Title: Short Duration Base Heating Test Improvements

Authors: Robert L. Bender — Research Specialist, Qualis Corporation
Mark G. D'Agostino — Engineer, NASA Marshall Space Flight Center
Bradley A. Engel — Engineer, Qualis Corp.
Carl D. Engel — Associate Fellow, AIAA; Senior Engineer, Qualis Corp.

Addresses: ED32/Mark D'Agostino
NASA/MSFC
MSFC, AL 35812
mark.d'agostino@msfc.nasa.gov
(256) 544-0065

Qualis Corporation
3225 Bob Wallace Ave., Suite C
Huntsville, AL 35805
qualis2@traveller.com
(256) 533-9282

Significant improvements have been made to a short duration space launch vehicle base heating test technique. This technique was first developed during the 1960's to investigate launch vehicle plume induced convective environments. Recent improvements include the use of coiled nitrogen buffer gas lines upstream of the hydrogen / oxygen propellant charge tubes, fast acting solenoid valves, stand alone gas delivery and data acquisition systems, and an integrated model design code. Technique improvements were successfully demonstrated during a 2.25% scale X-33 base heating test conducted in the NASA/MSFC Nozzle Test Facility in early 1999. Cost savings of approximately an order of magnitude over previous tests were realized due in large part to these improvements.

Introduction

All multi-engine launch vehicles experience heating near the aft end (base) during ascent induced by the hot exhaust plumes of the propulsion system. These heating environments are important to the vehicle design because they determine the weight, cost, and complexity of the TPS for the vehicle base region and engines. One way to estimate flight vehicle base environments is to conduct a ground based subscale, hot flow, model test during which the environments are measured; then to scale the measured model data to flight conditions. The typical test technique employs a short duration (on the order of 100 milliseconds) combustion simulation using flight vehicle propellants. Designing the model for these tests has historically been a difficult, time consuming, and an iterative process.

The hot firing short duration base heating test technique was developed at Cornell Aeronautical Laboratories in the early 1960's. Gaseous propellants supplied from charge tubes through sonic venturis sized for proper metering are mixed and burnt in the model combustor. The hot gas is then routed to the model nozzles. A test is initiated by mechanically rupturing Mylar diaphragms (or opening fast acting valves) located downstream of the venturi in each propellant supply tube. The rapid opening produces an unsteady expansion wave, which propagates through the venturi and up the charge tube. During the time required for the expansion wave to traverse the charge tube and reflect back to the venturi, a steady supply pressure exists at the venturi entrance. When the fast acting valve is fully open, the flow in the venturis is sonic and a constant flow of fuel and oxidizer is supplied to the combustor.

Innovative improvements in launch vehicle base heating test models and procedures have been recently developed (Ref. 1, 2 and 3) for application on the X-33/RLV and future programs. The new technology provides rapid and less costly model and gas delivery system development, enabling test programs, which enhance vehicle design, to be conducted earlier in the design cycle and at substantially less cost than was achievable during the Saturn and Shuttle programs. Similar test efforts on the Saturn launch vehicle and the Space Shuttle required an order of magnitude more resources in 1960's and 1970's dollars. The X-33 project cost savings using the SBIR (Small Business Innovative Research Program) developed model versus the old technology cannot be accurately estimated in 1998 dollars but are easily in excess of $5M.

The X-33, which is a key element in NASA's Reusable Launch Vehicle Technology Program, was selected by Qualis Corporation and NASA MSFC as the focus of the model development and testing effort for the SBIR project. The X-33 is a wedge-shaped vehicle, which employs an innovative propulsion system utilizing a linear aerospike engine(s). Qualis developed a 2.25% scale model of the aft third of the X-33, which simulates the linear aerospike engine and base region geometry.

The 2.25% model with instrumentation and associated gas delivery system hardware was completed, assembled, and successfully fired in November 1998; followed by a full altitude simulation test in the Nozzle Test Facility at NASA MSFC in February and March of 1999. The model design and operational design has permitted 110 hot fire runs to be made in less than two months, thus minimizing test facility and test personnel time. The data will be used to validate the X-33 flight environment predictions and for preliminary design of the RLV. A computer code which enables the model designer to iteratively size the model components and estimate internal losses was developed and can be used as a training tool for future model designers.

The objectives of this base heating model program were to bring the short duration test techniques in line with current technology; specifically, the utilization of computer design tool, CAD, and rapid prototyping to quickly design and implement model fabrication as well as the utilization of modern computers and data acquisition systems to acquire and manage data quickly and efficiently. The overall objective was to demonstrate the base heating test innovations by developing a working model which could be hot fired repeatedly without compromising the model performance, which produced useful data to the launch vehicle developer, and which lowered the cost of the test program. All of these general objectives were met and the innovations reduced the model development time while providing data that was obtained more easily and analyzed more expeditiously. At the same time, a series of lessons were learned concerning the model design and fabrication which will be useful to expedite similar model development efforts in the future.

Test Description

A short duration (less than 100 milliseconds) base-heating test is conducted by releasing fuel and oxidizer into a model where combustion is initiated and the hot gases are released through a nozzle or nozzles. The model is designed to create fully established scaled plumes in a flight vehicle's correspondingly scaled base geometry. Tests are run for such a short time that the model can be designed to survive the high heating without a cooling system. Quick response instrumentation and data acquisition systems are used to collect pressure, temperature, and heat transfer data from the base geometry.

Upon the release of the fuel and oxidizer, there is an expansion wave that travels from the release point to an obstruction (in this case a closed valve), and then back to the release point again. During the time the expansion wave travels down and back, the venturi at the entrance of the model are provided with a constant pressure equal to the initial pressure in the system minus the pressure drop across the expansion wave. It is the expansion wave's travel time that determines the maximum effective run time for the system.

In traditional systems hydrogen and oxygen were released and then, shut off with a valve to bring the combustion process to an end. The expansion wave travels at the speed of sound. The speed of sound increases as the molecular weight of the gas is decreased. This resulted in approximately four times the path length for the hydrogen than for the oxygen. There were also many safety issues that had to be considered when dealing with an abrupt shut off to the hydrogen and oxygen lines.

To improve upon these traditional methods, a buffer gas with a higher molecular weight than hydrogen is introduced upstream of the release points of the fuel and oxidizer paths. The fuel and oxidizer is then supplied to a separated section between the buffer gas and the release point. The oxidizer sections are designed with a capacity equal to the exact amount of oxidizer needed for a given run time. The fuel section is designed to have a capacity equal to the amount needed for the longest run time. Using this design, the combustion event is limited to the amount of oxidizer contained in the appropriate section. After the fuel and oxidizer have been exhausted, the buffer gas immediately follows into the model, effectively purging the model and providing some cooling for the internal flow passages. Nitrogen was chosen for the buffer gas in this effort. A schematic showing this general procedure is presented in Figure 1.

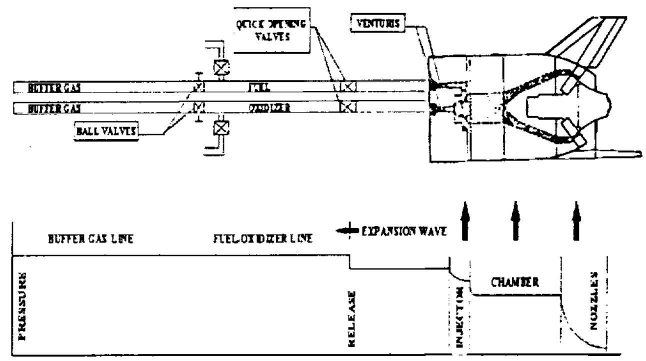

Figure 1 Operational Schematic

The baseline operating condition for the model combustor duplicates the X-33 flight engine operating condition at 100% power level; i.e.- H2/O2 combustion at an O/F ratio of 5.85 and a chamber pressure of 857 psia. Therefore, the thermodynamic and transport properties of the model exhaust gas in the nozzle(s) throat will be essentially the same as that expected for the flight vehicle nozzle throat gas. This also means that the terms in the nozzle throat Reynolds numbers are the same for both the model and flight vehicle except for the characteristic dimension term. Since the Colburn turbulent heat transfer relationship is assumed applicable to the nozzle throat and base region flows, the Nusselt number, Reynolds number, and Prandtl number relationship can be expressed as shown below:

$Nu \propto Re^{0.8} Pr^{0.33}$ Since the throat properties are the same, this relationship for the X-33 model can be simplified to: $h_c \propto \frac{1}{(L)^{0.2}}$ or flight h_c = model h_c (scale factor)$^{-0.2}$ and for the 2.25 % X-33 model

flight $h_c = 0.468$ model h_c

A similar scaling approach was utilized with good success on the Shuttle base heating tests. Comparisons of flight and scaled model data in the Orbiter base region showed good agreement at most locations.

There are many advantages to the short duration test technique including:

1) The model does not require nozzle or base plate cooling so base region external geometry can be scaled exactly.

2) The exhaust flow rates are small so the supply gases are minimized and the models can be easily adapted to wind tunnels and vacuum chambers for testing.
3) The heating rate instruments are small (in terms of thermal mass) permitting a relatively large numbers of gages to be flush mounted in the base region so that distributions in heating rate and pressure can be determined.
4) Model throat damage and nozzle throat erosion are minimized; providing greater predictability in model performance and data repeatability.

Model Description

The X-33 base heating model configuration consists of three systems; the 2.25% scale propulsion model of the aft third of the X-33 flight vehicle, the charge gas system, and the buffer gas system. The propulsion model is comprised of eighteen separate components plus wings and fins. The components are bolted together and attached to a 14-inch diameter circular flange which is mounted to a test stand support as shown below in Figure 2. The model develops approximately 200 lbs. of thrust during high-pressure firings.

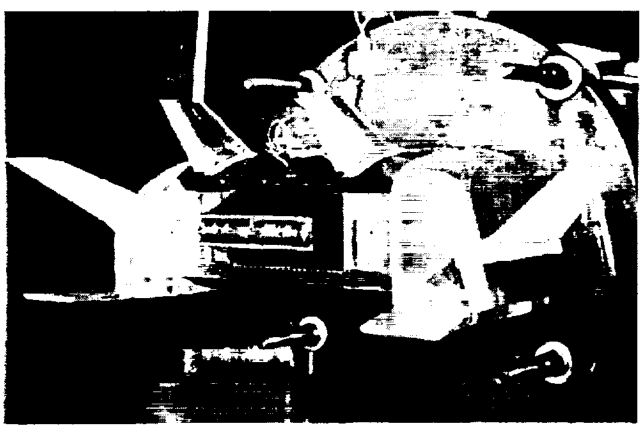

Figure 2 Model Aft View

Model operation follows these steps. High-pressure fuel and oxidizer gases are fed to the model at the attach flange and metered to the injector/combustor through venturis. Ignition of the gases results in combustion at an O/F ratio of 5.85 at chamber pressures, which match the X-33 vehicle. Hot exhaust gases are routed out of the combustor and split into equal mass flows, which feed two rows of 20 nozzles located at the top and bottom of the model base. These gases expand through the individual nozzles and flow externally along the curved wall of the aerospike plug, eventually converging into two sheets of hot plume gases, which dissipate into the surrounding atmosphere. Duration of the combustion process is controlled by the amount (volume) of charge gas; nominally about 65 milliseconds of constant pressure combustion is achieved.

The charge gas system is designed to control the release of the fuel and oxidizer gases into the model. Two electronic solenoid valves, made by Circle Seal Controls, provide quick release of the gases, as the valve becomes fully open in approximately five milliseconds. An adjustable delayed signal from the data acquisition system ensures simultaneous delivery of the gases. Four electronically controlled ball valves separate the gases from their supply, separate the fuel and oxidizer from the buffer gas during pressurization of the system, and provide a means of control from a remote location. The charge gas tubes attach to the head end of the model attach flange. The charge gas valves and tubing are supported and attached to 40 inch steel tie rods, which connect the model, attach flange to an identical flange. Both flanges are bolted to the test stand. The open tie rod arrangement offers easy access to the charge gas system hardware and wiring, see Figure 3.

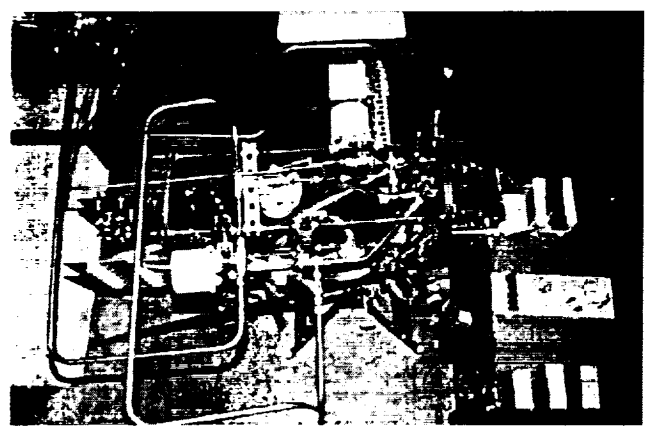

Figure 3 Charge Tube and Buffer Gas System (top view)

The buffer gas system is comprised of two sets of 5/8 inch coiled stainless steel tubing. The coils are attached together with 37-degree flared fittings. Three electronically actuated ball valves separate the coiled sets and the system from the supply. The buffer gas oils were designed to equal the effective length for a maximum system run time of 100 milliseconds
Oxygen, hydrogen, and nitrogen gases are supplied from high-pressure gas cylinders. The gas cylinders are pressurized to a maximum of 2400 psia. All of the gas lines in the supply system are 1/4-inch stainless

steel 37 degree flared tubing. There is a regulator for each gas. Downstream of the regulator, the gases are passed through a 2 micron filter, then to a flared tee connector which can release the gas to a manual purge valve or routes the different gases toward either the buffer gas or charge gas systems.

Model Design

The volumes and L/D of the model internal flow passages were determined by the Qualis ICE code (Ref. 4) and IBFF code (Ref. 5) for the selected scale size, combustor chamber pressure, and run time. Given these design specifications, hardware design was completed using the external configuration features of the X-33 known in February 1997. The design process, using AutoCAD 13 software, produced a model design with 18 major components as shown in the exploded isometric drawing shown in Figure 4. Solid model CAD drawings were produced during this period and translucent stereolithography resin model components grown to the drawing specifications.

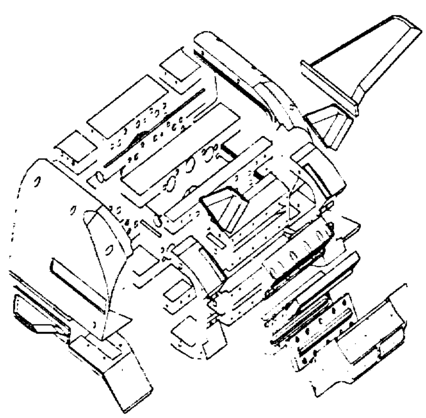

Figure 4 Model Components

This SLA model permitted early assessment of form and fit as well as a method of visualizing the internal flow paths.

Concurrent with the AutoCAD design activity, a series of analyses were conducted to determine heat transfer parameters in the combustor and nozzles to assess model survivability. Stress and load calculations and bolt design choices were made based upon a safety factor of 5, which is dictated by the safety requirements and good design practices for pressure vessels.

Ignition of the hydrogen and oxygen occurs in the central combustor via the glow plug. Note that the It is desirable to use all circular O-ring raceway geometries. However, non-circular O-ring raceway geometries are required to minimize the interior area exposed to the gases and thus the pressure forces on bolts.

Materials were also selected for the model components as a result of the heat transfer and stress calculations. The injector manifold was made of Monel due to its oxygen compatibility. The injector, combustor and combustor manifolds were made of oxygen free copper because of its high heat capacity and thermal conductivity.

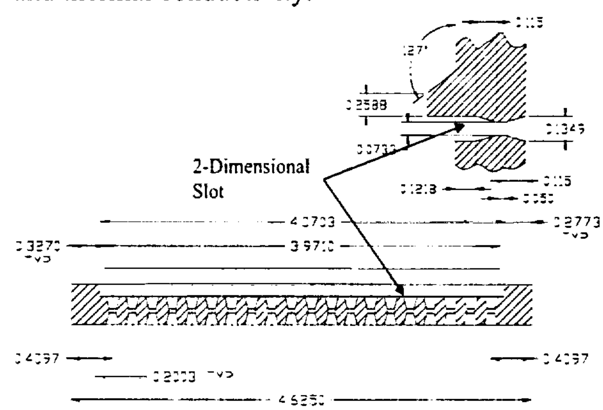

Figure 5 Nozzle Block Geometry

The nozzle entrance and nozzles receive the highest heating of any component during motor firing. The nozzle entrance was made of the molybdenum alloy, TZM, to provide a greater thermal capability. Nozzle throats sections, Fig. 5, were made of TZM and copper. The set of copper nozzles were made to compare the erosion effects of copper with TZM. The nozzles were made with a special reamer tools.

Bench tests on the SLA material used to perform the rapid prototyping showed that the material could withstand at least 10 Btu/sft-s without damage. Since our test were planned for less than 100 milliseconds, it was found that the outer shell components and wings and flaps, Fig. 2, could be made from SLA material thus reducing hardware cost. Moreover, this material is excellent for inserting pressure tap holes during original manufacturing and for adding gages during the test process.

Instrumentation

The propulsion model is instrumented internally to measure operating conditions and externally to measure base region environments and response to these environments. Instruments are also located on the charge gas and buffer gas systems to monitor pressures in the gas delivery system.

Six (6) Omega pressure transducers are also located in the buffer gas and charge gas tubing to monitor pressures during charging and release of the propellant gases and buffer gases for each model firing. They are designed to measure pressures under both static and dynamic pressure events.

The internal instruments included:

1. Three (3) Medtherm co-axial thermocouples to measure internal surface temperature (and deduce heating rate) in the combustor and the upper and lower legs of the hot gas manifold.

2. Six (6) PCB pressure transducers to measure high pressures in the throats of the venturis, in the entrance raceway to the injector, in the combustion chamber, and in both the upper and lower legs of the hot gas manifold.

The internal instruments are also designed for fast response and were used to provide data necessary to measure mass flows to the injector/ combustion, to assure correct chamber pressure in the combustor, and assure symmetry in the hot gas flows between the upper and lower hot gas manifold. These instruments are located as shown in Fig. 6.

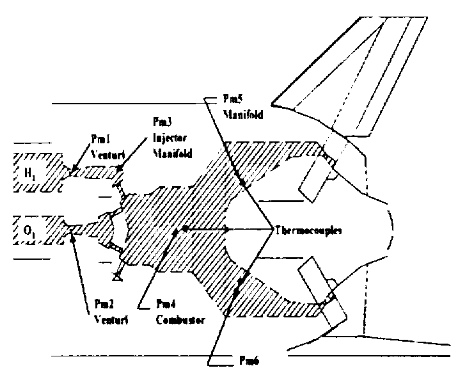

Figure 6 Internal Model Instrumentation Locations

The model base region external instruments include:

1. Sixteen-(16) Medtherm platinum thin film gages to measure heat transfer rates on the aerospike plug, the upper nozzle section, and the outer body shell.
2. Twenty-one (21) Kulite miniature pressure transducers to measure pressures on the aerospike plug the upper nozzle section, the outer body shell, and the body flap.
3. Four (4) Medtherm co-axial thermocouples to measure surface temperature (and deduce heat transfer rates) on the curved high heating surfaces of the aerospike plug.

All of these external instruments are specifically designed and calibrated to provide fast response measurements of the thermal and pressure environments. They are located as shown in the schematics of Figs. 7 and 8. These locations were selected to be coincident with design body points and flight instrument locations on the X-33 flight vehicle. The sensing surfaces or pressure ports are small or flush with the component surfaces and do not interfere with the base flowfields. The thin film heat transfer gages require Wheatstone bridge circuits to convert resistance change into millivolt output that is calibrated to heat transfer rate. The bridges are contained in a housing located forward of the propulsion model.

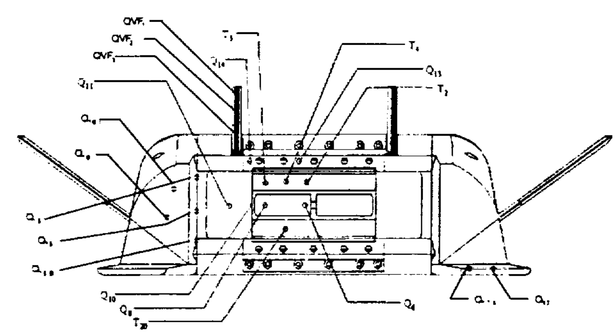

Figure 7 Heating Rate Instrumentation Location

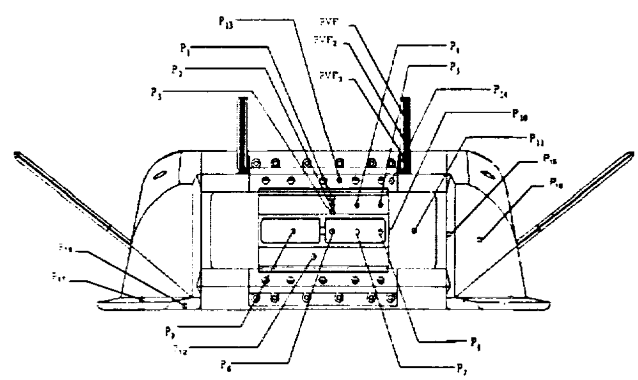

Figure 8 Pressure Instrumentation Location

The instrumentation leads are routed from the model to a connector board which is used to organize the leads into functional groups and to allow a disconnect location between the model and the data acquisition cabinet.

Data Acquisition System

The data acquisition system (DAQ) is a stand-alone system designed for the baseline test requirements. It also serves the dual function of test control and operation.

The system was designed by National Instruments for the base heating model specific requirements compiled by Qualis and includes approximately 160 analog channels, 18 digital channels, and 6 analog output channels. An Intel Pentium processor provides computational capability (the computer core of the DAQ) with a clock speed of 166 MHz. The computer has 96MB of RAM, a 1.2GB hard drive, a 3.5" floppy drive, and a keyboard, monitor, and mouse. The computer utilizes a Windows 95 operating system.

Three DAQ devices (cards) are used to acquire data and to control the system. A RITSI cable connects the three cards. The DAQ Devices mount directly into the backplane of the computer. The CPU of the computer (and the DAQ devices attached to the CPU) is mounted in the cabinet within inches of the connector blocks and power supplies.

A PC Extender was used to separate the monitor, keyboard, and mouse from the CPU for distances up to 300 feet. This allowed the DAQ electronic hardware mounted on the cabinet to be located near the model and the control and data visualization functions to be located in a control room at some distance from the test hardware.

The LabView software used to develop the test control and data acquisition offers many variations and a wide range of possibilities for arranging the data obtained during the test. The initial data reduction program is set to begin data collection one second before Circle Seal valve opening command and discontinue data collection one second after the valve opening command. At a sample rate of 0.5 msec, this set-up resulted in 4000 individual records of response from all instruments on each run. This allowed the test operator to easily identify the beginning and end of the useful test time on each run so a nominal number of records can be isolated for plots and comparisons. Since most tests will run about 25 to 65 msec at the selected chamber pressure, the number of useful records from each instrument is about 60 to 130. The tabulated data is automatically formatted as an Excel spreadsheet and can be displayed on the monitor directly after each firing. A run log is automatically generated for each day in a file, which records all specifying variables and user input comments.

Results

Buffer Gas Tubes--The operational method for the gas supply calls for a buffer gas, nitrogen, to be used in both the hydrogen and oxygen lines. The approximate size of the buffer gas tubes is 0.495 internal diameter and 72 feet long. Figures 9 shows the time histories of the oxygen buffer gas tube for a typical run. Note that the first wave time is approximately 125 msec corresponding to a length of 142 ft/(1148 ft/sec) = 0.125 sec for nitrogen.

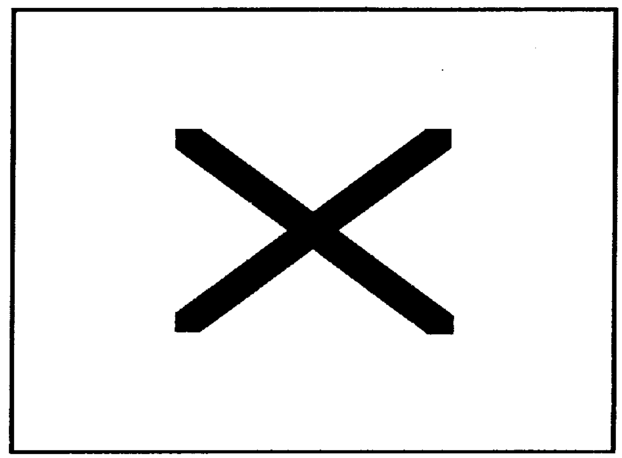

Figure 9 Oxygen Buffer, Charge, Upstream Venturi and Venturi Throat Pressures

Charge Tubes--The charge tubes contain the hydrogen and oxygen to be burned in the combustion chamber. The propulsive run time of the system is determined by the mass in the charge tubes. For a one-dimensional tube system the internal tube diameter and length determine the amount of mass. In order to minimize the number of hardware changes required to make a run time change, the hydrogen tube was made as long as required for the longest anticipated run time (65 msec). By selecting and inserting the oxygen charge tube length required for a given run time, the run time can be controlled. Flowing hydrogen mixed with nitrogen through the system will perform the cooling and not oxidize any of the metal components.

Quick Opening Valves-- One objective of this development effort was to utilize off the shelf quick-opening valves. Past short duration testing hardware used special made valves. The valves were very costly and required significant calendar time to implement in a model.

The valve selected for our application was a _ inch right angle fast opening solenoid valve produced by Circle Seal Controls of Corona, California,VR-4177T-ZDD. The right angle valve was selected for its relatively high valve coefficient, Cv = 2.7. Circle Seal engineering personnel indicated that Cv is near 2.5 rather than the 2.7 quoted in the company literature. The operating pressure level limit is 3600 psia and the duty cycle is 5%. The low duty cycle design gives the fastest opening time but it limits the time the valve can be in the power-on open condition. To limit heating of the valve, the maximum open time is one second. The internal seal soft goods have temperature limitations of 160° F. Two valves were purchased and cleaned by Circle seal to the MSFC oxygen cleaning specification 164B. They performed quite well.

Valve to Venturi Volume--The volume between the quick opening valve and the venturi should be minimized to minimize the start time of the system. Valve geometry and hardware assembly constraints, places constraints on minimizing this volume.

The selection of the fittings and pipe length for each charge tube was based on matching the fill time of each side.

Response time = $\tau = V/(A^*C\,K)$

V = volume

$C = (\gamma R\,T/M)^{0.5}$ Speed of sound

K = function of gamma

For the response time (fill time) of the volumes to be equal then

$$V_H / V_O = (A^*_H/A^*_O)\,(M_O/M_H)^{0.5}$$

Where A^* is the venturi throat area and M is the molecular weight of oxygen or hydrogen.

Venturi-- The hydrogen and oxygen venturis control the mass flow into the model. The weight flow rates of the oxygen to hydrogen, O/F, can be written as:

$$W_O/W_H = O/F = (A^*_O P_O)/(A^*_H\,P_H) x\,(Mw_O/Mw_H)^{1/2}$$

$$O/F = (A^*_O P_O)/(A^*_H\,P_H) x\,(32/2)^{1/2}$$
$$= 4(A^*_O P_O)/(A^*_H\,P_H)$$

$O/F = 5.783(P_O/P_H)$ where

P_O = oxygen upstream venturi total pressure

P_H = hydrogen upstream venturi total pressure

The O/F history, through the venturis, for two typical runs are shown in Figure 10. The input O/F is

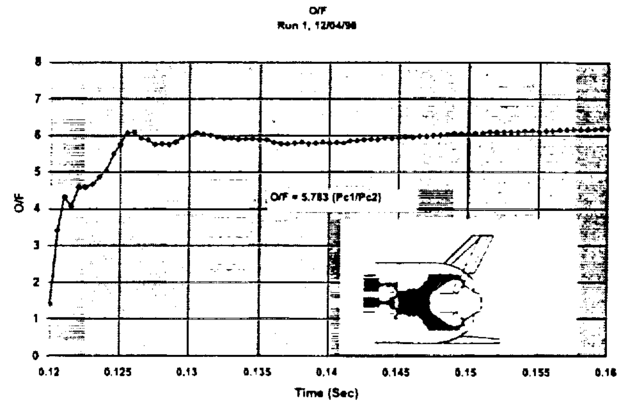

Figure 10 Typical O/F History

stabilized by the time the pressures are at steady state in the upstream tubes and is not affected by charge tube pressure. The steady state values are slightly above the design objective of 5.85.

Injector-- The injector elements are sized and directed to balance the radial momentum of the hydrogen and oxygen jets. The key to simplicity for the doublet is the hydrogen manifold, which feeds the outer most ring of elements. This outer ring manifold was made by sizing two offset circles providing a flow passage with approximately the correct area ratio to feed each element with the correct mass flow. For an O/F of 5.85 the O_2 and H_2 element tube Mach numbers are calculated to be 0.277 and 0.189 respectively to yield a modest but stable pressure drop across the injector. The element hole lengths and diameters are sized to produce a pressure drop of two dynamic heads.

Combustor-- The combustor design consists of the central combustor and the hot gas manifold. The primary function of the central combustor is to provide the proper volume and stay time for complete mixing and combustion to take place. Test data indicate that a total $L^* = V_c/A^*$ of 10 is sufficient for H_2 and O_2. Thus for multi engine configurations a large portion of the combustor volume is in the hot gas manifold which directs the gases to the engines. The current design has a modest central combustor with the largest volume in the two hot gas manifolds feeding each side of the linear aerospike plug. Compared to previous models the current model has a relatively large L^* = 82.8 and corresponding time constant. The total theoretical time constant for the injector manifold and combustor is 2.82 msec corresponding to 14.1 msec to reach steady state in 5 time constants. The actual time response of the venturi throat and combustion chamber is shown in Figure 11 for a typical case. Notice that the venturi

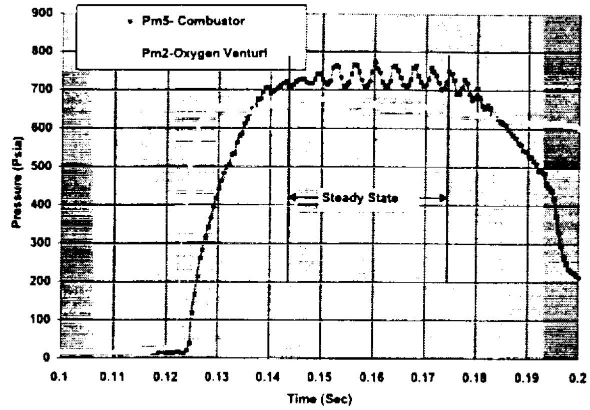

Figure 11 Venturi and Chamber Pressures

responds first approximately 2 msec before the chamber pressures shows a rise. The chamber pressure drops off rapidly as the nitrogen buffer gas starts purging the system at 0.175 seconds.

The internal hot gas manifold wall temperatures were measured using coaxial thermocouples to reduced to heating rates using a semi-infinite slab method (Ref. 6 and 7). The heating data are correlated with chamber pressure in Figure 12. The top manifold measurement is located at a different station than the bottom measurement resulting in different heating rates. The exponent on the pressure term is lower than the expected value of 0.8. The theoretical values are from Bartz equation (Ref. 8).

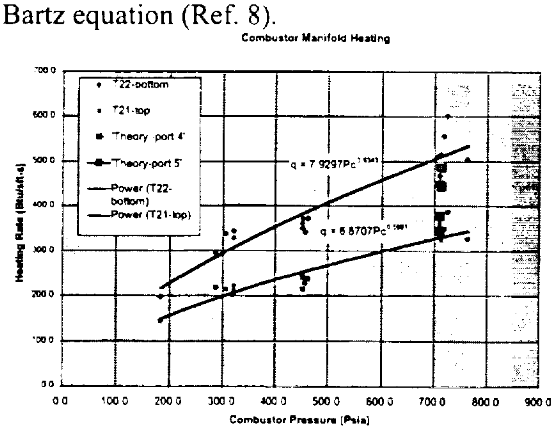

Figure 12 Manifold Sidewall Heating

Nozzle Throats-- Nozzle throats receive the highest heating in the model and consequently are the limiting component from a thermal design viewpoint. The conventional design used copper inserts for the nozzle throats to act as a heat sink during a short duration heating pulse. Run times were limited by the capability of the copper to absorb the heat without melting. The relative low wall temperature promoted the heat loss from the combustion gas. This in turn reduced the base gas recovery temperature since the base is fed from the nozzle boundary layer. The use here of the molybdenum based TZM allowed higher wall temperatures without deterioration, i.e., 2500 C versus 1083 C for copper, thus reducing the gas heat loss and improving the simulation. TZM throat oxidation was minimized by flowing inert nitrogen gases until the throat is cooled after a hot run. Throat measurements were made of each nozzle using a set of pins with accuracy of 1/10,000 inch to monitor erosion.

The nozzle upstream manifold was made from TZM. No apparent deterioration of this manifold has been observed. Over 110 runs have been made with the instrumented copper nozzles without any measurable change in the nozzles throat diameters. Four runs have been made with the TZM nozzles without any measurable change in the throat diameters

Operations—Approximately 120 hot fire runs were successfully completed with this model. Figure 13 shows the plume from a typical sea level firing. The model was fired in a check-out test at atmospheric conditions and then installed in the Nozzle Test Facility at Marshal Space Flight Center where test were conducted from sea level to as simulated altitude of 110,000 feet. Large amounts of base heating and pressure data were produced for application to X-33 flight and CFD validation.

Figure 13 Sea level Firing at Pc = 630 psia

Typical pressure data on the aerospike plug base are shown in Figure 14. The bulk of the measured base environment data will be presented in a subsequent paper.

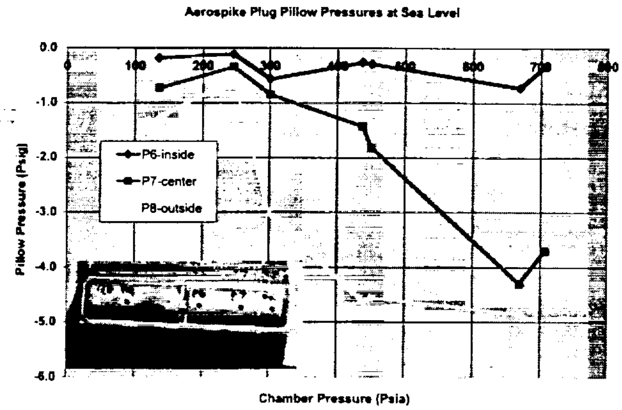

Figure 14 Aerospike Plug Base Pressure at Sea Level (no mass injection)

Conclusions

1) The current charge-gas system design which uses a nitrogen buffer gas system works well and is significantly safer than previous models.
2) The commercial fast opening valves used in this model are an order of magnitude cheaper than special made valves used in the 1970's, have performed with the same opening times over many operations, and are sufficiently rapid for short duration testing.
3) Flexible tubing with non-uniform internal diameters have been successfully used in the charge and buffer gas system. This has significantly decreased model–facility integration time.
4) The data acquisition system controlled the model equipment and acquired the data in a highly efficient manner; at a fraction of the cost and personnel time needed for short duration testing in the 1970's.
5) The LabVIEW software developed for this project handles device activation and data sampling for three types of pressure gages, thermocouples and thin film gages.
6) The short duration model performed as designed and produces consistent hydrogen-oxygen plumes for base flow studies. No measurable erosion was observed in the copper or TZM nozzle throats at peak design operating conditions.

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