

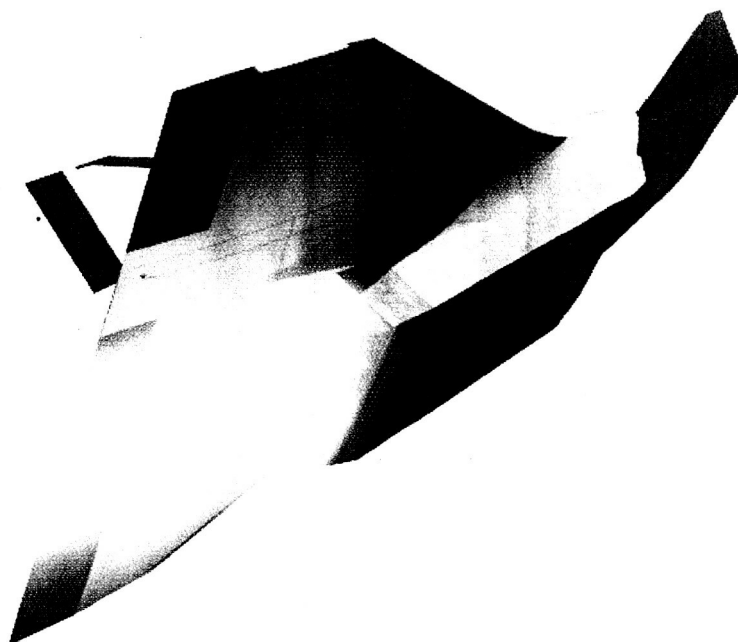


**AIAA-2003-5235**

**ISTAR: Project Status and Ground Test  
Engine Design**

**Jason Eugene Quinn**

NASA Marshall Space Flight Center, Huntsville, Alabama



**AIAA/ASME/SAE/ASEE  
39<sup>th</sup> Joint Propulsion Conference and Exhibit  
20-23 July 2003  
Huntsville, Alabama**

For permission to copy or to republish, contact the copyright owner named on the first page.  
For AIAA-held copyright, write to AIAA Permissions Department,  
1801 Alexander Bell Drive, Suite 500, Reston, VA, 20191-4344.

# ISTAR: PROJECT STATUS AND GROUND TEST ENGINE DESIGN

Jason Eugene Quinn, NASA Marshall Space Flight Center, Huntsville, Alabama

## Abstract

Review of the current technical and programmatic status of the Integrated System Test of an Airbreathing Rocket (ISTAR) project. November 2002 completed Phase 1 of this project: which worked the conceptual design of the X-43B demonstrator vehicle and Flight Test Engine (FTE) in order to develop realistic requirements for the Ground Test Engine (GTE). The latest conceptual FTE and X-43B configuration is briefly reviewed. The project plan is to reduce risk to the GTE and FTE concepts through several tests: thruster, fuel endothermic characterization, engine structure/heat exchanger, injection characterization rig, and full scale direct connect combustion rig. Each of these will be discussed along with the project schedule. This discussion is limited due to ITAR restrictions on open literature papers.

## Introduction

The Advanced Space Transportation Program at NASA Marshall Space Flight Center has assembled a government / industry team to conduct the system development and ground test of a Rocket Based Combined Cycle (RBCC) propulsion system. Government team membership includes participants from several NASA centers: Dryden Flight Research Center, Glenn Research Center (GRC), Langley Research Center (LaRC), Marshall Space Flight Center (MSFC) and Stennis Space Center. The primary industry team member is the Rocket Based Combined Cycle Consortium (RBC<sup>3</sup>), which includes Boeing Rocketdyne, Gencorp Aerojet, and United Technologies Pratt & Whitney<sup>1</sup>. Additional industry team members include Boeing, for vehicle activities, and several other companies. The management team roles for the RBCC/ISTAR project are shown in Figure 1..

Current plans for the propulsion system development and ground test of the RBCC engine system are funded through NASA MSFC as the RBCC/ISTAR project in the Next Generation Launch Technology (NGLT) Program. The ISTAR project has multiple objectives along the path of accomplishing its primary goal of developing a propulsion system which would be capable of powering a flight demonstrator vehicle from launch off a B-52 aircraft (approximately Mach 0.7) up to

scramjet speeds of about Mach 7 (Figure 2). This flight velocity range would demonstrate all of the RBCC engine operational modes: Air Augmented Rocket (AAR), Ramjet, and Scramjet (Figure 3). The ISTAR project plan has been developed to accomplish this goal as well as increasing our system level understanding of RBCC systems, validating predictive tools and system models, and serving as a test bed for other promising component technologies. The current ISTAR project effort will be successful if it designs and fabricates an RBCC GTE, that stays within budget and schedule constraints, and is tested in all RBCC modes.

## Project Plan

NASA's 2003 Strategic Plan has "Goal 8: Ensure the provision of space access and improve it by increasing safety, reliability, and affordability." This same goal has been worded differently in the various NASA plans over the past several years but the though behind it, of creating a technology that will allow the construction of a true highway to space, has not changed. The RBCC / ISTAR project will evaluate airbreathing propulsion technology with the potential to drastically reduce the loss of vehicle failure rate, reduce the cost of access to space, and introduce airline flight like operations. The National Hypersonics Roadmap shown in Figure 4 includes the ISTAR project as one of the propulsion ground testbeds. ISTAR is also being considered for use in the joint US Air Force / NASA Reusable Combined Cycle Flight Demonstrator (RCCFD) project.

This project will increase our system level understanding of RBCC systems, validate predictive tools and system models, as well as serving as a test bed for other promising component technologies. The ISTAR project's success criteria is to design and fabricate a RBCC ground test engine (GTE) within budget and schedule constraints that is tested in all RBCC modes. Currently the baseline NASA program budget is only funding the GTE portion of the project and the Flight Test Engine (FTE) and vehicle activity will be funded as of 2004 at the earliest.

This NASA MSFC led project to explore air breathing combined cycle systems that could address these NASA goals was initiated with several study contracts early in FY2000 (see Figure 5). Multiple concepts were reviewed including both RBCC and TBCC systems. After considering the various

options, the NASA project office decided to proceed with a RBCC concept.

In its most basic form, the project plan was to develop a demonstrator vehicle and FTE system conceptual design, and then design, build, and test a GTE system to prove the FTE designs feasibility. Figure 5 shows a history and projected schedule for the project with the top portion being the FTE and vehicle efforts and the lower half the GTE work.

Boeing Rocketdyne, Gencorp Aerojet, and United Technologies Pratt & Whitney formed the RBC<sup>3</sup> in the summer of 2000 and immediately started working on selection of a single flowpath concept from the multiple contractor concepts<sup>1</sup>. (It might be of interest that it was at this point in the program that the name ISTAR was selected.) From this initial flowpath selection, until the initial Conceptual Design Review (CoDR) in Fiscal Year (FY)2001, the project was planning on utilizing existing RBCC legacy hardware along with a large budget augmentation in FY2003. This was to culminate in a full scale fully regeneratively fuel cooled structurally flight-like ground test engine to be tested at NASA Stennis in FY2006<sup>1</sup>.

At the initial CoDR the propulsion system and vehicle integrated performance was not sufficient to achieve the demonstrator mission objectives (see Figure 6). When the large budget augmentation in FY2003 was declined, the project management team redirected the project to consider additional flowpath performance concepts and changed the project baseline to using a much smaller budget enhancement beginning in 2005. This project plan was to culminate in a full scale single flowpath module fully regeneratively fuel cooled structurally flight-like ground test engine to be tested at AEDC (APTU facility).

During the remainder of FY2001 and FY2002 the ISTAR team refined complete engine and vehicle systems in order to meet the demonstrator mission objectives (primarily final Mach number). Figure 6 summarizes the many engine vehicle iterations. By early FY2003, the project team had designed an engine vehicle system which met the demonstrator objectives to within the uncertainty of the conceptual design process used. This latest FTE design was used to generate the initial GTE lines and requirements – kicking off the GTE phase of the program.

In January of 2004 the program was re-planned with no budget enhancement. This restructured project would retain many of the full scale component tests, while inserting additional risk reduction tasks and earlier rig testing. ISTAR would now develop, build and test a GTE roughly 50% of flight scale. This GTE would initially be heat sink

with fuel cooled sections to be inserted later in the project.

The following sections of this paper review the major project tasks. First, the flight engine related tasks are summarized: flight demonstrator vehicle engine, systems engineering effort, and full scale thruster risk reduction. These are followed by the ground test engine risk reduction activities.

### **Flight Demonstrator Vehicle**

The ISTAR demonstrator vehicle was designed around an existing hypersonic vehicle shape designed for SSTO which was then modified for our particular mission (Figure 2) and propellant combination of 90% Hydrogen Peroxide (HTP) and hydrocarbon (HC) fuel<sup>2</sup>. Generically this configuration is a lifting body with external forebody compression, moving cowl flap inlet with fixed internal geometry, and external aft expansion (artist concept in upper right of Figure 3).

A generic mission (shown in Figure 2) begins when the ISTAR vehicle is dropped from the NASA B-52 at Mach 0.7 and 40,000 ft, accelerates to approximately Mach 7 at 90,000 ft before shutting down the engine and gliding back for re-use. After being dropped from the B-52 vehicle the vehicle freefalls for a few seconds before starting the rocket thrusters and accelerating in AAR mode. In this propulsion mode the rocket thrusters are firing at full thrust and additional fuel is injected to burn with the incoming air (See Figure 3 for engine operating modes). As the vehicle accelerates through Mach 3-4 the rocket thrusters are turned off and the vehicle continues to accelerate in Ramjet mode. Upon reaching Mach 6-7 the vehicle transitions fully into Scramjet mode before shutting down - completing the demonstration of all the airbreathing propulsion modes and the transitions between them for an RBCC engine.

The vehicle and associated propulsion system design was developed to a considerable level of conceptual design in order to provide a good set of requirements for the ground test engine project. Following initial flowpath selection<sup>1</sup> in September of 2000 many iterations of the engine-vehicle system were performed. As can be seen in Figure 6 the process continually iterated using analytical spreadsheet tools and more detailed vehicle simulation programs from the vehicle contractor. By November 2002 it was judged that the engine vehicle integration had been sufficiently iterated at this conceptual level and the next step was to develop the engine system to a much higher level of fidelity before iterating with the vehicle again.

Throughout these vehicle level studies the ISTAR team traded various parameters in order to achieve a high final Mach number. For example, vehicle propellant fraction could be enhanced significantly with thickening of the vehicle cross-section but this also increased drag (especially transonic). Many other analytical studies examine this trade but the limited Mach number range of the demonstrator vehicle (Mach 0.7 to 7.0) allowed a thicker vehicle shape than is normally optimum for a hypersonic vehicle. Many such vehicle engine parameters were traded in order to come up with the final conceptual system. From this conceptual FTE design, a set of flowpath lines and requirements for the GTE was developed.

### **Systems Engineering**

The systems engineering effort is being emphasized in ISTAR to make certain that the technical team answers the right technical questions. The logic path from the demonstrator vehicle system requirements to the GTE design requirements is shown in Figure 7.

Beginning with the vehicle system requirements document the projects system engineering resources were directed toward developing the flight test engine requirements. These FTE requirements were documented in the Engine System Design Requirements Specification (ESDRS). Technical teams from RBC<sup>3</sup> and the NASA centers then identified a set of technology gaps posing risk to the development of an FTE meeting the ESDRS. This "gap" team then prioritized and selected the set of technical risks to be mitigated by the ISTAR project. Development of a risk mitigation plan along with our overall project objectives then determined the RBCC/ISTAR Systems Requirements Document for our ground test risk mitigation effort. Currently the ISTAR systems engineering team is developing the GTE Requirements Document (GRD), GTE test plan and interface requirements to guide the GTE design.

The entire ISTAR project, up to the completion of Design Cycle 2 in early FY2003, was conducted in order to develop the FTE design in enough detail to allow the systems engineering team to determine the technology gaps and GTE requirements that the ISTAR team needs to address. The remaining Phase 2 - Engine System Design, Development, and Test 6 year effort will be conducted to close these technology gaps. From one point of view the entire program is simply a series of GTE risk reduction activities along the path to full scale FTE design activity.

### **Full Scale Thruster Development**

Early in the FTE activity the 90% Hydrogen Peroxide (HTP) / Hydrocarbon (HC) thrusters were identified as a high technology risk item. The ISTAR FTE system was designed around several identical flowpath modules each of which contained several struts in the base of which were multiple rocket thrusters. The physical challenges of producing a set of rockets to fill the base of these struts (a strut-rocket) using the selected 90% HTP/HC propellant combination was high. In order to reduce the risk to the project, a task to develop a full scale FTE injector design and test task was started in FY2002.

The first design, injector "A", was short duration tested in August 2002 using a heat sink combustion chamber. A repeatable start sequence was established, preliminary injector /combustor performance was measured and HTP film cooling effectiveness was determined. Like many injector tests the injector face experienced some heating issues and several test anomalies were encountered (including propellant overpressure). As the test results were promising and the injector face heating issues looked solvable, a second test series was initiated.

Goals for the second test series were to develop an injector design that did not experience face heating issues, had high performance and measured the combustion chamber heat flux. Injectors "B" and "C" were designed to address these issues with injector "C" trading performance for lower face heat flux. Additionally a calorimeter combustion chamber and nozzle was designed and constructed to allow long duration (steady state) testing and measure the heat flux directly (Figure 8 shows a typical test with calorimeter installed). This series of testing went very well with no test anomalies, performing mixture ratio sweeps with measured Pc and thrust. The data from this test series will be used to determine the requirements for the GTE thrusters.

Due to the decision (January 2003) to test the GTE at 50% of FTE scale, the thrusters need to be roughly 50% scale also. After examining the issues around constructing smaller 90% HTP/HC thrusters, the project technical team recommended using a gas/gas thruster to simulate the FTE thrusters. A trade study to determine the "best" propellant combination to simulate the FTE thrusters determined that a methane, gaseous oxygen, and water thruster would be the best compromise. This thruster design is on the same order of size as gaseous thrusters developed for a previous RBCC test program. The gaseous thruster development effort is part of the GTE rig design and fabricate line item shown in Figure 5.

### Fuels Characterization

RBCC vehicles operate over a large Mach number range inside of the atmosphere. This results in the need for a large heat sink in the fuel to keep the engine surfaces below their thermal limit. The total heat sink required is particular to the specific engine design and construction but, for our trajectory, is generally more than can be obtained from the HC fuel without thermally cracking it. Using thermally cracked, or endothermic, HC fuel allows our demonstrator vehicle to perform its mission but introduces the need to understand how that fuel will behave in our engine system.

The fuel characterization task examined HC fuel characteristics for channel diameters and residence times specific to the ISTAR engine, including levels of endothermic reaction and propensity for coke formation. Standard practice of using electrically heated tubes was conducted over a range of tube diameters and flow rates applicable to the ISTAR engine. This testing included cycle testing designed to simulate the reusable life of the flight test engine. As can be seen in Figure 5, this task has been completed. Data acquired during this series of tests and previous investigations provides sufficient data for us to proceed with ISTAR engine specific panel level testing in the engine structures and heat exchanger (HEX) task, which is described below.

### Engine structures / HEX

RBCC engines are required to be structurally efficient and still operate in extremely high heat flux environments. The total heat sink available from the HC endothermic fuel is utilized to enable the engine to remain below its thermal limits. From the fuel characterization task and previous work, we have determined the total heat sink available from the HC fuel. The engine structures and HEX task is needed to determine the thermal and structural limitations of a flight type structure in a simulated flight environment. The final objective of this task is to develop optimally stiffened HEX panels, and the fabrication technology to make them, that are the lightest weight allowed by the thermal/structural requirements.

ISTAR has completed burst pressure and load testing of coupon sized HEX samples using various fabrication methods. The primary challenges facing the ISTAR HEX development are the high average heat flux environment at the high Mach number flight point and the high peak heat flux downstream of the rocket thrusters impingement zones. In order to explore the high average heat flux environment, the ISTAR team is going to test a full

scale (length & height) flight like single cowl side HEX in the Air Force Research Labs radiant heat facility. The design solution for the high peak heat flux from the rocket plume impingement issue may be tested via a small panel section mounted downstream from the full scale rocket thruster and nozzle tested previously. These independent tests results will later be used to develop the fuel cooled flight like combustor test section which is planned for installation in the GTE in FY2007.

### Subscale Inlet

Successful GTE operation requires that the inlet operate and provide a reasonable mass distribution to the combustor over the design range of Mach numbers. The ISTAR inlet design is a unique, highly three-dimensional configuration, based upon a database with some significant scatter. CFD can, and is, used to design the inlet for on-design conditions but is currently unable to reliably predict inlet operability. As subscale inlet testing is quite inexpensive when compared to the GTE test, a subscale inlet test was added to the program during the January 2003 re-planning activity.

NASA GRC 1x1 Supersonic Wind Tunnel will be used to test the ISTAR inlet model from Mach 2.5 to 7. This test series will verify the inlet starting point, operating contraction ratio margin, isolator pressure ratio, and determine unstart loads. Performance parameters such as mass capture and inlet efficiency will also be determined. This data will be specifically used to design the GTE inlet and will generally influence the entire combustor design.

### Injection Characterization Rig (ICR)

An efficient Ramjet/Scramjet needs to do at least one thing really well – burn the fuel. The Injection Characterization Rig (ICR) is designed to develop what the fuel injection / combustion should be in the much more expensive direct connect rig using an inexpensive setup. As the ICR is relatively cheap to run and modify, multiple injector configurations and methods of lighting the engine can be tested – verifying (hopefully) the analytical predictions of the rig operation. In either case, it introduces reality into the engine design cycle as early as possible.

The ICR is a small full scale section of the ISTAR flowpath from the start of the isolator through the end of the internal nozzle. This heat sink engine flowpath section is installed in the Direct Connect Supersonic Combustion Test Facility at NASA LaRC. This facility will provide the Mach 3.5 inlet flow to the ICR and heated HC fuel simulating the

Ramjet conditions that are to be tested. The facility is setup to measure pressure, temperature and video of the combustor during testing.

Testing is planned to start in August of this year and should be completed by this December. The primary test objectives are to determine the combustor back pressure level required, type and location of injectors, and validate the analytical models. Combustor back pressure required to achieve engine ignition is an important parameter to validate as it may influence our direct connect design if it doesn't match the pre-test predictions. Injector type and location (i.e. injector characterization) parametrics need to be tested in order to locate the thermal throat where it needs to be located in the engine. Ideally our pre-test predictions would be "good enough" to locate the injectors without needing the ICR, but historical engine development experience is that a test like the ICR is necessary.

#### **Direct Connect Combustion Rig (DCCR)**

The primary purpose of the Direct Connect Combustion Rig (DCCR) is to characterize the combustion performance of the ISTAR flowpath. The previous ICR testing is used to design the DCCR ignition scheme and gross location of the fuel injectors. The DCCR is designed to explore the fuel distribution, injection, atomization and combustion of the flowpath, allowing the team to characterize the injection schemes & kinetics associated with endothermic hydrocarbon fuel. This experimental work should validate the analytical and computational combustion models used to design the DCCR (HYCAD, FAST, RASCAL, and several empirical mixing models). Generally the DCCR is less sensitive to unstart than the GTE and, with its better known air distribution, allows testing without the complications of the inlet.

The ISTAR FTE engine is made up of several identical flowpath modules – the DCCR is 1/2 of a single full FTE scale module - extending from the front of the isolator to the end of the internal nozzle (basically everything aft of the inlet). The DCCR is to be tested in the Hypersonic Tunnel Facility (HTF) and is a copper heat sink rig. The NASA GRC "HTF, located at the Plum Brook Station, is a blowdown, non-vitiated free-jet type facility capable of testing large-scale propulsion systems at Mach numbers up to 7.<sup>3</sup> The facility is shown in Figure 9 and can handle models up to 10 ft in length. This facility has been recently reactivated as described in Thomas et. al.<sup>3</sup> Figure 10 shows the current DCCR design installed in the HTF.

The HTF was originally designed as a freejet facility, and in order to test the DCCR, several

facility modification were necessary. Additional hot train hardware to connect the front and back of the DCCR to the facility nozzles was required as well as new nozzles for Mach 3.5, 5 & 7. Upgrades to the facility Silane system and instrumentation were also required. Note that the DCCR will only be tested in the Ramjet/Scramjet engine modes as it does not contain thrusters. In order to test the DCCR, a large fuel heater to simulate the hot endothermic fuel that would be exiting the FTE HEX and being injected into the flowpath is being constructed. This same fuel heater will be used for the GTE testing.

#### **Ground Test Engine (GTE)**

The purpose of the GTE testing is primarily to investigate the integration issues between the inlet, isolator, combustor, and internal nozzle. The air distribution from the subscale inlet test and DCCR data along with analysis gives the team guidance as to how the engine will perform. Component testing gives us a partial picture, but GTE testing is the only place where air distribution from the inlet through the rest of the engine is integrated – determining the operability of the entire system. GTE testing provides the closest data to flight we can obtain with current tools. In the current ISTAR project the GTE is also the only testing we perform for AAR engine mode performance.

Figure 11 shows a side view of the GTE mounted on an HTF adapter. The GTE is approximately 50% of the FTE scale and is a full engine module. Testing of a full scale DCCR and a 50% scale GTE will allow the ISTAR team to validate our modeling tools at both scales – filling the deliverable database at both scales. The GTE is constructed of thick wall copper design (heat sink) with inset water cooled steel where necessary. The previously described methane, gaseous oxygen and water thrusters simulate the FTE 90% HTP / HC thrusters at this smaller scale and allow fewer facility modifications than the FTE propellants. The large assembly above the GTE inlet in Figure 11 is the actuator for the inlet cowl flap.

In order to test the ISTAR GTE at the HTF, several facility modifications were necessary. Although the force balance system can handle the model, the tunnel flow rates needed to be enhanced by additional gas injection and mixing hardware. New nozzles for Mach 2.5 and 3.5 were also required. Testing is planned for sea level static, Mach 0.7, 2.5, 3.5 AAR, 3.5 Ramjet, 5.0, and 6.8. Due to the limitations in dynamic pressure level supplied by the HTF at Mach 7.0, the ISTAR technical team has recommended testing at Mach 6.8 and full dynamic pressure. This will allow the Scramjet mode to be

demonstrated without significant modifications to the HTF. Currently the GTE is in the conceptual design phase and the test matrix is still in review, but the final test series will include at least these test points.

Initial testing of the GTE will be with an entirely heat sink engine, but later testing will add a flight like, fuel cooled combustion section (see Figure 5). This second GTE test entry will demonstrate large scale fuel cooled component(s) in a flight like environment. Upon completion of the second GTE test entry, the ISTAR project will have completed the objective of delivering a test database that verifies operability of a hydrocarbon reusable RBCC engine in AAR, Ramjet and Scramjet modes in wind tunnel conditions equivalent to Mach 0-7 flight vehicle operation.

### Summary

This paper reviewed the current technical and programmatic status of the ISTAR project. Development of the GTE requirements necessitated development of the FTE and demonstrator vehicle conceptual design. Current progress through June 2003 on the GTE conceptual design is proceeding on

schedule with the thruster testing and fuel characterization completed. Direct connect testing of the GTE flowpath will begin at the NASA GRC HTF next spring and the test hardware is currently being designed & constructed. The project plan is to reduce risk to the GTE, and ultimately the FTE, through these tests.

### References

1. Faulkner, Robert F., "INTEGRATED SYSTEM TEST OF AN AIRBREATHING ROCKET (ISTAR)," AIAA 2001-1812.
2. Quinn, Jason Eugene, "OXIDIZER SELECTION FOR THE ISTAR PROGRAM (LIQUID OXYGEN VERSUS HYDROGEN PEROXIDE)," AIAA 2002-4026, July 2002, 13 pgs.
3. Thomas, Scott R., Trefny, Charles J. and Pack, William D., "Operating Capability and Current Status of the Reactivated NASA Lewis Research Center Hypersonic Tunnel Facility," AIAA-95-6146, (NASA TM 106808), April 1995, 11 pgs.

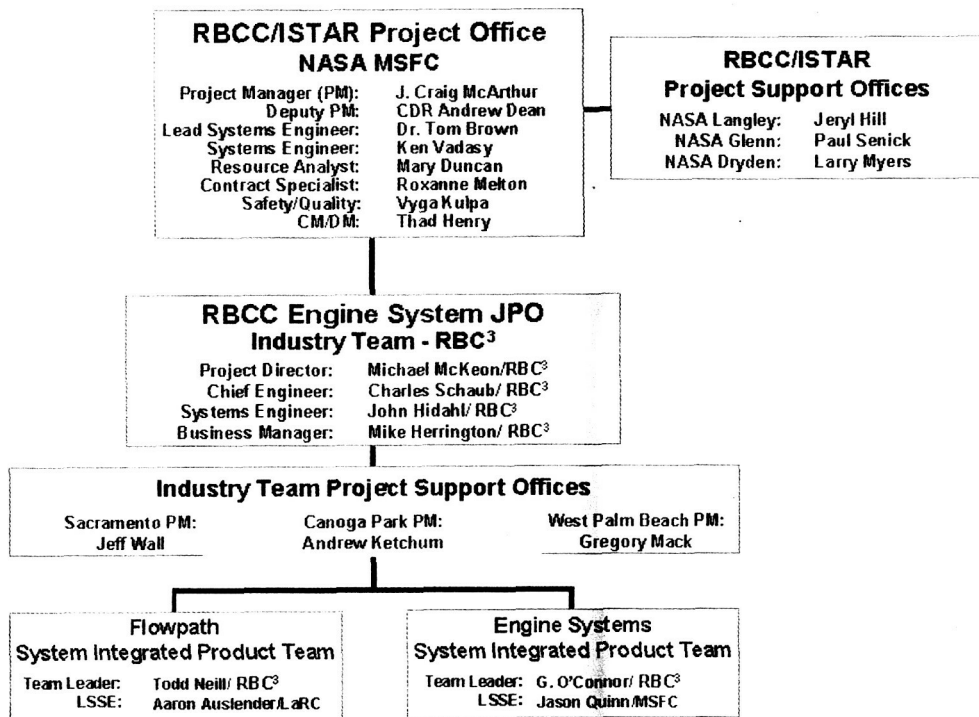


Figure 1: RBCC/ISTAR Management Team.

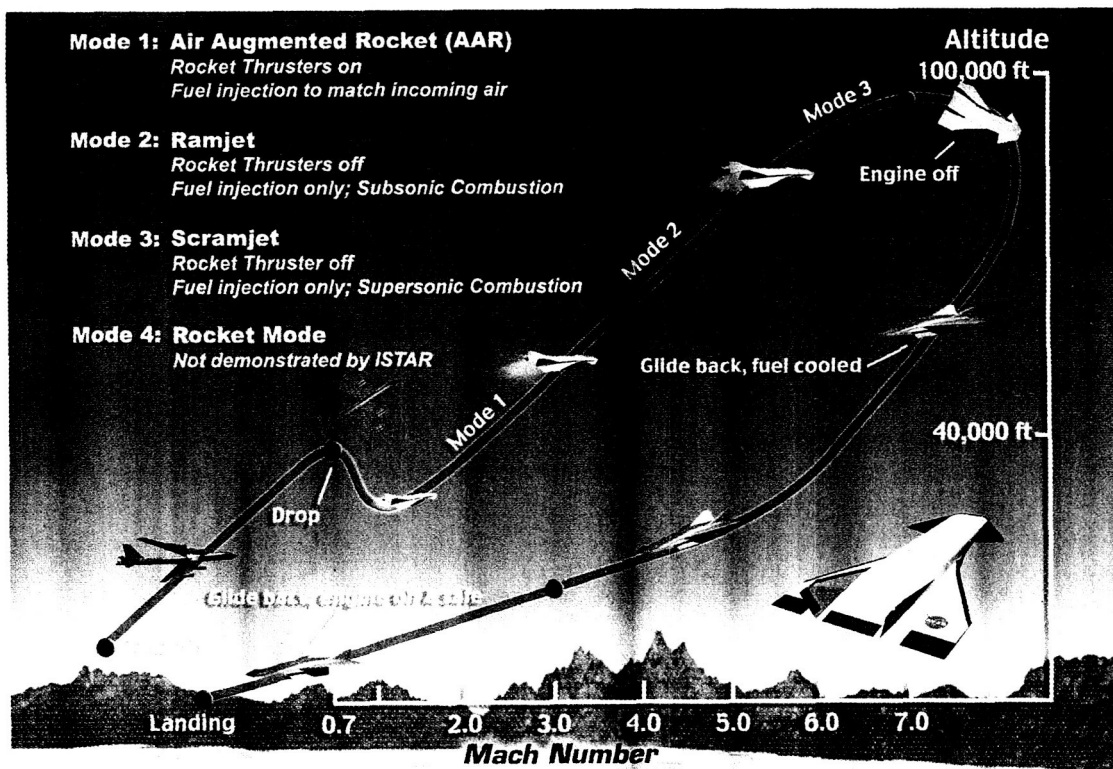


Figure 2: ISTAR Demonstrator Vehicle Mission Profile.



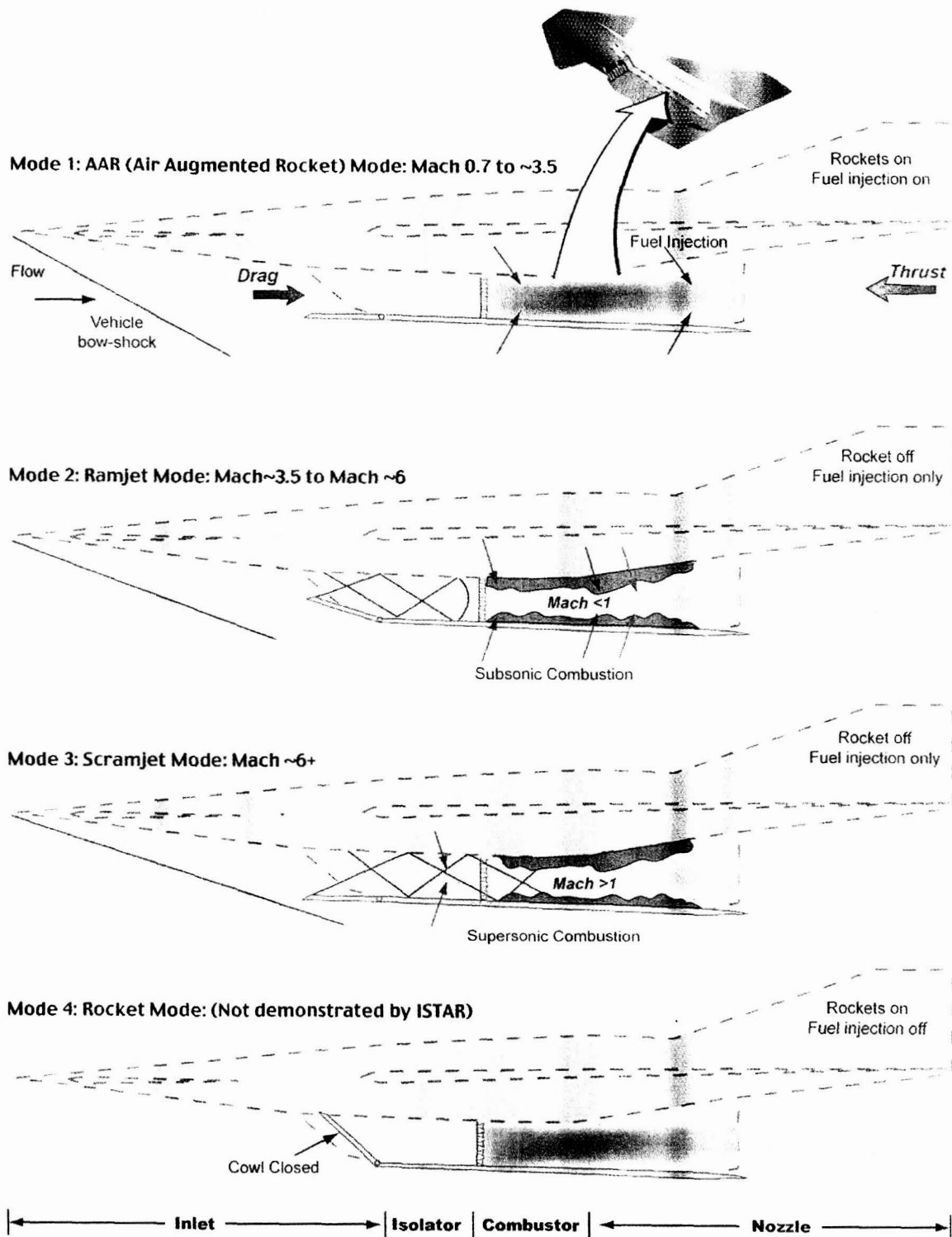


Figure 3: ISTAR Engine Operating Modes.

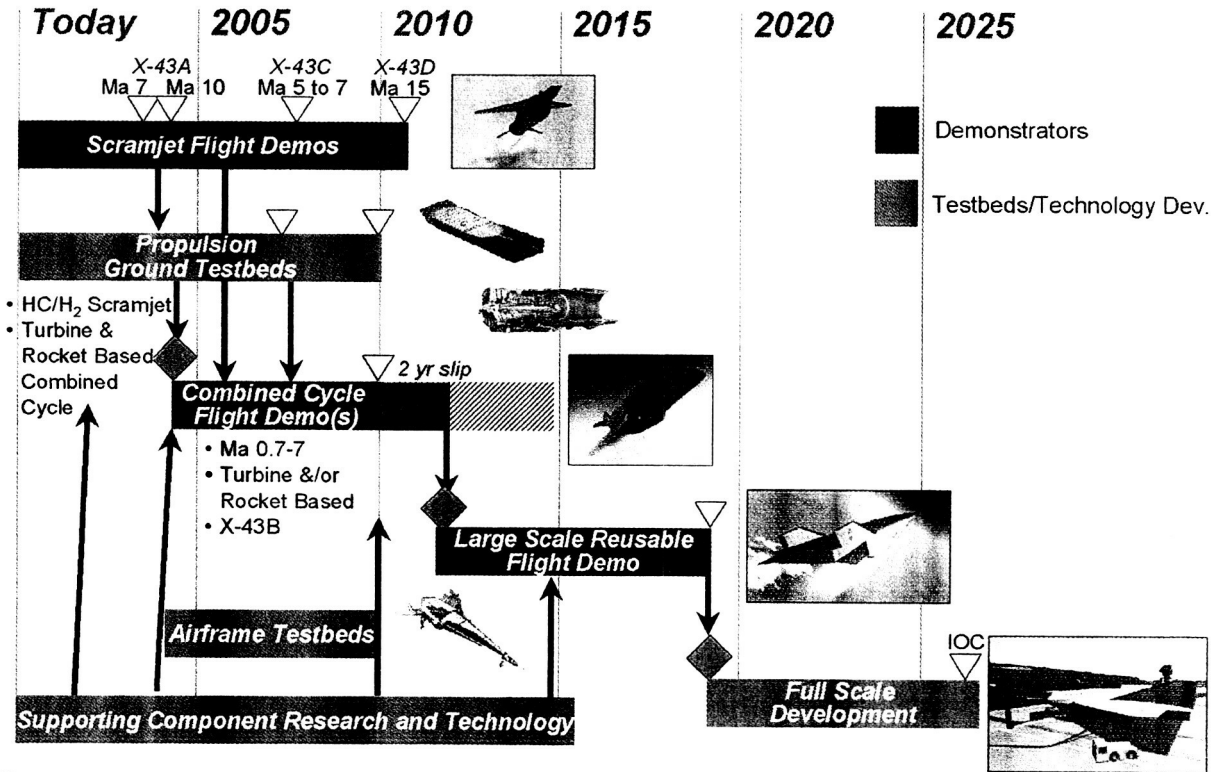


Figure 4: National Hypersonics Roadmap.

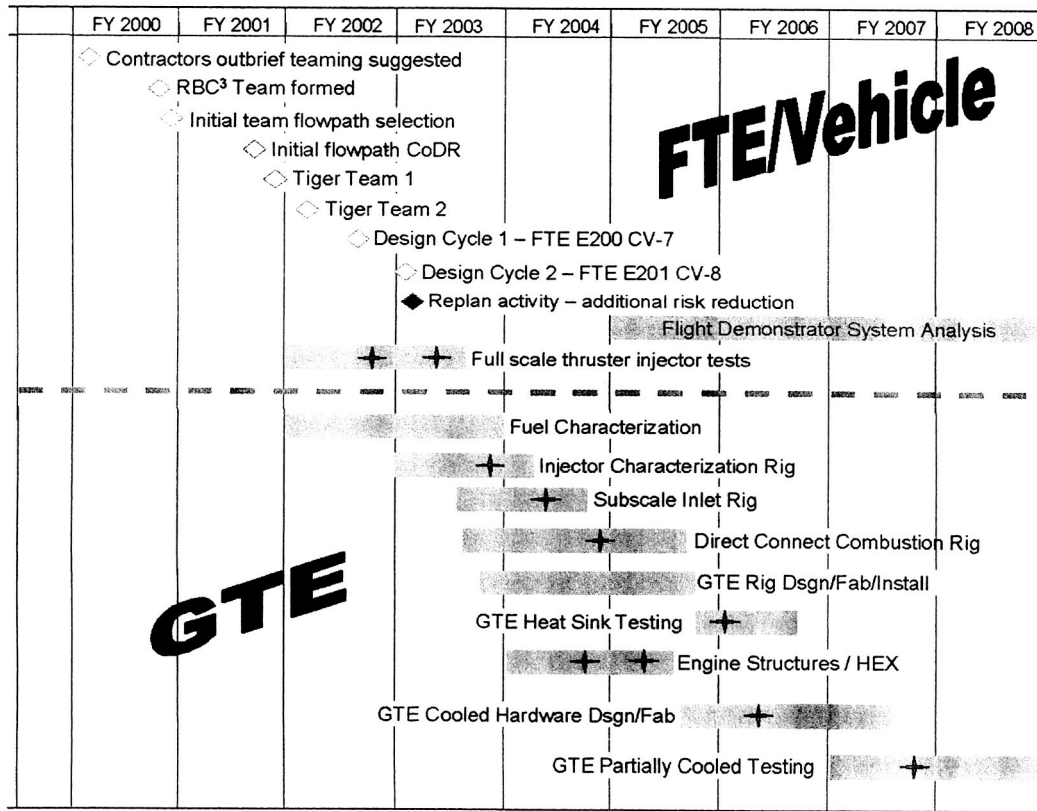


Figure 5: ISTAR History / Schedule.

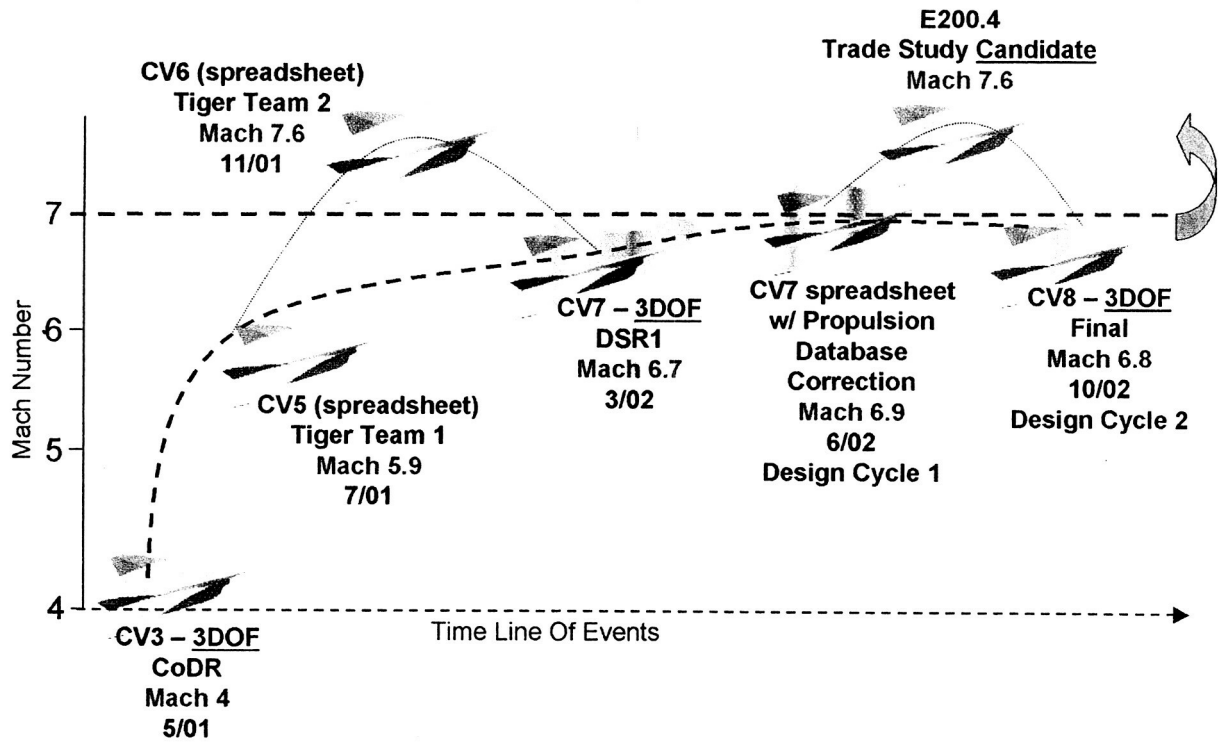


Figure 6: FTE/Vehicle Final Mach Number Achieved Versus Design Iteration.

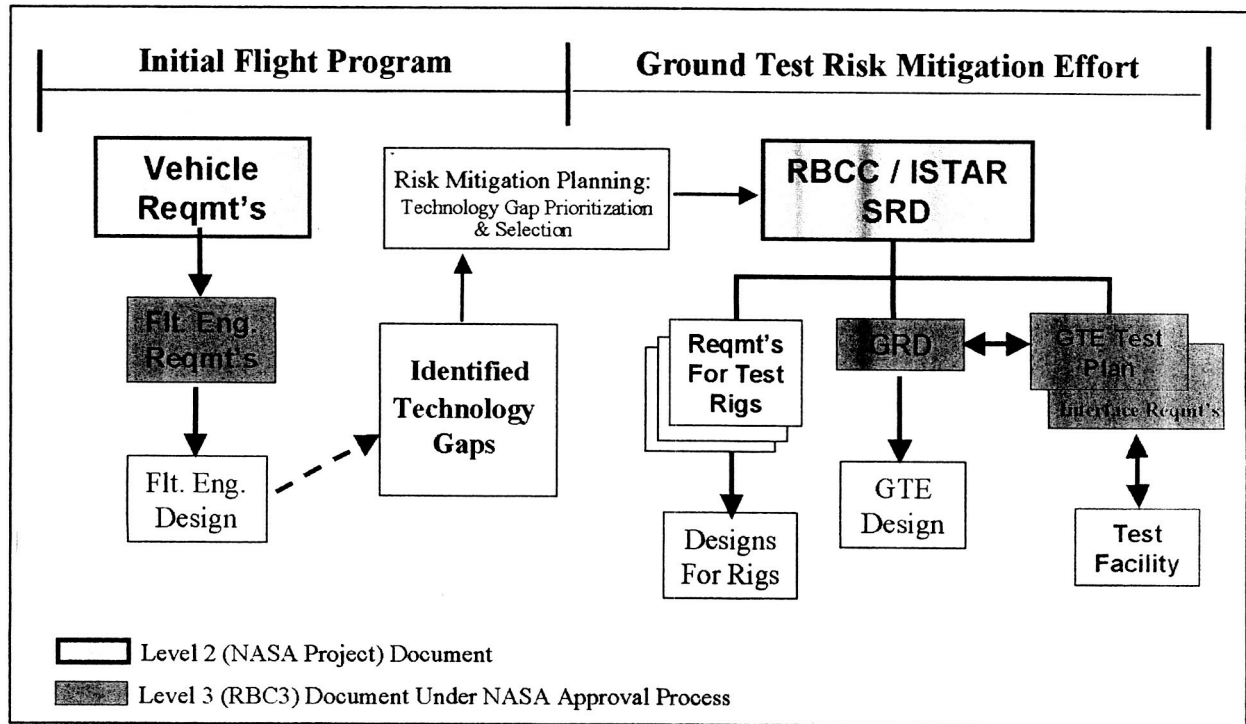


Figure 7: ISTAR GTE Requirements Development.

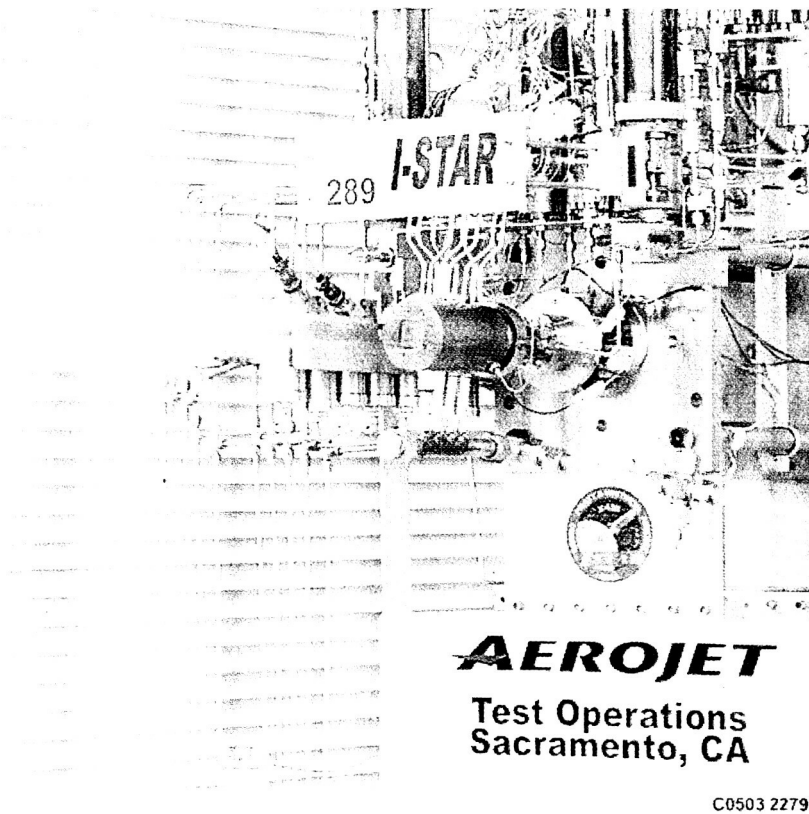


Figure 8: Typical ISTAR Thruster Test.

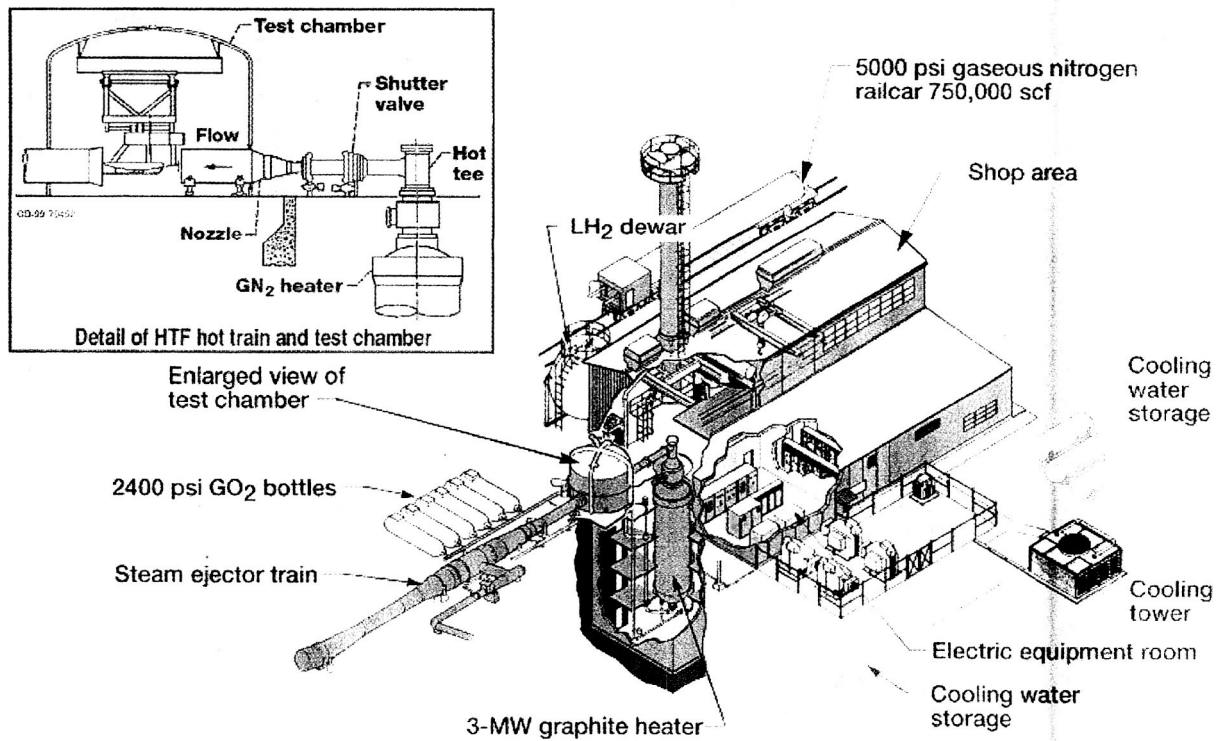


Figure 9: Hypersonic Tunnel Facility (HTF).

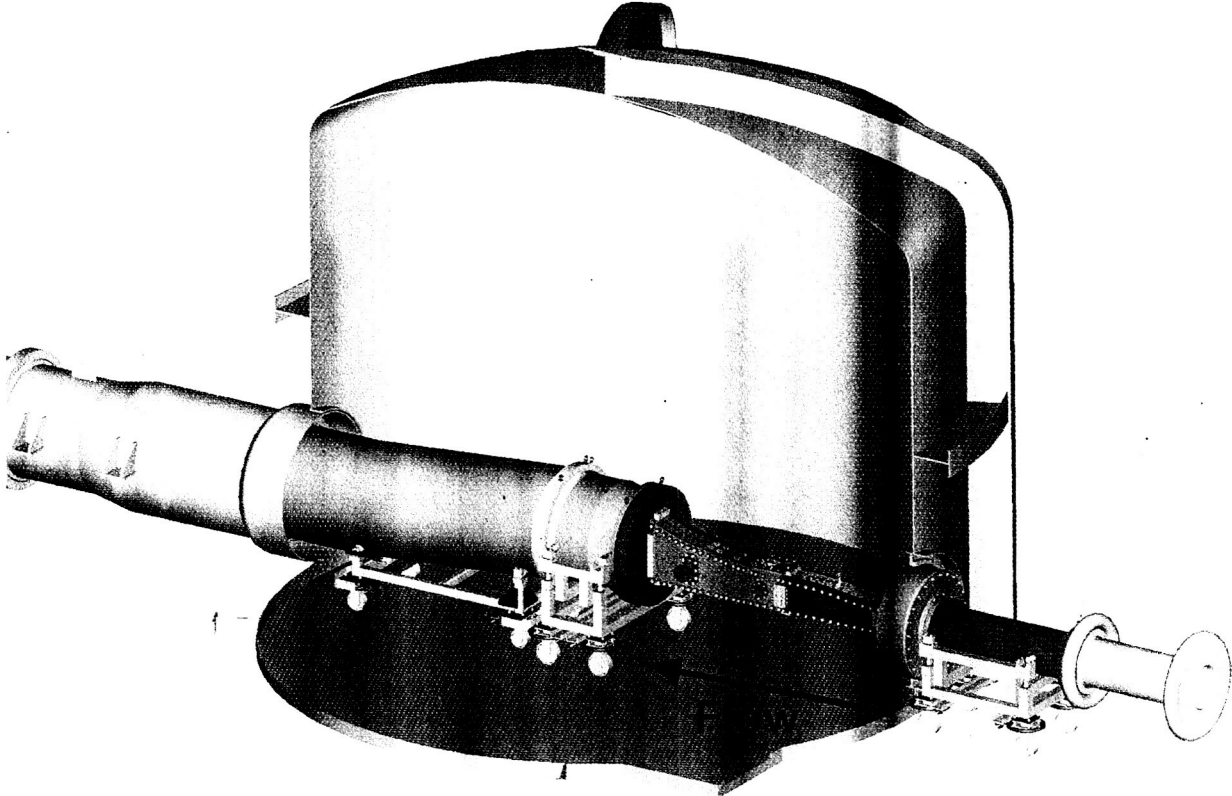


Figure 10: DCCR Installed into the HTF.

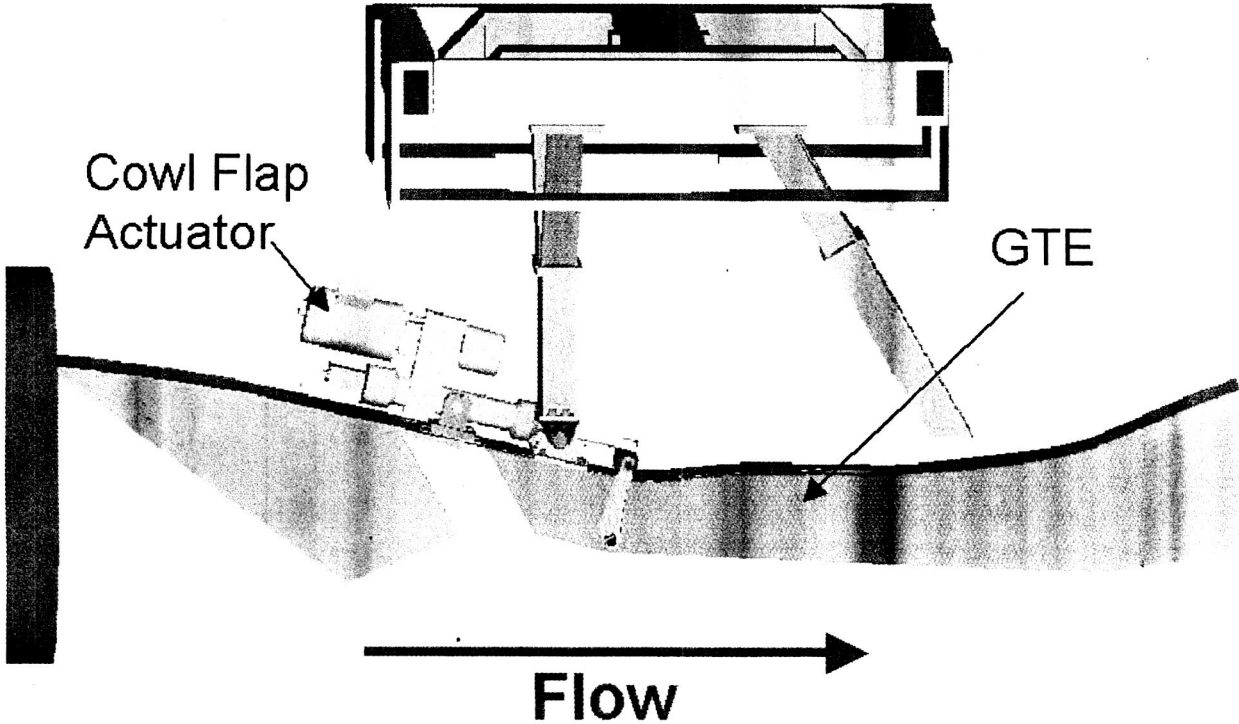


Figure 11: ISTAR GTE Hanging from HTF Mount.