Overview of Propellant Delivery Systems at the NASA John C. Stennis Space Center

L. Haynes Haselmaier[*], Robert E. Field[†] and Harry M. Ryan[‡]
NASA, Stennis Space Center, MS, 39529, USA

and

Jonathan C. Dickey[§]
Mississippi Space Services, Stennis Space Center, MS, 39529, USA

A wide range of rocket propulsion test work occurs at the NASA John C. Stennis Space Center (SSC) including full-scale engine test activities at test facilities A-1, A-2, B-1 and B-2 as well as combustion device research and development activities at the E-Complex (E-1, E-2, E-3 and E-4) test facilities. One of the greatest challenges associated with operating a test facility is maintaining the health of the primary propellant system and test-critical support systems. The challenge emerges due to the fact that the operating conditions of the various system components are extreme (e.g., low temperatures, high pressures) and due to the fact that many of the components and systems are unique. The purpose of this paper is to briefly describe the experience and modeling techniques that are used to operate the unique test facilities at NASA SSC that continue to support successful propulsion testing.

Nomenclature

ASTM	=	American Society of Testing and Materials
C_v	=	Flow Coefficient
CFD	=	Computational Fluid Dynamics
CLV	=	Crew Launch Vehicle
ET	=	External Tank
GH2	=	Gaseous Hydrogen
GN2	=	Gaseous Nitrogen
H_2O_2	=	Hydrogen Peroxide
HC	=	Hydrocarbon
GFE	=	Government Furnished Equipment
GHe	=	Gaseous Helium
GOX	=	Gaseous Oxygen
IPD	=	Integrated Powerhead Demonstrator
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
MTO	=	Mississippi Test Operations
NASA	=	National Aeronautics and Space Administration
NASP	=	National Aerospace Plan
NIST	=	National Institute of Standards and Technology
NLS	=	National Launch System
PI	=	Proportional Integral
PLC	=	Programmable Logic Controller
PWR	=	Pratt & Whitney Rocketdyne

[*] Component Specialist, NASA SSC/Mail Stop EA32, SSC, MS 39529.
[†] Aerospace Technologist, NASA SSC/Mail Stop EA33, SSC, MS 39529 and AIAA Member.
[‡] Aerospace Technologist, NASA SSC/Mail Stop EA33, SSC, MS 39529.
[§] Mechanical Engineer, NASA SSC, Bldg 3225, SSC, MS 39529.

RBCC	=	Rocket Based Combined Cycle
RPTA	=	Rocket Propulsion Test Analysis
SSC	=	Stennis Space Center
SSSF	=	Steady State Steady Flow
SSME	=	Space Shuttle Main Engine
USUF	=	Uniform State Uniform Flow

I. Introduction

THE NASA John C. Stennis Space Center (SSC) located in Hancock County, MS, was originally designated the Mississippi Test Operations (MTO) on December 18, 1961, and first tested the Saturn V rocket booster (S-II-T) on April 23, 1965. Over the intervening years there were several changes in designation, until May 20, 1988, where by Executive Order of President Ronald Reagan, it became the John C. Stennis Space Center. NASA SSC is surrounded by over 120,000 acres of land having a restrictive easement which provides an acoustic buffer zone around the facility. This buffer zone, which is subject to the intense sound pressure levels and noise resulting from full power and duration engine firings, is an irreplaceable national asset. The restrictive easement on this land prohibits construction or maintenance of structures for human habitation. Over the past four decades, SSC has been, and continues to be, NASA's primary center for testing and flight certifying large rocket propulsion systems.

A wide range of rocket propulsion test work occurs at SSC including full-scale engine test activities at test facilities A-1, A-2, B-1 and B-2 as well as combustion device research and development activities at the E-Complex (E-1, E-2, E-3 and E-4) test facilities. Rigorous test campaigns are pursued to ensure rocket engine and rocket engine component systems satisfy their design requirements and to allow for an understanding of the system/component operational envelope. The testing also allows for the development and validation of accurate simulation models. A further overview of the strategy and challenges of various large liquid rocket engine test campaigns is given by various authors.[1, 2] A brief summary of the capability of each test facility is given next followed by a detailed description of the sub-systems and components of the E-1 test stand with a particular emphasis on giving one an appreciation of several of the important factors that are considered when operating the facility.

II. Test Complex Characteristics and Capabilities

The SSC testing facilities are collectively referred to as the A, B, & E Complexes.[3] A brief description of the individual test stands in these test complexes and their capabilities are given below.

The A-complex consists of the A-1 (see Fig. 1) and A-2 test stands, both of which are being used to test the Space Shuttle Main Engine (SSME). Each stand is a single-position, vertical firing test stand that can accommodate full-scale, liquid propellant rocket engine and systems testing. They can be utilized to static fire a test article up to 33 ft in diameter with a maximum dynamic load of 1.1M lb_f vertical (up), 1.7M lb_f vertical (rebound), and 0.7M lb_f horizontal. The A-2 Test Stand is equipped with an altitude diffuser that is utilized to simulate altitude conditions during engine testing. Nominally, the diffuser can simulate altitudes from 54,000 to 70,000 ft. The A-1 test stand will likely be employed to support NASA Exploration System Mission Directorate Crew Launch Vehicle (CLV) testing including power pack and full engine system testing.

The B-Complex consists of the dual position, vertical firing B-1/B-2 test stand. This test stand accommodates full-scale, liquid propellant rocket engine and systems testing. It can be utilized to static fire test articles with a

Figure 1. A-1 Test Stand

maximum dynamic load of 11M lb_f vertical (up), 8.5M lb_f vertical (rebound), and 6M lb_f horizontal. The B-1 Test Stand is currently being leased to Pratt & Whitney Rocketdyne (PWR) to conduct RS-68 Engine Testing and the B-2 position is currently not being used.
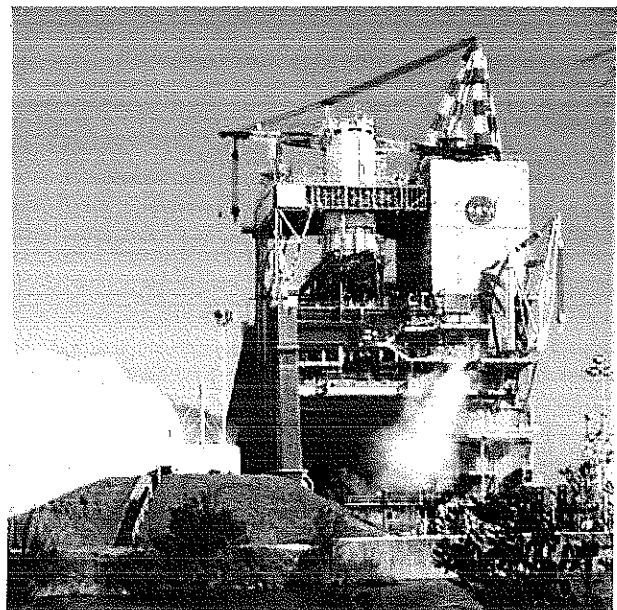
The E-Complex consists of the E-1, E-2, E-3 and E-4 test stands. The E-1 Test Facility shown in Fig. 2 was originally designed as a developmental rocket engine component test facility for the National Launch System (NLS) Program. The E-1 test facility is available for developmental testing projects requiring high-pressure and high flow rate cryogenic fluids (e.g., hydrogen (LH2), oxygen (LOX)) or hydrocarbon (HC), inert gases, and industrial water. E-1 was primarily designed for pressure-fed LOX/LH2, LOX/HC, and hybrid-based test articles. E-1 is a unique national asset due to its high-flow, high-pressure capability for cryogenic and gaseous propellants. The E-1 test stand consists of Cells 1, 2 and 3 (see Fig. 2).
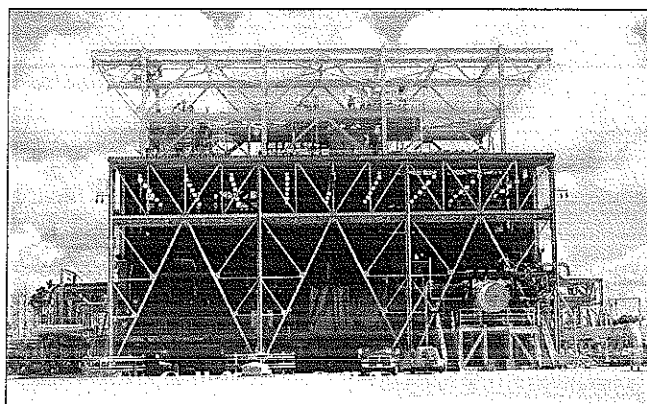

Figure 2. The E-1 Test Stand

E-1 Cell 1 is primarily designed to test pressure-fed LOX/LH2, LOX/HC, and LOX hybrid combustion devices up to 1.1M lb$_f$ of horizontal thrust and 500K lb$_f$ vertical thrust. It can also be used to test individual LH2 and LOX turbo-pump assemblies. Recent propulsion test projects include the 250K lb$_f$ hybrid and the TRW 650K lb$_f$ thrust chamber assembly. E-1 Cell 2 is primarily designed to test LH2 and LOX turbo-pump assemblies. Recent test projects include the Integrated Powerhead Demonstrator (IPD) Fuel Turbo-Pump (cold-flow) and the SSME Flow Liner. E-1 Cell 3 is primarily designed to test LOX turbo-pump assemblies and engine systems. The test article support structure for cell 3 is designed for test articles, generating up to 750K lb$_f$ thrust at angles up to 10 degrees above horizontal. Recent test projects include the IPD Oxidizer Turbo-Pump (cold-flow & hot-fire),[4, 5] the IPD Workhorse Preburner and the IPD Engine System.[6]

E-2 (see Fig. 3) is available for development testing projects involving hot gas, cryogenic fluids, gas impingement, inert gases, industrial gases, specialized gases, hydraulics, de-ionized and potable water.[7, 8] E-2 Cell 1, formerly known as the High Heat Flux Facility, was originally constructed to support materials development for the National Aerospace Plane (NASP) by subjecting special test articles to extreme temperature conditions. The facility has been modified to support advanced component and engine development projects. Multiple test positions
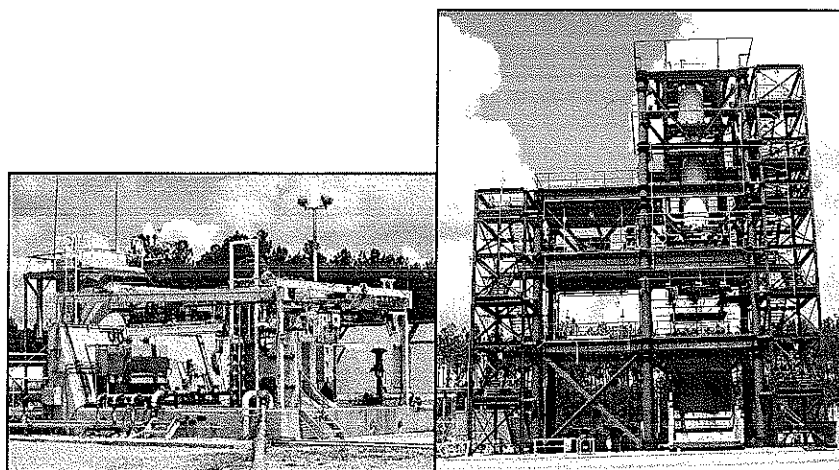

Figure 3. The E-2 Test Facility with Cell 1 shown on the left and Cell 2 shown on the right.

are available. E-2 Cell 1 is a versatile, ultra-high pressure test stand that can be utilized for testing a variety of next generation propulsion cryogenic system components. E-2 Cell 2 was developed for testing LOX/LH, LOX/HC, and Hydrogen Peroxide (H$_2$O$_2$)/HC full stage systems in the 100K lb$_f$ thrust or greater range. Recent test projects include the RS-84 Subscale Preburner. E-2 Cell 2 is capable of supporting tests of complete flight or "flight-like" stages. Cell 2 has the capability to provide low-pressure LOX and HC propellants to a test article, mounted vertically in the test cell. Cell 2 also has an environmentally-approved H$_2$O$_2$ dilution, safeing, and dump system to support H$_2$O$_2$ stage testing. Recent tests conducted at E-2 include the Space Shuttle External Tank (ET) ice frost tests and Space Shuttle ET diffuser characterization tests.

The E-3 Test Stand is a versatile test complex that is available for component development testing of combustion devices, rocket engine components and small/subscale component engines and boosters. E-3 Cell 1 was primarily designed to test pressure-fed H$_2$O$_2$/HC, LOX/HC, GOX/HC, GH2/GOX, and hybrid rocket motor combustion devices. It is a horizontal test cell that can support horizontal thrust loads up to 60K lb$_f$ (120K lb$_f$ impulse load). The

American Institute of Aeronautics and Astronautics

E-3 Test Facility is unique in its ability to test H_2O_2 articles and components in both a horizontal and vertical configuration.

E-3 Cell 2 was primarily designed to test H_2O_2/HC and rocket motor combustion devices up to 25K lb_f of vertical thrust (50K lb_f impulse load). Cell 2 has an additional capacity to test mono-propellant configuration subscale combustion devices such as catalyst beds and components. It is primarily for vertical testing with provisions for limited horizontal testing. Cell 2 has a flame bucket below the firing position.

Succinctly, the E-4 test facility was designed to support the testing of large scale Rocket Based Combined Cycle (RBCC) test articles up to 50K lb_f thrust.[9] Propellant capabilities were to include LH2, LOX, HC and H_2O_2. Since funding to study RBCC propulsion systems is limited, only the concrete work package, the preparation building and the test control center have been completed.

III. E-1 Test Facility Operation and Global Analysis

Each test stand described above has its own individual configuration of propellant delivery, thrust measurement, and instrumentation systems making their capabilities and "operational personalities" unique. In this paper we will focus on the E-1 test stand and discuss the uniqueness of its components, its capabilities, and how the operational character of a system is determined through experience, analysis and modeling. However, the experience and simulation philosophies can be applied to many test facilities.

The E-1 test stand is capable of delivering all of the necessary fluids to allow for the operation of a liquid bi-propellant rocket engine. The facility can provide purge gases (e.g., GHe, GN2) at a low and high pressures, spin start gases (e.g., GH2, GH2) and propellants (e.g., LOX, LH2). All of these fluids are delivered to an engine system (or component) at precise times and precise conditions (pressure and temperature). The experience of operating all of these systems simultaneously to support an engine system or component test project is irreplaceable with regards to understating facility components and capabilities. Over the past several years, the SSC engineering team has been developing and tailoring a global Rocket Propulsion Test Analysis (RPTA) model for the test facility fluid systems with the goal of providing comprehensive propellant system thermodynamic modeling and test simulation. This effort supplements and compliments the operational experience with these facility systems.

As propellant systems are designed for a particular test project, an RPTA model is developed. The RPTA model is then used to predict the behavior of the propellant system. The RPTA model substantially improves the understanding of the fluid systems component interactions and overall performance. This has translated into efficient test facility activation and operation for the various propulsion test programs.

The RPTA model is based on uniform-state, uniform-flow (USUF) and steady-state, steady-flow (SSSF) thermodynamic process constructs for pressurization and propellant control volumes, respectively. The model is developed and executed using the FORTRAN programming language on a personal computer (PC) and employs the NIST 12 database for the necessary thermodynamic property data. The model has been exercised over a broad range of thermodynamic systems including high-pressure cryogenic liquid and gaseous systems.

Programmable logic controllers (PLC) are used at the E-1 test facility to execute a preprogrammed test sequence which typically is comprised of various valve commands. Hence, a PLC subroutine was developed, validated and incorporated into the RPTA model. The subroutine is programmed to simulate the control logic, techniques, and hardware utilized at the E-1 test facility. More specifically, the PLC scan times, proportional-integral (PI) controller parameters, valve ramp rates and limits are incorporated into the PLC subroutine.

The RPTA model has been used extensively to predict individual E-1 test facility propellant systems behavior during activation and testing, especially during the IPD project.[6]

Consider the comparison between the RPTA model of a gaseous propellant system and facility activation data shown in Figure 4. Predictions were made for gaseous propellant system pressures at three different locations, including the bottle pressure, intermediate system pressure at a mixer and the test article interface pressure. Good agreement between the RPTA model and activation data was obtained.

One of the benefits of having a model is the ability to quickly assess the sensitivity of various system pressures and valve control parameters on the test article interface requirements.

Once the global system characteristics and limitations have been determined using an RPTA model, it is often necessary to further investigate individual system components. These investigations require the use of two- and three-dimensional modeling techniques.

IV. E-1 High Pressure LOX System Components Overview

The major components of the E-1 high pressure LOX system are five ultra-high pressure gaseous nitrogen (GN2) bottles, a 2600 gallon, vacuum-jacketed LOX tank, and the associated valves, piping, and instrumentation required

for delivery of high pressure LOX to any of the three test cells of the E1 test stand. The ultra-high pressure nitrogen bottles, which provide the pressurization of the LOX run tank, are capable of being pumped up to a maximum of 15,000 psia with ambient temperature nitrogen. The usual practice, however, is to only pressurize the bottles to 13,500 psia, both for system safety margin and bottle life conservation. The LOX run tank can effectively operate over a range from 200 psig to 8000 psig and various pressurization ramp rates up to 2000 psi/sec with minimal pressure overshoot and slump.[5]

The flow conditions occurring in this system encompasses the entire fluid dynamic spectrum of highly superheated vapor to a highly compressed liquid, supercritical mixtures, and supersonic flows. During the pressurization process, the LOX goes into the highly compressed liquid region, while highly superheated nitrogen exhibits compressible flow in the piping and valves, as

Figure 4. Comparison between RPTA model predictions of pressure (psi) and facility activation test data for a gaseous propellant system.

well as within the diffuser in the tank, culminating in free jet expansion into the tank ullage. Once the tank has been pressurized, it holds a supercritical mixture of cryogenic nitrogen and oxygen. The fluids in the high-pressure LOX system usually pass through all these state regimes during the first one second of test article firing. Successfully modeling such a system requires a simulation which can accurately determine the fluid thermodynamic properties for multiple species and phases.

A. LOX Run Tank Analysis

The LOX run tank is enclosed within a vacuum container where the space between the tank and container is filled with insulation (pearlite) to suppress radiation from the container walls to the LOX run tank. The LOX flow rate leaving the tank during operation is measured using a flow measurement device in each cell. The flow measurement devices are selected to match the range of flow requirements for the specific test article. The flow measurement instrument of choice is usually a cavitating venturi since it has no moving parts. Components with moving parts can break, creating debris that will be carried downstream and impact other components. Any debris being carried in a LOX stream represents the possibility of test article damage and a potential ignition source for an oxygen fire.

The performance of the LOX tank is measured in terms of the quantity and quality of the LOX supplied to the test article. The quantity of usable propellant sets the maximum test duration which can be obtained. The quality of the propellant is assessed in terms of the propellant density, i.e. delivered temperature, as well as any contamination from the interaction of the nitrogen pressurization gas dissolving/mixing with the LOX before it leaves the tank, especially at supercritical conditions.

The primary thrust in the analysis of the high pressure LOX tank has been the assessment of the mixing/dilution of the pressurization gas (GN2) with the LOX. This is a particularly difficult computational fluid dynamics (CFD) problem since, as stated before, it covers the entire range of thermodynamic states from superheated gas and compressed liquid to supercritical mixtures.
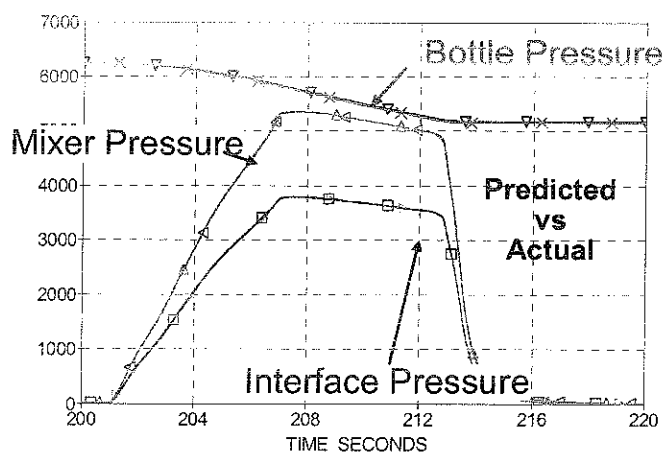
During the system operation, superheated nitrogen enters the tank through a diffuser having a large number of small holes directing the gas against the spherical tank wall. The gas travels down the tank wall and impinges on the LOX surface resulting in very high heat transfer rates, mixing, and entrainment of LOX from the surface. Since nitrogen and oxygen are infinitely miscible there is no natural limit to the contamination/mixing process. Obtaining an accurate CFD analysis of the problem has been very difficult as most CFD programs do not have sufficiently accurate fluid state equations for the determination of the required thermodynamic properties; especially near the critical points of nitrogen and oxygen. At SSC, in conjunction with our partners, we have been continually striving to upgrade our CFD tools and program capabilities to adequately handle this as well as other similar computational problems.

The results using state-of-the-art CFD techniques for the LOX run tank thus far indicates there is significant mixing of the nitrogen with the LOX in the tank. A snap shot of the CFD simulation of the LOX run tank is shown in Fig. 5. The velocity magnitude and oxygen mass fraction are shown for a LOX mass flow rate of 2195 lb_m/s at a LOX run tank pressure of 7600 psi for elapsed times of one and five seconds. After about five seconds, the CFD analysis shows that the quality of LOX at the tank bottom is decreasing quickly due to mixing with the GN2. Hence the LOX propellant supply at the aforementioned mass flow rate and pressure would be limited to only about five seconds versus ten seconds as determined using nominal facility pressurization and propellant supply limits.

As the tank empties, more and more nitrogen from the pressurization system is pushed into the tank, increasing the temperature in the tank, and continually producing more agitation of the contents. Depending on the test article demand and the required supply pressure, the mass of nitrogen and the mass of oxygen in the tank become equal sometime during the test duration, and the violence of the mixing will be greatly influenced by both the required tank pressure and the outflow rate of the LOX. For high outflow rates and high run tank pressures, a very significant amount of mixing will take place in the first one to three seconds of a test. Predicting the point where the nitrogen dilution of the LOX becomes a significant factor is a challenging task and is an area of continued emphasis.
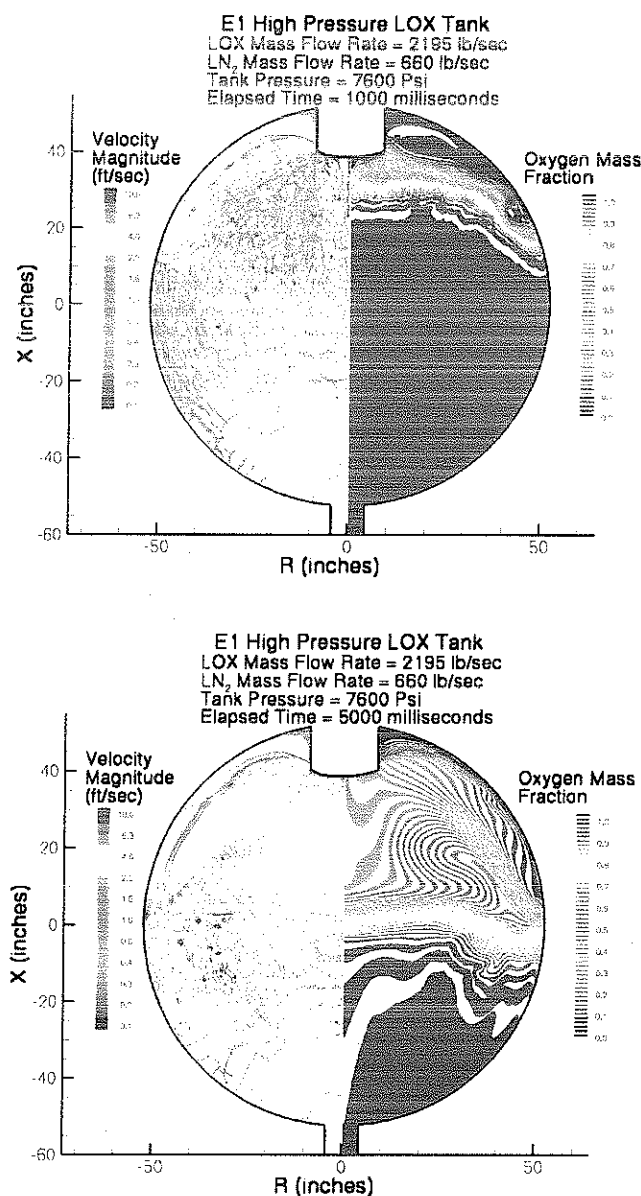

Figure 5. The oxygen mass fraction and velocity magnitude predicted using CFD techniques for a high-pressure run tank test case. The calculations correspond to a flow rate of 2195 lb_m/s and a run tank pressure of 7600 psi. The top view corresponds to an elapsed time of one second and the bottom view corresponds to an elapsed time of five seconds.

B. Cryogenic Oxygen Valve Design and Analysis

The cryogenic oxygen service valves used on the E-1 test stand and the other stands at SSC are a critical part of the system. They are one-of-a-kind valves and their designs have evolved over the course of many years from the demands rocket engine testing.

Performance characteristics of the cryogenic LOX valves are judged by their through flow rate versus pressure drop, resistance to leakage, mechanical durability, maintainability, operational stability (in terms of inducing or responding to flow fluctuations, and their response time to control system position commands).

Evolution in the normal course of a valve design usually results in added features or capabilities not considered in the original design. The most frequent result of an evolutionary path is previous configurations do conform to the most recent requirements; the design becomes more complicated and eventually impractical. It is prudent to reassess complex valve designs from time to time and attempt to incorporate newer features and capabilities into the base design, or develop a new design entirely. A new design should have a minimum of parts and failure modes. Our experience has shown that a focused redesign can reduce the number of wear parts (those parts which represent the greatest likelihood of component failure) by as much as one-half the number in an evolved configuration offered by a valve manufacturer.

Simply put, parts not installed cannot fail. Most valve designs are not optimized to a configuration comprised of the least possible parts. Part-intensive configurations are not usually the result of design oversight but simply a manufacturing convenience. Manufacturers are prone to add parts as a trade to avoid machining steps inside a valve cavity. Whereas this practice is an effective means to streamline the production of complex metal parts, it can account for as many as one third of the overall piece parts in the configuration. An additional consideration is that certain seal types tend to fail suddenly whereas others tend to degrade in performance more gradually over the service life of a given component. Typical o-rings, even in an excellent design, tend to perform well up to a point after which they rapidly leak (fail). Pressure-energized Teflon or other plastic seals usually do not afford greater seal efficiency; however, they rarely fail suddenly and can continue to perform with no more than very modest leak rates. As an example, in 2002, a particular ball valve design installed in the ultra-high pressure nitrogen pressurization system (up to 15 kpsi) was prone to generating debris that threatened the cleanliness of the downstream LOX run tank and associated piping. The ball valve was re-designed improving the seat design, seal design and ball support and resulted in 70 parts per valve being removed thus eliminating the debris issue.

NASA has unique requirements for materials used in contact with certain fluids such as oxygen. Most often this means that all nonmetallic parts must be traceable to lots or batches of material that have been impact tested in oxygen or approved by other screening methods. The effort to acquire sample materials and secure the testing support from an ASTM-certified laboratory or NASA-owned test facilities can easily represent the single largest cost consideration in pricing a component. It will certainly add months to the delivery of the final component. Effective steps have been taken at SSC as well as other field centers to pre-qualify large inventories of nonmetallic seal materials such as Teflon, Kel-F, Vespel, Viton, etc. so that they can be made available to the manufacturer as government furnished equipment (GFE). This practice has had a tremendous and favorable impact on both component cost as well as delivery schedule.

Despite the most successful design development, eventually mechanical devices will require repair. Valve designs should consider their capability to be repaired, with the least possible difficulty, or requirement for technical expertise. This may not affect the way a given component will operate but will certainly affect the configuration in regard to how it is assembled. Major parts of a given valve assembly are traditionally held together using threaded shoulders, bolt circles, clamps, etc. Almost all of these arrangements involve a large and diverse assortment of special tools. Valve designs should be optimized to incorporate assembly features that, as much as possible, eliminate the need for special tools. By eliminating the need for special tools, the valve can be easily repaired conserving the project test schedule.

Valve performance, in terms of the flow through the valve versus the valve plug position is described by the valve's flow coefficient (C_v) versus valve plug position (% open) curve. It is often necessary to calibrate the valves of the propellant delivery system in-situ prior to testing. The data to construct the C_v curve can be gathered during the test stand activation tests being performed to confirm the stand's readiness for testing. However, the experimentally determined C_v curve is not always consistent with the expected valve performance assumed in the global analysis and design of the test article adaptive hardware, or in the case of a new valve, its design goals.

Computational fluid dynamics analysis has proved to be very helpful in both the design of new valves and the understanding of existing valve performance data. Shown in Figure 6 are the results of the calculations using CFD techniques for a LOX control valve. The figure presents the calculated velocity, streamlines, and pressure field predicted as a function of valve stroke length along with the computed and experimentally determined flow

American Institute of Aeronautics and Astronautics

coefficient for the valve. As can be seen in Figure 6, careful CFD analysis can produce good estimates of a valve's flow versus opening position characteristic.

Cryogenic valves are also the subject of detailed heat transfer analysis. Since the fluid flowing through them can range any where from 163°R to 36°R, depending on whether it is in LOX or LH2 service, there are many issues with expansion, contraction and sealing in the valves which are highly temperature dependant. One particularly temperature sensitive component is the valve stem packing seal.

Currently the length of the stem and bonnet in large cryogenic valves is primarily determined by the constraint of maintaining the valve stem packing seal above the freezing point of water in order to obtain good seal compliance.

The results of previous heat transfer analysis conducted by the valve manufactures have indicated the stem length for these valves need to be multiple feet. Little experimental data is available to verify these analytical results.

Operational observation, however, as shown in the photograph of Figure 7, of a large cryogenic valve installed in the test stand seems to indicate the previous design analyses have been quite conservative. Observations of many other large cryogenic valves at SSC have also suggested the possibility exists for a significant reduction in the stem length of future valves.

A review of the design analyses reports for several valve heat transfer studies indicates heat transfer from the surroundings due to radiation had not been taken into account. Internally, the cryogenic fluid being controlled by such a valve is a very powerful coolant, and to keep the packing seal on the stem above freezing, all energy necessary to accomplish this must be supplied from the ambient.

The heat transfer to the bonnet external surface is provided by both radiation and natural convection.

Figure 6. Velocity, streamlines and pressure inside a valve body predicted using CFD techniques as a function of valve stoke length (top graph). The associated C_v curve is shown in the bottom graph

Preliminary estimates of natural convection heat transfer coefficients on the external surface of the valve bonnet indicate, as expected, the natural convection mechanism is a very week mode of energy transfer. Especially since the lowest acceptable temperature for the stem seal is only approximately 48°F below an 80°F ambient. The metal thickness of the bonnet between the seal and the external surface also aggravates the problem as it is often several inches of 304 stainless steel making the actual temperature difference of the driving potential for convection much less than 48°F.

A model was developed to predict the stem temperature as a function of heat transfer mechanism (i.e., free convection and radiation) in order to begin to quantify the effects of radiation. The preliminary results are shown in Fig. 8. The predicted stem temperature is greater if radiation heat transfer is considered. Hence, from a valve stem packing seal temperature perspective, the length of the valve stem may be shortened. Radiation heat transfer continues to be an active area of interest with regards to cryogenic valve and piping operations.
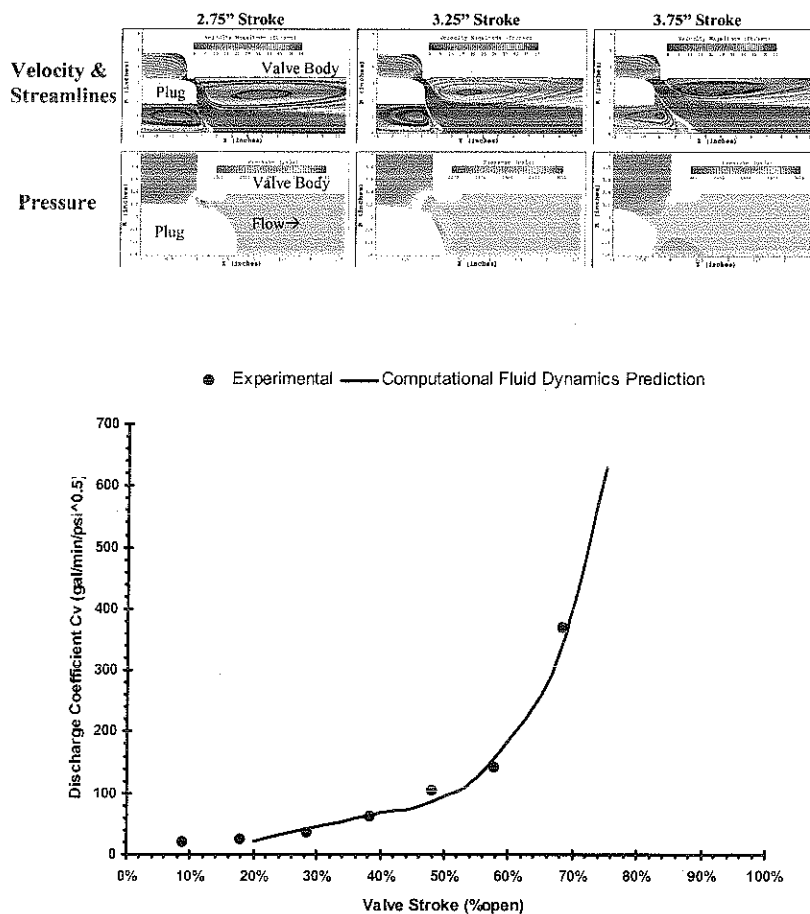
V. Conclusion

Operating a test facility to meet rocket propulsion test requirements is a challenging task due to the uniqueness of many o the facility components and the often extreme operating conditions of high-pressure and cryogenic temperatures. A variety of tools and experiences are used to successfully operate each test facility at SSC. For example, experience with operating cryogenic valves has led to better design practices. These experiences are complimented by modeling and analysis techniques. A global one-dimensional thermodynamic and fluid model is employed to provide predictions of propellant systems pressures and temperatures. More detailed modeling techniques including CFD are used to investigate the behavior of individual components.

Acknowledgments

The authors would like to recognize the entire NASA and contractor team at SSC, all of whom make safe and cost-effective propulsion testing a reality.

References

[1]Rahman, S.A. and Hebert, B.J., "Large Liquid Rocket Testing – Strategies and Challenges," AIAA Paper 2005-3564, *41st Joint Propulsion Conference*, Tucson, AZ, July 10-13, 2005.

[2]Rahman, S., Hebert, B., Glorioso, M. and Gilbrech, R., "Rocket Propulsion Testing at Stennis Space Center: Current Capability and Future Challenges," AIAA Paper 2003-0538, 3*9th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Huntsville, AL, July 20-23, 2003.

[3]NASA Facts: "John C. Stennis Space Center, America's Largest Rocket Propulsion Testing Complex," NASA Facts, NASA SSC Public Affairs Office, May 2002.

[4]Sass, J. P., Raines, N. G., Farner, B. R. and Ryan, H. M., "Facility Activation and Characterization For IPD Oxidizer Turbopump Cold-Flow Testing at NASA Stennis Space Center," *52nd JANNAF Propulsion Meeting/1st Liquid Propulsion Subcommittee*, Las Vegas, NV, May 10-13, 2004.

[5]Sass, J. P., Raines, N. G. and Ryan, H. M., "Facility Activation and Characterization For IPD Workhorse Preburner and Oxidizer Turbopump Hot-Fire Testing at NASA Stennis Space Center," *52nd JANNAF Propulsion Meeting/1st Liquid Propulsion Subcommittee*, Las Vegas, NV, May 10-13, 2004.

[6]Carmouche, G, Sass, J., Ryan, H., Coote, D. and Sabbagh, M., "Integrated Facility Simulation and Analysis in Support of IPD Engine System Testing at NASA Stennis Space Center," *53rd JANNAF Propulsion Meeting*, Monterey, CA, December 5-8, 2005.
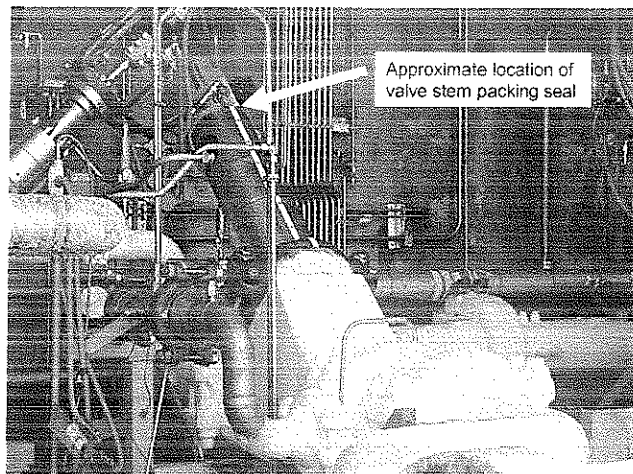
Figure 7. An image showing a large cryogenic valve during system chill down (LOX) at the E-1 Test Facility. The location of the valve stem packing seal and the frost line are shown. It is desirable that the valve stem seal packing temperature remain above freezing.
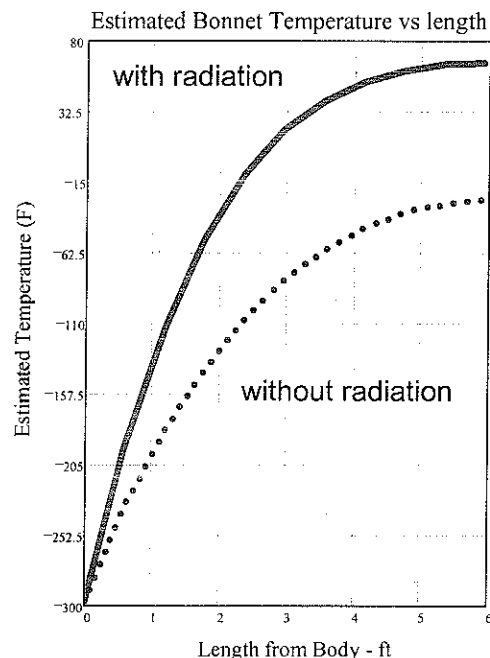

Figure 8. Predictions of valve stem temperature as a function of heat transfer mechanism. The inclusion of radiation heat transfer appreciably increases the valve stem temperature.

[7]Jacks, T.E., Klein, K.D., Camus, W.J., Lott, J.W. and Mulkey, C.A., "Propulsion Testing Capabilities at NASA's John C. Stennis Space E-2 Cell 1 Test Facility," AIAA Paper 2005-4419, *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Tucson, AZ, July 10-13, 2005.

[8]Jacks, T., and Beisler, M., "Expanding Hydrogen Peroxide Propulsion Test Capability at Stennis Space Center E-Complex," AIAA Paper 2003-5041, *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 20-23, 2003.*

[9]Ryan, H., Canady, R., Sewell, D., Rahman, S. and Gilbrech, R., "E-4 Test Facility Design Status," *PERC 13th Annual Propulsion Symposium*, Huntsville, AL, October 22-23, 2001.

American Institute of Aeronautics and Astronautics