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MODEL SHUTTLE VEHICLE DEVELOPED TO SUPPORT VANDENBERG HYDROGEN DISPOSAL INVESTIGATION

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INTRODUCTION

Space Shuttle Main Engines (SSME) discharge a significant quantity of unburned hydrogen during normal start and shutdown operations. At Vandenberg Air Force Base (VAFB), a Flight Readiness Firing (FRF) or launch abort could introduce this unburned hydrogen into the enclosed SSME exhaust duct. This hydrogen in a closed duct creates a risk of detonation which could result in significant overpressure at the aft heat shield thereby causing damage to the Space Shuttle Vehicle (SSV).

To mitigate the detonation hazard the Air Force (AF) initiated a Hydrogen Disposal System (HDS) program. Extensive analyses and feasibility testing were conducted on possible solutions. In December 1986 the AF Shuttle Test Group (STG) selected the Steam Inerting System (SIS) concept as the most technically feasible resolution to the unburned hydrogen issue. The following January, STG directed the Shuttle Processing Contractor (SPC) to complete the development and design of a SIS for the VAFB SSV launch pad (Refs. A & B).

As part of the SPC SIS Program development, test agencies which participated in the feasibility program were evaluated for their continuing contribution. Astron Research and Engineering, Sunnyvale, California; Wyle Laboratories, Norco, California and Martin Marietta Corporation, Denver, Colorado had each made major contributions in establishing SIS feasibility. A decision was made to continue using their experienced staffs and facilities to support SIS development testing which ultimately resolved many of the development and design issues.

Resolution of the remaining issues required the services of additional test agencies. Cermak, Peterka, Petersen, Incorporated of Fort Collins, Colorado performed testing which established effects of wind on the VAFB SSV launch pad and SIS. Marshall Space Flight Center (MSFC), Huntsville, Alabama was selected to determine the effects of SIS on the VAFB launch pad induced environments. The existing MSFC 6.4% model SSV test facility, containing hot firing hydrogen/oxygen engines, had previously established an acoustic, thermal and overpressure data base for VAFB's launch pad design.

The MSFC 6.4% scale model did not provide variable control of engine power levels or start and shutdown sequences. These control features are critical to SSME start and shutdown transients simulation. Therefore, a different facility was needed to resolve the SSME transient operation issues (Ref. C).

SPC selected Lockheed Missiles and Space Company's Santa Cruz Facility (LMSC/SCF) to design and construct a SSV model which could provide the transient data necessary to assure SIS operational success.

This paper examines the requirements, engine and facility configuration, and instrumentation for the model SSV transient test facility developed for SPC at LMSC/SCF. Also presented are comparisons between model engine test results and predictions and the conclusions drawn from the program.

FACILITY DESIGN REQUIREMENTS

Scaling

The scaling relationships developed for the model SSV transient test facility design were derived from the basic equations of mass, momentum and energy conservation. These equations were normalized utilizing appropriate system parameters. The resulting non-dimensional parameters were then evaluated for relative magnitude and a determination made as to which were most important for the HDS development.

The critical issues to be resolved by the testing program dictated that the "features of the duct flow which must be preserved in the scale model tests include air entrainment and jet mixing at the inlet to the duct, the combustion of the hydrogen entering the duct, the flashing and mixing of the steam inerting spray system and the interaction between the burning hydrogen-air mixture and the water-steam spray which may extinguish the hydrogen flame at the duct inlet." (Ref. D) The model characteristics shown in Table 1 satisfy these requirements.

Additionally, the model test facility was required to be flexible enough to accommodate changes in the exhaust duct velocity and media flow rates. This flexibility would allow detailed experiments in plume behavior at the duct exit if dictated by future requirements.

In order to achieve direct correlation of appropriate results with the 6.4% model at MSFC, the size selected for the transient investigation model facility was 6.4% of full scale (scale factor 0.064).

TABLE 1

SCALE MODEL CHARACTERISTICS

PARAMETER	MODEL CHARACTERISTICS
Velocities	Full Scale
Mach Number	Full Scale
Temperatures	Full Scale
Thermal Properties	Full Scale
Pressures	Full Scale
Geometry	Scale Factor
Time	Scale Factor
Flow Rates	Scale Factor Squared

Vehicle and Launch Pad

As previously noted, critical parameters to be simulated by the model were entrained air, engine exhaust, steam flashing and their subsequent mixing. To meet these requirements the model needed to properly scale:

- Pertinent external geometry of the SSV and the VAFB launch facility
- SSME exhaust conditions
- SIS injection nozzles in the SSME exhaust duct
- SIS nozzle upstream pressure and temperature
- Time

Engine

A model engine was required to simulate full scale SSME exhaust conditions. Based on the scaling criteria, exit plane velocity and Mach number were to be the full scale engine values and the mass flow rate was to be the full scale value multiplied by the scale factor squared. Table 2 compares the model engine characteristics with a full scale SSME and a scaled SSME (Ref. E). Three model engine compromises were accepted: chamber pressure, mixture ratio and the method of thrust chamber ignition. The effects of these compromises on the engine exit conditions were considered minor and acceptable for meeting the program objectives (Ref. E).

TABLE 2

ENGINE COMPARISON

CHARACTERISTIC	SSME FULL	SSME SCLD	MODEL
Total Flow LBS/SEC	1029	4.21	4.10
Mixture Ratio	6:1	6:1	5:1
Chamber Pres PSIA	3005	3005	1100
Exit Mach Number	4.23	4.23	4.02
Exit Vel FT/SEC	13445	13445	13195

The SSME thrust chamber pressure at Rated Power Level (RPL) is 3005 PSIA. Since pressure levels to feed high chamber pressure model engines would have caused a significant propellant feed system design impact, the chamber pressure requirement for the model was established at 1100 PSIA. However, the scaling requirement to produce the SSME exit velocity and Mach number was maintained.

The SSME mixture ratio (MR) (the ratio of oxidizer to fuel flow rates) was set at 6.0 for optimum thrust and specific impulse. The MR for the model engine was limited to approximately 5.0. The lower MR permitted using a simple water-cooled chamber design without causing film boiling at the highest heat transfer area near the throat. The mixture ratio compromise caused two major effects: the model nozzle exit temperature is lowered slightly, and more unburned hydrogen relative to the scaled SSME is discharged at RPL.

For main thrust chamber ignition the SSMEs utilize an Augmented Spark Igniter (ASI) system. A small quantity of hydrogen and oxygen is injected into a small chamber located at the center of the injector. The propellants are ignited by a spark ignition system. The resulting flame ignites the main propellants as they are introduced into the main thrust chamber. Because of the complexity of modeling the SSME ASI system, a decision was made to use a pyrophoric mixture (triethylborane (TEB) and gaseous oxygen (GOX)) ignition system. This TEB/GOX system is similar to one previously utilized in engines of this scale.

Control System

Engine system operation requirements for HDS development were defined by the "Hydrogen Disposal System Specification" (Ref. F). To meet these requirements an engine propellant feed system control must provide a large variation in oxygen and hydrogen flow rates as functions of time. This variation capability would provide for testing with normal SSME start and shutdown or with special simulations such as an abort shutdown. In addition, the overall control system was required to provide order and timing variations in the initiation of the three engine starts and shutdowns. These features would allow simulation of normal shuttle firings and potential abort cases.

FACILITY CONFIGURATION

Model Engine

Technology obtained by LMSC/SCF from development of similar thrust rocket engines for other programs was utilized to minimize model engine development. A 6.4% scale liquid oxygen/gaseous hydrogen rocket engine was designed, fabricated and developed. It consisted of an injector, combustion chamber and 25:1 exit-to-throat-area-ratio bell shaped nozzle extension. Figure 1 shows the major elements of the SSV transient test model engine.

The injector design incorporates fuel cooling and a coaxial propellant injection technique similar to the full scale SSME injector.

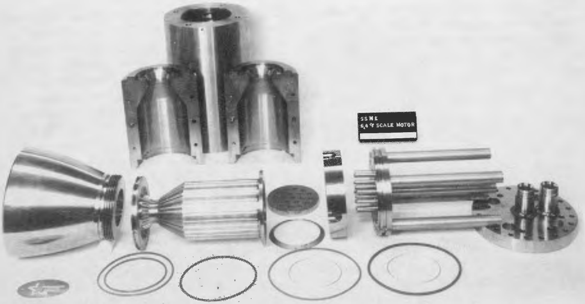


Figure 1 Model Engine Components

Liquid oxygen propellant is injected through an array of nickel tubes which penetrate the injector face. The upstream end of these tubes contains an orifice providing stable oxidizer flow control. The injector face is fabricated of a nickel alloy sintered woven wire material commonly known as Rigimesh. Cooling of this face is accomplished by flowing a portion of the gaseous hydrogen propellant through the Rigimesh material. The balance of the hydrogen propellant flows through an annulus around the periphery of the oxidizer injection post.

The center of the injector contains a triaxial tube which supplies the engine ignition propellants. A 0.062 inch diameter inner tube carries gaseous oxygen, a 0.125 inch diameter middle tube carries triethylborane, and a 0.250 inch diameter outer tube is used to measure chamber pressure.

The engine combustion zone consists of a cooled chamber/throat section and an uncooled nozzle extension section. The one piece combustion chamber and nozzle throat area element is machined from oxygen-free high conductivity copper. Axial water coolant passages are machined into the outside surface of the copper element which is enclosed within a stainless steel housing. For the uncooled bell-shaped stainless steel nozzle extension, resistance to erosion by the high temperature combustion process is provided by a zirconium oxide ceramic coating on its internal surface.

The assembled engine is shown in Figure 2.

Figure 2 Assembled Model Engine

Ignition System

The SSME fuel-lead start provided a departure from the normal LMSC/SCF engine design.

Previous fast-start sequence LMSC/SCF rocket engines used an oxidizer lead with TEB injected for ignition. The oxidizer lead provided a smooth start by preventing excess fuel buildup, which could lead to delayed ignition and/or detonation. The technique developed for the model fuel-lead engine provided an ignition flame at the center of the main injector face prior to initiating flow of hydrogen propellant. This flame was generated by mixing GOX and TEB fed through the center post of the model engine injector - corresponding to the location of the SSME ASI system. TEB/GOX ignition/combustion was detected by burn wires located below each nozzle exit. Burning open these wires enabled computer control of the main propellant valves. Ignition TEB/GOX flow was terminated after 80% of RPL chamber pressure was achieved. The TEB/GOX engine ignition system also satisfied a requirement for ignition of the unburned hydrogen which exists during engine start. The ignition occurs because the TEB/GOX flame extends beyond the nozzle exit where the excess hydrogen becomes flammable as it mixes with the surrounding air. A series of development tests perfected this ignition technique, resulting in a successful fuel-lead start sequence.

Propellant Feed System/Computer Control

Model engine transient conditions were obtained by utilizing hydraulic, servo controlled, variable cavitating venturi propellant valves. An IBM PC "AT" computer and amplifier system established closed loop control of the main propellant valve positions resulting in appropriate flow - time histories to meet the specific requirements for each test. The master command computer, used for facility functions and initial start sequencing, was a SYMAX system manufactured by the Square D Company. The SYMAX was also used for ground safety monitoring. During the start sequencing the SYMAX transferred control to the IBM PC "AT" computer which commanded the main propellant valves servo amplifiers through shutdown.

The necessary propellant valve flow calibration characteristics for engine ignition, RPL and shutdown conditions, were obtained from cold flow and hot fire tests on a single prototype engine. The variable venturi valves were incremented from minimum to maximum flow to determine the command settings for each run condition. Utilizing these data, LMSC/SCF personnel generated the required control software programs for each planned type of test.

Vehicle and Launch Pad

The model SSV orbiter, external tank, and solid rocket boosters were configured to provide aerodynamic similarity to the full scale vehicle/launch pad interface zone. The model of the VAFB SSV launch pad included the Launch Mount structure with its Tail Service Masts, the SSME exhaust duct, and a simulated ground plane at the exit of the duct. Two viewing ports in the duct inlet section provided access for motion picture recording of the engine plume impingement area.

SIS simulation was accomplished by utilizing a pressurized water-filled serpentine section of pipe with clamp-on electric heaters, a computer-controlled valve to initiate water flow, and scaled water flow manifolds and spray nozzles fitted into the duct entrance section.

The model SSV was serviced with high pressure water, liquid oxygen, gaseous hydrogen, gaseous oxygen, triethylborane, LOX purge, fuel purge, igniter purge, a LOX bleed, hydraulics, carbon dioxide deluge, pressure and temperature transducers, and associated valving for controlling these systems. These services were housed within or fed through the external tank and orbiter model. The engines were mounted in the scale positions with engine one in the 16 degree pitch up mode and engines two and three at 10 degree pitch up and 3 degree outward yaw mode.

The three engine module with all of the required service hardware is shown in Figure 3 and installed in the model orbiter in Figure 4.

The complete SSV model is shown performing a hot firing test in Figure 5. This model SSV, with its computer controlled engines, provided the required precise scaling of SSME transient and steady state performance conditions.

Figure 3 Three Engine Module

Safety Features

A variety of safety features were incorporated into the firing sequence and the procedures to protect both hardware and personnel. Shutdown was initiated automatically for any of the following reasons:

- Low coolant pressure
- Loss of burn wire prior to ignition
- No ignition detected on any engine burn wire
- Loss of hydraulic pressure to main prop valves
- Loss of computer control function

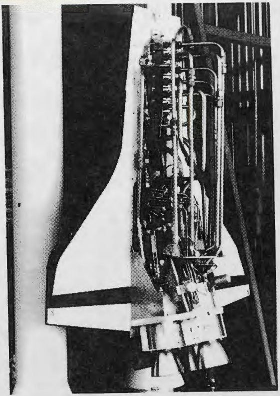


Figure 4 Engine Module Installed in Orbiter

Instrumentation

There were 128 data parameters monitored using a Tustin Analog to Digital Data Acquisition System running at a throughput sample rate of 50,000 samples per second. This provided an average basic sample rate per channel of approximately 390 samples per second. Recorded data were processed using General Automation and IBM PC "AT" type computers. Tabulated printouts and curve plots of each parameter were provided. Selected channels of information which required high frequency response were recorded directly on a 2 megahertz tape recorder and data processing was run on a playback through a Transient Data Acquisition System and VAX computer link.

The basic types of instrumentation transducers utilized in this program are listed in Table 3.

TABLE 3

INSTRUMENTATION TYPE

ITEM/MFG.	MODEL INFO.
PRESSURE	
Sensotec®	Strain Gage Type
Taber®	Strain Gage Type
Statham®	Strain Gage Type
PCB®	Piezo Type
TEMPERATURE	
Beckman Co.®	Platinum/Platinum 13% rhodium .001 open tip T/C
Beckman Co.®	Chromel/Alumel .001 open tip T/C
Omega®	Chromel/Alumel .010 open tip T/C
Rosemont®	Platinum Resist. Temp Device
FLOWMETERS	
Fox®	Cavitatin Venturi
Flow Measurment®	Turbine
Potter Aero Co. ®	Turbine (H20) Model 3C-50189
TSI®	Anemometers Model 1210-60 Platinum Hot Film
HYDROGEN SENSORS	
Gas Tech®	Model 2312
A. G. & C.®	Models 813 and 821
LMSC®	Grab Bottles
Xybion®	Multispectral Solid State Video

Measurement of air entrainment flow rate and the SSME exhaust duct internal temperature were critical in meeting the model program objectives. In both cases, because the model

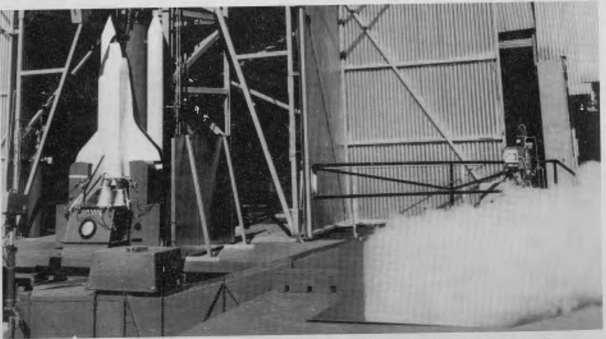


Figure 5. Operating Model SSV

operates on a compressed time scale, the model facility required fast response instrumentation to record the model transient characteristics. For example, the full scale SSME requires 4.5 seconds to reach RPL whereas the model reaches RPL in less than 0.3 second.

Air entrainment velocity was measured by 24 rapid-response, calibrated, hot film anemometers placed above the duct entrance as shown in Figure 6. An algorithm was used to calculate total air flow rate into the exhaust duct. The algorithm summed each flow rate of the 24 zones represented by the velocity measured by the anemometer and its representative flow area and corrected for air density. A wide variety of specialized calibrations and computer reduction/matrix programs were developed. This program development improved the state of the art for the difficult task of acquisition and reduction of information from these fast response hot film anemometers. The anemometers provided major inputs to the HDS transient analysis.

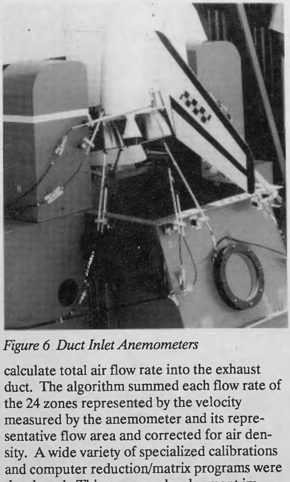


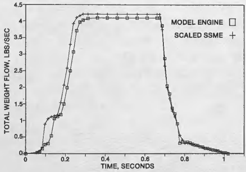
Figure 6 Duct Inlet Anemometers

Measurement of the duct internal temperature response to the SIS and engine-caused transients was accomplished with an array of nine fast-response thermocouples. These thermocouples were located within the duct about 2/3 of its length from the entrance. The thermocouples were to be used for inferring the transient's effect on steam concentration. Open tip thermocouples with 0.001 inch diameter junction wire were selected to satisfy the fast response requirement. In order to ensure survivability during the engine hot firing period, platinum/platinum-13% rhodium materials were utilized initially. However, since temperatures hotter than 2000 degrees F were not encountered, they were replaced with Chromel/Alumel thermocouples. This replacement improved the data accuracy at lower temperatures while maintaining the required fast response characteristics. These instruments provided the fidelity necessary to establish the duct internal temperature through the complete test cycle of ambient; steam injection; engine start, RPL and shutdown; and post test steam conditions.

COMPARISON OF MODEL PERFORMANCE TO PREDICTIONS

Start and Shutdown

Single-engine tests were used to develop the start and shutdown characteristics to be used during the three-engine HDS development testing. Figure 7 shows the comparison of the total propellant flow rates for the actual model engine to the mathematically scaled SSME. With these flow rate schedules established, the resulting rise rates of the chamber pressure and nozzle exit conditions were evaluated. The comparison of the chamber pressure during start is shown in Figure 8 and a calculated force parameter comparison in Figure 9. The calculated force parameter (wV/g) is the product of the engine total weight flow rate (w) and the calculated exit plane velocity (V) divided by gravity (g). Even though the chamber pressure



Fugure 7 Total Weight Flow Rate Compraison

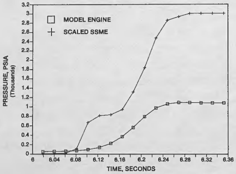


Figure 8 Chamber Pressure Compraison

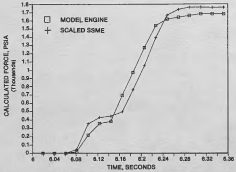


Figure 9 Calculated Force Comparison

rise rates and maximum values do not coincide, the critical exit conditions, represented by the calculated force parameters, show excellent agreement.

Three-Engine Integration

Sequencing of the initiation of the three-model-engine starts and shutdowns was controlled by the same computer which regulated the control valve position. The orbiter-controlled SSME start sequence begins with position three followed by positions two and then one at 120 millisecond intervals. A normal full scale FRF shutdown initiates with engine position one followed 1100 milliseconds later by position two which is then followed 1300 milliseconds later by position three. Figure 10 shows the FRF model hydrogen and oxygen valve position schedules which controlled the start and shutdown conditions. Figure 11 shows the response of the three engine chamber pressures. The curve clearly shows the staggered start and shutdown intervals. The interval values at start are within three milliseconds and at shutdown are within ten milliseconds of the scaled SSME values.

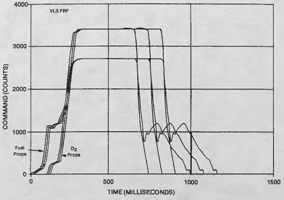


Figure 10 Valve Position Schedule

One abort case was tested. This Clustered Abort (Ref. F) postulated that engine position one is commanded off while at RPL, and that an avionics failure causes engine positions two and three to initiate shutdown simultaneously 1.19 seconds later (full scale). The Clustered Abort occurrence is considered a low probability; however, it is the three-engine shutdown scenario which discharges the maximum unburned hydrogen. The scale model Clustered Abort simulation is shown in Figure 12. The start sequence is normal - engine position one reaches RPL and begins its shutdown followed 120 milliseconds later by shutdown initiation for positions two and three.

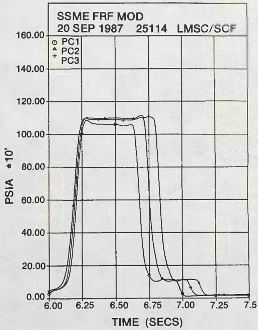


Figure 11 Model Engine Chamber Pressures - FRF

CONCLUSIONS

The SSV transient model provided an excellent scaled simulation of the physics of the start, RPL and shutdown operations of the SSMEs. By performing the FRF and the Clustered Abort cases, the model engine, with its computer-controlled fuel and oxidizer valve design, demonstrated the potential for being programmed to produce any desired start, mainstage level or shutdown scenario. This 6.4% model test facility, along with major contributions by the other five test facilities, accomplished the development and sub-scale verification testing of the SIS.

Installation of the SIS, developed by this program, will alleviate the hydrogen detonation hazard at VAFB (Ref. C).

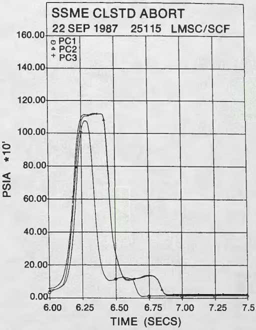


Figure 12 Model Engine Chamber Pressures - Clustered Abort

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