel operation ambient gaseous nitrogen enters the bottom of the heater vessel and pressurizes the space between the core and external shell. The nitrogen gas is routed back to the bottom of the heater where it flows through the holes in the graphite blocks and is heated. The heated nitrogen flow exits through the top of the heater vessel and enters the facility hot train. The maximum heater exit flow conditions are 8.27 MPa (1200 psia), 2755 K (4500 degrees F) and 59 kg/s (130 lbm/s).

Facility Hot Train

The heated nitrogen gas exiting the heater flows through a series of bolted, water cooled components that are collectively referred to as the “hot train”. The facility hot train, nozzle, and test cabin are shown in Figure #4. The hot train has an inside flow diameter of 0.46m (18 in.) and consists of the following components: the hot-tee, the radiation shutter valve, the diluent injection flange, the water cooled flange and the mixer.

The hot-tee is graphite lined and turns the flow from vertical to horizontal as it exits the heater. The radiation shutter valve is used to keep heat from radiating out of the heater into the test cabin when the facility is between test runs. It also seals the heater and allows a positive nitrogen purge to be maintained on the heater during stand-by. The valve is opened prior to a facility test run and is closed once the test run is completed. The diluent injection flange injects the ambient temperature oxygen and nitrogen into the flow to generate the simulated air

composition and desired temperature condition. The water cooled flange is a water cooled component that is used to remove heat from the o-ring seal on the mixer. It does this by injecting cold nitrogen into the seal cavity. The mixer's primary function is to allow proper mixing of the heated nitrogen flow with the injected ambient oxygen and nitrogen. The mixer consists of an Inconel 718 cylindrical liner that is 1.5m (5 ft) in length and has an internal flow diameter of 0.46 m (18 in.).

All of the above mentioned components are actively water cooled during facility operation. Corresponding component skin temperatures, cooling water pressures, cooling water flows and cooling water temperatures are actively monitored to assess the health of the components during facility operation. In addition, double o-ring seals are used at all of the component interface points. The annular spaces between the o-rings are pressurized with nitrogen at a pressure higher than the facility run pressure. This cavity pressure is monitored to assess the integrity of all of the o-ring seals. The hot train components are certified to operate at a pressure of 8.37 MPa (1200 psig).

Facility Nozzles

Axi-symmetric nozzles are used to expand the test flow to hypersonic conditions. Three discrete water cooled nozzles with nominal Mach numbers of 5, 6 and 7 are currently available at HTF. Each of the nozzles has a 1.07m (42 in.) exit diameter with internal contours that expand

the flow to the desired Mach number condition. The nozzles bolt on to the end of the facility hot train and extend into the test cabin.

The nozzles were fabricated using an electroforming process. The Mach 5 nozzle was completely formed from nickel. The Mach 6 and Mach 7 nozzles' throat section were machined from zirconium copper forgings and were electroformed to the nickel expansion sections. Each nozzle can be equipped with freejet shear layer energizers that are capable of injecting gaseous nitrogen into the nozzle exit flow at rates up to 18 kg/s (40 lb/s).

Test Chamber and Thrust Stand Assembly

The test chamber is a domed cylindrical structure that is 7.6m (25 ft) in diameter, 6.1m (20 ft) in height and is made of high carbon steel. The test article is mounted on a translating single axis thrust stand. The thrust stand was designed to handle a test article up to 7,260 kg (16,000 pounds) in weight and 3,860 kg (8,500 pounds) in thrust. The test article can be translated up to 0.76m (30 in.) along the freejet axis and can be pivoted to a 5 degree angle of attack. The facility can accommodate test articles that are up to 4.3m (14 ft) in length.

Diffuser / Steam Ejector System

The simulation of altitude within the test cabin and the exhausting of test article and facility flow is accomplished using a diffuser / ejector system. This system consists of a water cooled supersonic diffuser, a spray cooler and a single stage steam ejector. The exhaust system components are shown in Figure #5.

The supersonic diffuser converts the kinetic energy of the high speed freejet flow into potential energy in the form of 'recovered' pressure. It consists of a translatable, water cooled 1.2m (48 in.) diameter inlet collection cone followed by a 1.1m (43 in.) diameter constant area section that is 9.1m (30 ft) in length. The subsonic diffuser incorporates water spray nozzles that are designed to cool the exhaust gases to saturation temperatures. The single stage steam ejector is used to evacuate the test chamber and exhaust the tunnel and test article gases to atmosphere. The single stage steam ejector utilizes a co-axial nozzle and uses 227 kg/s (500 lbm/s) of steam supplied at a pressure of 1.14 MPa (150 psig).

Steam is supplied to the steam ejector through a 0.76m (30 in.) diameter pipe from 5 accumulators that have a combined useful capacity of 65,540 kg (144,500 pounds) of steam. These accumulators are cylindrical in shape, 16.3 (53.5 ft) in length and 3.7m (12 ft) in diameter. The accumulators are located approximately 0.9km (3000 ft) from the facility. Two boilers capable of supplying 10,890 kg/hr (24,000 lb/hr) of saturated steam at a pressure of 3.55 MPa

(500 psig) are used to charge the accumulators. In the current configuration the steam accumulators can be fully charged for a tunnel run in 6 hours

Gaseous Nitrogen System

The high pressure gaseous nitrogen that is used to provide the flow for the tunnel is supplied from a railroad tank car. The vessel has a capacity of 18,775 m³ (663,000 scf) at its rated pressure of 31 MPa (4500 psig). The railcar is charged using a liquid nitrogen vaporizer station that is capable of generating gaseous nitrogen at a rate of 1,870 m³ (66,000 scf) per hour.

Gaseous Oxygen System

The gaseous oxygen that is used to generate the synthetic air for the facility test flow is supplied from a bottle farm that is located at the facility. The bottle farm consists of six carbon steel bottles that have a combined capacity of 10,930 m³ (386,000 scf) at their rated pressure of 15.3 MPa (2212 psig). The bottles are charged using a vaporizer station that is capable of generating gaseous oxygen at 565 m³ (20,000 scf) per hour.

Cooling Water Systems

Several systems are used to provide cooling water to the components of the Hypersonic Tunnel Facility. There are two low pressure water systems that are used to supply demineralized cooling water to the heater vessel, induction coils and hot train components. Each system can supply 2,370 liters (625 gallons) per minute at a pressure of 687 KPa (85psig). The systems are redundant and either one can supply all of the cooling water required by the components listed above. These systems incorporate separate supply and return loops for each water cooled component. Primary pumping is done with electric motor pumps. Diesel pumps are used to provide back up capability to the electric pumps. A raw water supply system is used to provide emergency cooling in the unlikely event that both primary systems fail.

Three high pressure water systems are used to supply demineralized cooling water to the facility's hot train components and test hardware. Each of the three systems is supplied water from a 24,600 liter (6500 gallon) storage tank. The first system is used to supply cooling water to the facility mixer and diffuser sections at a flow rate of 3,790 liters (1,000 gallons) per minute at 930 KPa (120 psig). The second system supplies cooling water to the facility nozzle at a flow rate of 1,140 liters (300 gallons) per minute at 2.86 MPa (400 psig). The third system supplies cooling water to the facility's shutter valve, diluent injection flange and water cooled flange at a flow rate of 2,200 liters (580 gallons) per minute at 2.86 MPa (400 psig). Excess cooling water from the high pressure water systems can be used to supply cooling water required by a test article.

Facility Control System

Control of the HTF is done by a state of the art computerized control system. The control system consists of three major components; the programmable logic controller (PLC), the Test Matrix Sequencer (TMS), and the Flow Computer.

A facility test run is completely automated through the use of this control system. The programmable logic controller (PLC) provides the overall supervisory control of the facility. It executes a predefined set of operations that are defined as the facility “run sequence”. It is responsible for setting up facility support systems prior to a test run, initiating the tunnel blow down, and shutting down the facility support systems after the test run is complete. The PLC is also used to monitor all critical facility operating parameters. It is used in this manner to provide “abort” alarming and monitoring during facility operation. The facility is operated by a primary PLC. In the event that the primary controller fails, a hot standby feature will switch control of the facility to a redundant back up PLC.

The Test Matrix Sequencer (TMS) is a computer based system that works in conjunction with the facility PLC in operating the facility. The TMS generates the pressure ramps and flow set points for the heater nitrogen control valve, the oxygen control valve, and the diluent nitrogen control valve. The system is fully programmable and allows the user to input the desired facility stagnation pressure, stagnation temperature and flow composition conditions needed for the tunnel run. The flow computer works with the TMS in setting these facility operating

conditions. It is responsible for generating the flow set point and feedback signals required for maintaining closed loop control on the facility diluent nitrogen and oxygen control valves.

The new control system was installed during the facility rehabilitation project that was undertaken in 1997. It is state of the art and fully operational. Its operation was verified during the facility check out runs that were accomplished in 2000.

Data Systems

The Hypersonic Tunnel Facility's data acquisition system consists of a steady state data system, a high speed data system, and an electronically scanned pressure data system. The facility's "Escort" data system is used for acquiring steady state "slow speed" data. This computer based system can acquire data from 528 channels at a sample rate of 1HZ. This system is mainly used to record and monitor facility operation parameters. The system is available for recording test article parameters if required.

The high speed data system is used to acquire analog data from the test article and its support systems. This computer based system can acquire data from 96 channels at an aggregate sample rate of 2MHZ. This system utilizes programmable anti-aliasing filters to filter the input signals. Wiring and signal conditioning is available for a variety of transducers and thermocouples.

An electronically scanned pressure system is used to acquire pressure data from the test article. The system is currently configured to accommodate 192 pressure channels at a sampling rate of 20HZ. The system is expandable to ~1000 channels. It can also accommodate a variety of modules ranging from 6.89 KPa (1 psi) to 4.14 MPa (600 psi). All systems are fully operational and have been successfully used to acquire data for previous test programs ran in the facility. A color video system is used to monitor the test article and record video data. A single pass Schlieren system is also available for use in the facility.

Test Article Support Systems

In addition to the systems described in the previous sections, the facility has numerous propellant and other support systems available to support hypersonic propulsion research test articles. These systems are described in the following sections.

Gaseous Hydrogen Fuel System

Gaseous hydrogen can be supplied to the test article from 6 tuber stations with total capacity of 1,190 m³ (42,000 scf) at a pressure of 16.6 MPa (2400 psig). The facility is currently configured to supply the test article at a maximum flow rate of 1.1 kg/s (2.5 lbm/s). This can be increased to accommodate future test article fuel requirements.

A gaseous hydrogen heater capable of supplying 1.1 kg/s (2.5 lbm/s) of heated hydrogen at a pressure of 8.37 MPa (1200 psig) and a temperature of 811 K (1000 degree F) is also available. This heater system is currently in stand by and is in need of minimal refurbishment to become operational. A 22,700 liter (6000 gallon), vacuum-jacketed, 15 MPa (2,160 psig) working pressure storage dewar is available to store liquid hydrogen for use as fuel.

Liquid JP Fuel Systems

Two systems currently exist to supply liquid hydrocarbon fuel to the test article. The first system operates at ambient temperature conditions and is currently configured to supply fuel to the test article at a flow rate of 0.45 kg /s (1.0 lbm/s) at 10.4 MPa (1,500 psig). The second system operates at temperatures up to 505 K (450 degrees F). It is also configured to provide fuel to the test article at a flow rate of 0.45 kg/s (1.0 lbm/s) at a pressure of 10.4 MPa (1,500 psig). These fuel systems can be modified to accommodate future test article requirements.

High Pressure Cooling Water

High pressure cooling water is available for the test article. One system can provide 38 liters (10 gallons) per minute at a pressure of 7 MPa (1,000 psig). Another system can provide 3,410 liters (900 gallons) per minute at a pressure of 2.86 MPa (400 psig). In addition, excess

cooling water from the facility systems is also available to satisfy test article cooling requirements.

Typical Facility Operation

The following section gives a brief description on the operation of the Hypersonic Tunnel Facility. Prior to a series of test runs, the heater and its support systems are activated and the heater is brought up to the required operating temperature. The steam plant is brought on line and all accumulators are charged to full capacity at a pressure of 3.55 MPa (500 psig). The facility cooling water systems are also activated and the facility gas systems are charged.

On run day, the facility support systems, the control systems and the data systems are prepared for a tunnel run. Prior to facility operation the steam line to the facility is preheated using steam supplied from the boilers. Once the steam line is heated the steam line pressure is brought up to 1.14 MPa (150 psig) at the facility ejector supply station. The facility operator then activates the “facility run sequence”.

The following actions are automatically executed through the use of the facility’s computer based control system, requiring minimal operator intervention. First, the test chamber vent valve is closed, cooling water flow is verified, and a 119 KPa (2.5 psig) purge pressure is placed on the facility hot train. Once the purge is established, the steam system accumulator valves and facility radiation shutter valve are opened. The main steam valve at the ejector

supply station is opened establishing flow in the ejector and commencing pump down of the test chamber. Once the test chamber is pumped down to a predefined set point the facility main nitrogen supply valve is opened and the heater / facility pressure is ramped up to the desired test condition and flow is established in the wind tunnel. During the pressure ramp, the diluent oxygen and nitrogen are introduced to the flow to achieve the required stagnation temperature and air composition. The spray cooler is also turned on to cool the exhaust gases in the ejector.

During the tunnel run the storage heater's temperature will drop several hundred degrees, requiring the facility controls to balance the mix of hot nitrogen, diluent nitrogen and diluent oxygen to maintain the desired conditions in the test chamber. The tunnel is held at the desired condition for a predetermined amount of time allowing data to be acquired for the test article. At the end of the test run, the oxygen flow is shut off and replaced with diluent nitrogen flow, and the facility pressure is brought back down to the 119 KPa (2.5 psig) purge pressure. The spray cooler is turned off and the radiation shutter valve is closed. Finally, the steam ejector is turned off and the test chamber vent valve is opened. The facility systems are then secured and preparation begins for the next tunnel run.

Depending on the test conditions, 1 to 2 test runs can be accomplished in one day. The limiting factors are the time required to recharge the facility gas and steam systems and the time required to reheat the facility graphite storage heater. Typical turn around time between tunnel runs is 6 to 8 hours. During test operations the facility is operated on a three-shift basis. A minimal crew is assigned to the "off shifts" to prepare the facility and test article for the next day's tunnel run.

Unique Value and Testing Capability

The facility is unique due to its large scale and its use of non-vitiated flow. Air breathing hypersonic propulsion testing is the primary purpose of the Hypersonic Tunnel Facility. Propulsion testing in a facility with non-vitiated flow most closely represents the actual flight conditions and minimizes potential errors between ground test results and true flight performance, thus mitigating the risk prior to actual flight testing. In addition, during flight testing the number of measurements and test conditions that can be accomplished is limited. Ground testing in a facility like the HTF allows more detailed measurements and test runs to be made, thus allowing for the refinement of the propulsion system.

The facility's size and long run duration allow for full systems testing of large flight rated structures and propulsion systems. The facility is capable of supporting both hydrogen and hydrocarbon fueled propulsion systems. In addition to freejet propulsion testing, the facility is also suited for aerothermodynamic and structures testing, since it provides true temperature and altitude simulation over a wide range of Mach numbers.

The use of the facility to support direct connect testing is currently being developed. This capability would allow the testing of large scale combustors in a non-vitiated flow. Thus, minimizing potential scaling errors and other errors associated with ground testing.

Summary and Conclusions

The NASA Glenn Research Center's Hypersonic Tunnel Facility is a unique national asset due to its large scale and use of non-vitiated flow. The facility provides true temperature, altitude and air simulation at Mach 5, 6 and 7 test conditions. Its run duration, size and existing infrastructure allows for the testing of large scale flight rated structures and propulsion systems. The facility provides unequaled capabilities to the hypersonic community and is available to support the development of hypersonic propulsion systems for the 21st century. In summary, the Hypersonic Tunnel Facility provides a critical capability for the research, development and testing of hypersonic propulsion systems.

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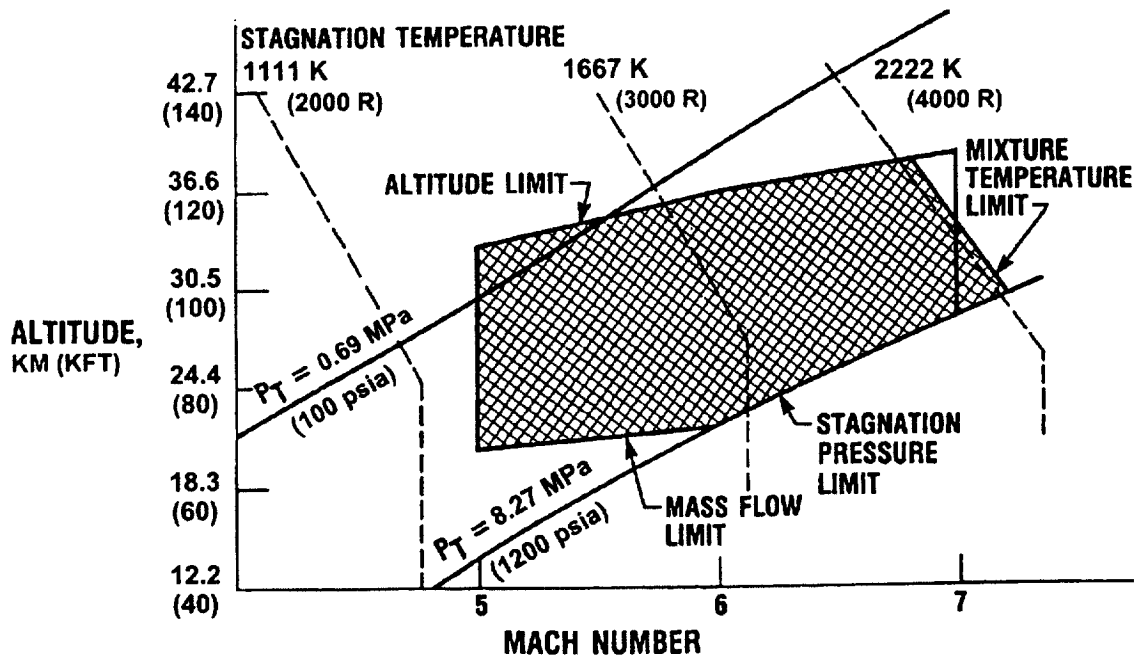


Figure 1. - Hypersonic Tunnel Facility Operating Envelope

Table 1. - Hypersonic Tunnel Facility Upper and Lower Operating Limits

Mach #	Nozzle			Test Section			
	Stagnation Pressure, MPa (psia)	Stagnation Temperature, K (degree R)	Mass Flow kg/sec (lb/sec)	Static Pressure KPa (psia)	Static Temperature K (degree R)	Altitude km (kft)	Run Time s
5	2.83 (410)	1222 (2200)	86 (189)	5.10 (0.74)	213 (384)	20.7 (68)	103 a
	0.48 (70)	1344 (2420)	14 (31)	0.81 (0.12)	238 (428)	32.9 (108)	294 b
6	8.27 (1200)	1647 (2965)	101 (222)	4.20 (0.61)	217 (390)	21.9 (72)	42 a
	1.00 (144)	1839 (3310)	12 (25)	0.49 (0.07)	251 (451)	36.6 (120)	294 b
7	8.27 (1200)	2128 (3830)	47 (104)	2.27 (0.33)	227 (412)	28.3 (93)	90 a
	2.96 (430)	2328 (4190)	16 (36)	0.49 (0.07)	251 (451)	36.6 (120)	180 c

a - Limited by maximum stagnation temperature change of 111 deg C (200 deg F)

b - Limited by steam availability

c - Limited by diffuser temperature limits

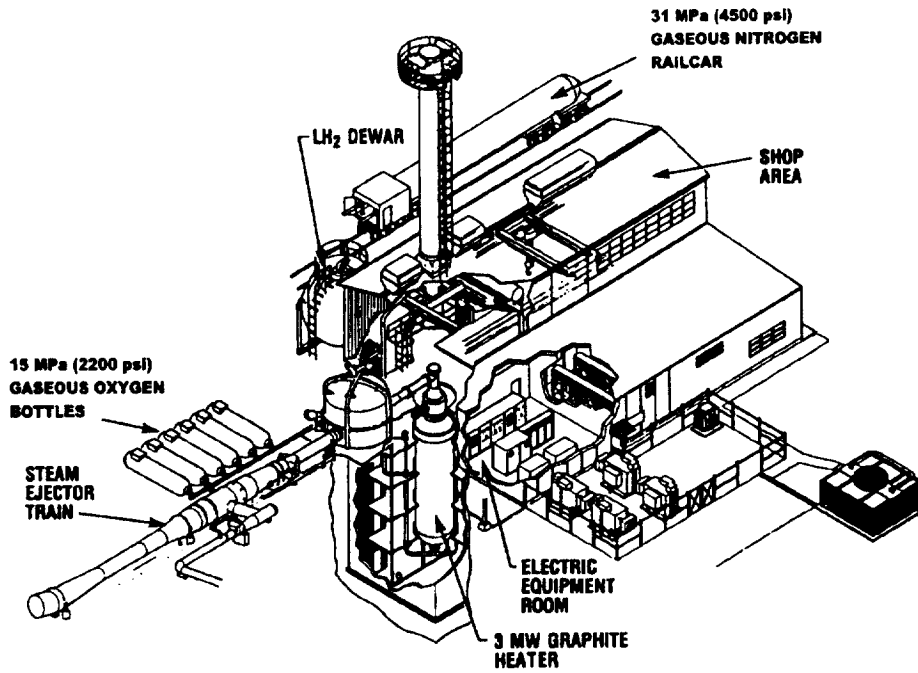


Figure 2. - Hypersonic Tunnel Facility, Isometric View

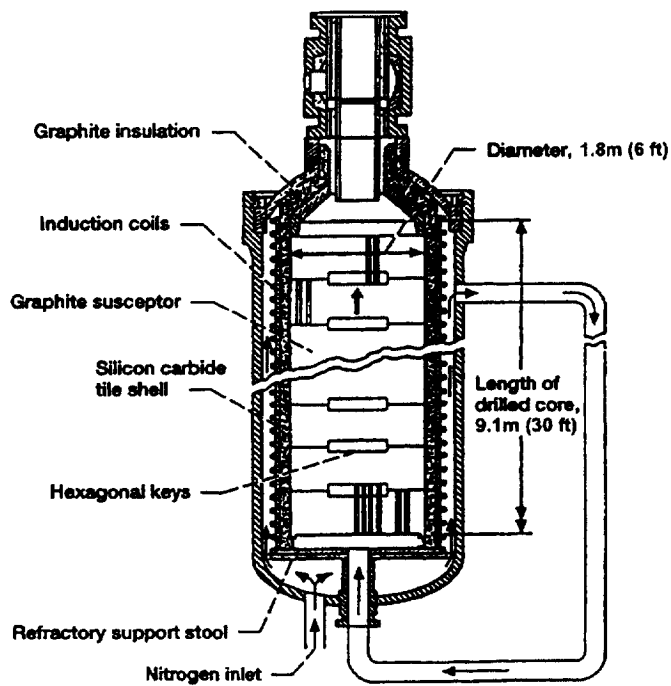


Figure 3. - Graphite Core Storage Heater

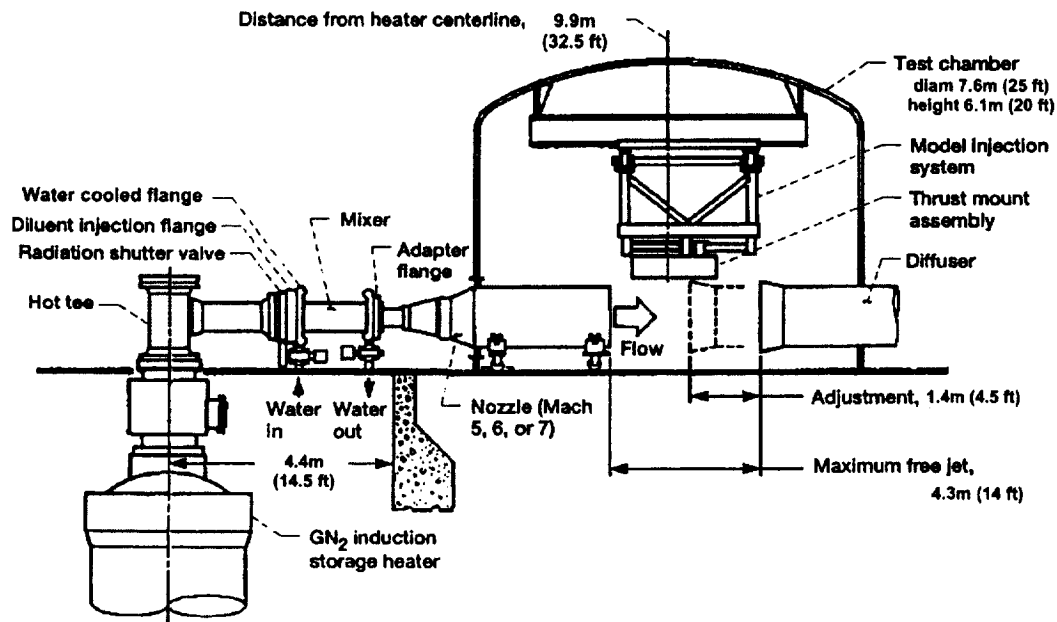


Figure 4. - Hypersonic Tunnel Facility; Hot Train and Test Cabin

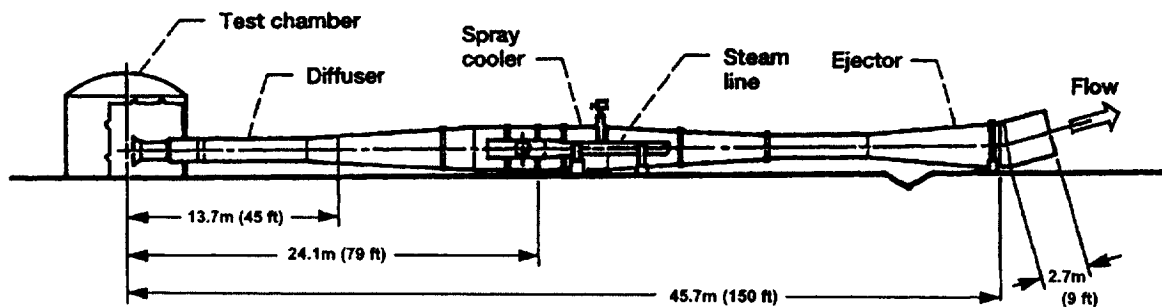


Figure 5. - Hypersonic Tunnel Facility Diffuser and Ejector