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Development of a liquid oxygen facility for rocket engine injector performance testing

Henry W. Mulkey

DEVELOPMENT OF A LIQUID OXYGEN FACILITY FOR ROCKET ENGINE INJECTOR PERFORMANCE TESTING

by

HENRY W. MULKEY

A THESIS

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ABSTRACT
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Abstract

This study demonstrated the successful operation of a new liquid oxygen – gaseous methane rocket engine test facility to characterize the performance of a swirl coaxial injector. In support of safe system functional development, an oxygen compatibility and hazards assessment was completed to identify and minimize operational risks. Facility changes were implemented to create a more fault tolerant system. Major upgrades included initiatives to manage the oxygen risk and mitigate specific oxygen ignition mechanisms. Oxygen compatible materials and facility configuration changes were instituted to achieve safer experimentation. The demonstration testing of the cryogenic propellant system employed the swirl coaxial injector element in an ongoing program to study liquid oxygen – methane injectors. The injector performance was evaluated by experimental determination of combustion efficiency. The combustion efficiency determined for the injector arrangement during the single operational test was 80% with a 95% confidence systematic standard uncertainty estimate of 4%. Random uncertainty estimation must await repeated tests.

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LIST OF SYMBOLS

A	Area
b	Systematic standard uncertainty
C^*	Characteristic velocity
C_D	LOX orifice discharge
C_G	Fuel orifice discharge
D	Diameter
ΔP	Injector pressure drop
G	Gas
γ	Specific heat ratio
L	Liquid
$\dot{m}$	Mass flow rate
η_{c*}	Characteristic velocity efficiency, combustion efficiency
OF	Oxygen to fuel ratio
P	Pressure
Pv	Vapor pressure
R	Gas constant
ρ	Density
s	Random standard uncertainty
S	Standard deviation
T	Temperature
u	Standard uncertainty
U	Uncertainty
V	Velocity

Subscripts

CH_4	Methane
F	Fuel
INJ	Injector
install	Install
LCH_4	Liquid methane

LOX	Liquid oxygen
Std	Standard
T	Throat
th	Theoretical
Tot	Total

NOMENCLATURE

AME	Ascent Main Engine
ASTM	American Society of Testing Materials
BD	Burst Disc
CGA	Commercial Gas Association
CP	Critical Point
DRE	Data Reduction Equation
GOX	Gaseous Oxygen
LOX	Liquid Oxygen
LRE	Liquid Rocket Engine
MBV	Manual Ball Valve
MISER	Modular Injector for Scientific and Educational Research
MTNV	Multi Turn Needle Valve
NBP	Normal Boiling Point
NIST	National Institute of Standards and Technology
NRCV	Non Return Check Valve
NTP	Normal Temperature and Pressure
NVR	Non Volatile Residue
OCA	Oxygen Compatibility Assessment
OFHC	Oxygen Free High Conductivity
PBV	Pneumatic Ball Valve
PGV	Pneumatic Globe Valve
PRC	Propulsion Research Center
PT	Pressure Transducer
RP – 1	Rocket Propellant - 1
SSME	Space Shuttle Main Engine
STP	Standard Temperature and Pressure
TC	Thermocouple
TP	Triple Point
UMF	Uncertainty Magnification Factors
UPC	Uncertainty Percentage Contributions

CHAPTER 1

THE PROBLEM

The Propulsion Research Center (PRC) at the University of Alabama Huntsville has developed a liquid oxygen (LOX) propellant feed system which has advanced into operational maturity. The current focus for this facility is rocket engine high pressure combustion injector performance testing employing LOX and gaseous methane (GCH_4) as the propellants.

1.1 Background

Research specifically centered on the behavioral characteristics of LOX – methane combustion continues at the PRC.[1] A comprehensive program was undertaken to design, build, and test a LOX – liquid methane (LCH_4) injector element in various experiments. The integrated approach to this comprehensive methodology has been structured to incorporate a series of experimental techniques and numerical simulations. The tasks comprising this program were to be executed in three separate experimental setups: a cold-flow spray evaluation, [2-4] a low-pressure combustion stability study, [5-8] and high-pressure combustion performance experiments.[9] The next step in the high pressure combustion experimentation was injector performance testing employing LOX as the oxidizing propellant. This requirement recognized the need for the LOX propellant feed

operational development. Thus, the facility was developed to support the high pressure combustion task of the LOX – methane combustion behavior research program.

Injector experimentation can only be realized by a safe and functional propellant feed system and successful engine operation. Rocket engine testing can be unpredictable and necessitates proper realization of the potential hazards. PRC students manage specific tasks, conduct research, and operate facilities containing inherent hazards. The transient nature encompassing students involved in university research results in high turn over of the PRC personnel that operate test system facilities. The objective from a facility design standpoint is to minimize failure associated with operator error. The ability to mitigate this error by minimizing potential hazards is especially important in oxygen systems. This requires upfront training into the operational risks, and additional uniformity into standard operating procedures to maintain personnel safety and long term system functionality. Each of these characteristics was considered in the LOX facility operational development representing a progressive step to the PRC achieving the safe system functional ability to operate high pressure rocket engines employing LOX propellant.

Although the PRC's developmental LOX and historical gaseous oxygen (GOX) propellant systems were designed and developed according to the American Society of Testing Material's (ASTM) standard[10-11] best practices for the safe use of oxygen, there exists in any situation a potential disconnect from the design to the final result. This can be a product of the aforementioned turn over rate of personnel constructing and operating the test facilities, insufficient documentation reflecting design decisions, lack of training, and misinterpretations of the design during the fabrication of the test facility. The most

significant complexity relative to making any new system operational is the unknown. Standard operating procedures and oxygen system experienced personnel provided confidence in the safe operation of the oxygen system test facilities. The GOX facilities have operated successfully without incident for many years and the design decisions and procedures relevant to these safe operations were formulated to protect the system, operation, and operators.

It was believed that there was a low probability that the existing LOX system could have had an incident resulting in damage or personnel injury; however, there exist tools and experimental test data to make the probability even lower. In a university setting this must be checked and rechecked to implement suitable redundancy and engineer fixes to minimize risks. This work documents the corrective actions specific to the LOX propellant developmental facility and the operation of this facility to provide predictable operational outcomes.

1.2 The LOX System

The LOX propellant facility is a new capability for the PRC's test stand, and thus it was necessary to investigate the practical requirements to achieve the desired LOX delivery to the research engine, the associated hazards, and methods to mitigate these hazards through design, development, and operation. In general, oxygen systems should be reviewed by knowledgeable personnel with training in various fire hazards and design principles inherent to the safe use of these systems. As such, an internal review was conducted and applied to the operational and developmental oxygen systems requisite to perform injector performance experimentation. As part of this process, a formal oxygen compatibility assessment (OCA) and hazards analysis was developed and implemented

into the existing LOX facility in accordance to the standards[10-11] for safe use of oxygen systems.

This thesis outlines the review procedures applied to the PRC oxygen propellant systems, summarizes the significant findings, and details the configuration changes made to the system. The review process identified several areas where the oxygen risk could be reduced or removed through design changes. Modifications were implemented to create a more fault tolerant system and minimize risks to test equipment, system hardware, and conductors. Discussed in detail are the system changes made to increase safety and decrease the risk of fire.

The LOX propellant feed system was designed, developed, and fabricated to make possible injector performance testing for high pressure combustion experimentation. In addition to the above safety issues discussed, this work documents initial experiments demonstrating successful LOX facility operation as well as LOX – GCH_4 research engine operation. These experiments utilized a baseline injector at a single operational engine specification to evaluate injector performance measures and the associated uncertainties. This documents a first step in a comprehensive PRC program to facilitate injector performance testing in high pressure combustion applications employing LOX as the oxidizer media.

To evaluate LOX – methane combustion behavior, the experimental program focused on a baseline injector element. The injector selected for these experiments was designed based on a LOX – LCH_4 lunar ascent main engine (AME)[12] concept for technology development that presented a regime of full scale engine specifications. The full scale AME nominal thrust (F), engine burn, and specific impulse (I_s) initiated the

injector design procedure. Engine operational conditions such as oxygen-to-fuel (*OF*) mass ratio, number of injector elements, injection pressure drop (ΔP), propellant inlet temperatures, combustion chamber and injector feed pressures, were utilized in the design process. The procedure was developed and executed in accordance with classical injector design methodology.[13] The Modular Injector for Scientific and Educational Research (MISER) was designed at the PRC. This single element injector was structured to these full scale AME specifications. Although this injector possesses the capability to provide multiple injection schemes through hardware change out, the MISER injector configured in the swirl coaxial injection arrangement was selected as the baseline.

1.3 Research Questions

The research questions stated below set the parameters of constraint[14] on the experimentation serving to organize and control the study.

I. Can the LOX propellant feed facility deliver successful operation providing predictable outcomes supporting engine operation?

II. Can the LOX – GCH_4 test facility facilitate safe and successful engine operation in a high pressure combustion environment?

III. What would a method of analysis look like to investigate the baseline injector performance at a single operational engine specification?

1.4 Summary

The remaining chapters outline the process and research objectives. Chapter 2 discusses literature relating to oxygen properties and propellant, inherent risks and ways to manage oxygen hazards and injector performance characterization techniques. Chapter 3 discusses the OCA documentation process. Chapter 4 identifies the injector performance characterization methodology. Chapter 5 presents results and Chapter 6 conclusions.

CHAPTER 2

REVIEW OF THE LITERATURE

The following sections provides an overview of the properties of oxygen, its importance to rocket engines, risks, and the basic guidelines that must be followed for the safe use of an oxygen system. Combustion efficiency as a measure of injector performance is also briefly covered.

2.1 Oxygen Properties

Oxygen contains the ability to sustain life and support combustion.[10] Although the latter is more fundamental to this work, the former is noteworthy. Twenty one percent (by volume) of Earth's atmosphere is oxygen. The remaining percentages consist of 78% nitrogen, less than 1% argon and small percentages of additional trace species. Higher oxygen concentration increases flammability; materials that normally do not burn in lower oxygen concentration can combust and propagate explosively in pure oxygen and enriched atmospheres.[10] The nitrogen, an inert gas, contained in atmospheric air dilutes and lessens the reactivity of oxygen.[15] The natural occurrence of the un-reactive nitrogen gas mitigates the inherent oxygen fire risk.

Oxygen is in a gaseous state at standard conditions of pressure and temperature. Thermophysical properties of oxygen at standard temperature and pressure (STP) and normal temperature and pressure (NTP) are given in Table 2.1. GOX is odorless,

tasteless, colorless, and transparent.[10] It is heavier than air with a specific gravity equal to 1.105. The denser oxygen gas contains the potential to enrich or increase the concentration in low lying areas. Notice in Table 2.1 the equivalent gas volume to volume of liquid at the normal boiling point (NBP). A small volume of liquid oxygen results in a substantial volume of oxygen gas.

Table 2.1 Properties of oxygen at standard (STP) and normal (NTP) conditions[10]

Properties	**Units**	**STP**	**NTP**
Temperature	*K (R)*	273.2 (491.7)	293.2 (527.7)
Pressure (absolute)	*kPa (psi)*	101.325 (14.696)	101.325 (14.696)
Density	Kg/m^3 (lb_m/ft^3)	1.429 (0.0892)	1.429 (0.0831)
Compressibility factor (PV/RT)	-	0.9990	0.9992
Specific heat			
At constant Pressure (C_p)	$J/g\cdot K$ $(Btu/lb_m\cdot R)$	0.9166 (0.2191)	0.9188 (0.2196)
At constant volume (C_v)		0.6550 (0.1566)	0.6575 (0.1572)
Specific heat ratio (C_p/ C_v)	-	1.40	1.40
Enthalpy	J/g (Btu/lb_m)	248.06 (106.72)	266.41 (114.62)
Internal Energy	J/g (Btu/lb_m)	177.16 (76.216)	190.30 (81.871)
Entropy	$J/g\cdot K$ $(Btu/lb_m\cdot R)$	6.325 (1.512)	6.391 (1.527)
Velocity of sound	*m/s (ft/s)*	315 (1034)	326 (1070)
Viscosity	*mPa·s (lb/ft·s)*	19.24 (0.01924)	20.36 (0.02036)
Thermal conductivity	*mW/m·K (Btu/ft·h·R)*	24.28 ($1.293\cdot10^{-5}$)	25.75 ($1.368\cdot10^{-5}$)
Equivalent volume/ volume liquid at NBP	-	798.4	857.1

Figure 2.1 shows the pressure – temperature phase diagram for oxygen. Typical to all fluids except helium,[16] this diagram presents defined boundaries of solid, liquid, and vapor regions. The oxygen triple point (TP) is highlighted in the bottom left of the figure where all three phase lines intersect. Solid, liquid, and vapor exist at this point under certain conditions. The critical point (CP) of oxygen is shown at the upper right. Reference 17 defines the CP as "the point at which the saturated liquid and saturated vapor states are identical." The critical pressure and temperature correspond to the point at which the liquid/gas equilibrium line terminates. To illustrate this principle consider a gas at pressure above the substance's critical point. There is no formation of two separate phase regions when this gas is cooled at constant pressure. Instead, the gas phase

properties, such as low density and large compressibility, steadily change to increased density and small compressibility representative of the liquid phase without a discernable phase transition. The physical properties of a substance between the liquid and vapor states decrease as the critical point is approached. The difference between these properties goes to zero at the critical point where the distinction between the liquid and gas phases vanish.[18]

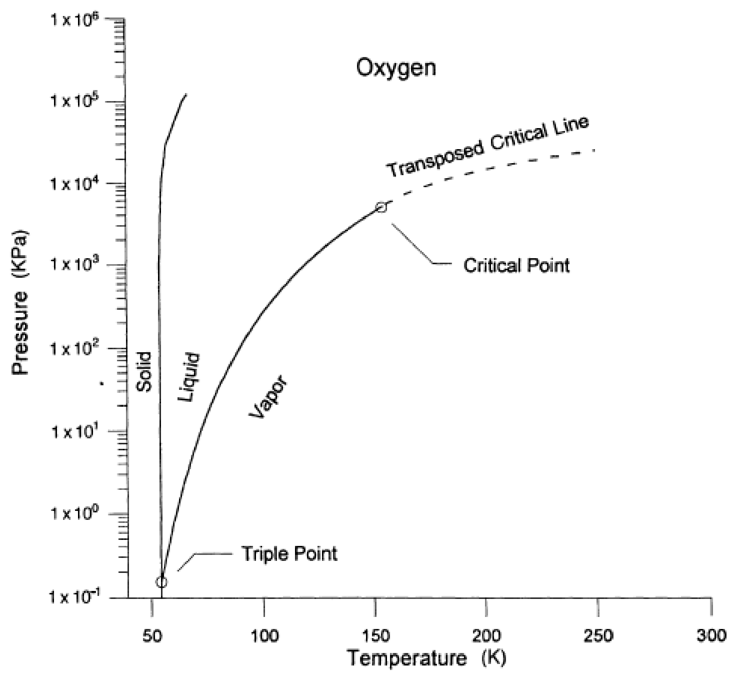


Figure 2.1 The pressure – temperature phase diagram for oxygen[15]

Reference 16 defines cryogenic fluids as "those fluids whose normal boiling temperatures at atmospheric pressure is below 273 K (491.7 R)." There are several cryogenic fluids that are characterized by this definition such as helium, neon, nitrogen, oxygen, argon, krypton, xenon, methane, ethane, and propane; however, due to the relevance to this thesis, only the common cryogens LOX and liquid nitrogen (LN_2) are addressed.

LOX is transparent and exhibits a light blue[19] physical color and is slightly denser than water with a specific gravity equal to 1.14. It is non toxic, chemically stable, and not shock sensitive.[10] LOX is slightly magnetic or paramagnetic, and this property indicates a significant difference from other cryogenic fluids. The ability to measure variations in magnetic susceptibility can be utilized to determine purity or concentration. This provides a means to monitor the oxygen levels in controlled environments.

LN_2 is transparent fluid similar to water. It is odorless, colorless, nonflammable, nontoxic, and nonexplosive.[19] LN_2 is utilized in many cryogenic engineering systems providing initial checkouts through system flushes[19] of an inert substance. Loading a newly assembled LOX system with clean LN_2 is recommended to cryogenically cold shock[10] the system. This introduces the system to the cryogenic temperatures. LN_2 has other applications such as pressurizing gas from the liquid boil off vapor or cooling to condition other substances or materials.

Table 2.2 presents the CP, TP, and NBP properties for LOX and LN_2. Figure 2.2 illustrates the vapor pressure curves of LOX and LN_2. The vapor pressure exhibits importance in cryogenic propellant cavitating[20] flow control, conditioning and phase discrimination from pressure and temperature measurements.

Table 2.2 LOX and LN_2 CP, TP, and NBP properties[16]

	Temperatures K (R)			Pressure kPa (psi)		kg/m^3 (lbm/ft^3)
	Triple Point	Normal boiling point	Critical point	Triple point	Critical point	Critical point
Oxygen	54.36 (97.9)	90.18 (162.32)	154.58 (278.24)	0.1517 (0.0220)	5042.7 (731.4)	436.1 (27.29)
Nitrogen	63.15 (113.7)	77.36 (139.25)	126.26 (227.27)	12.46 (1.807)	3399 (492.9)	313.1 (19.55)

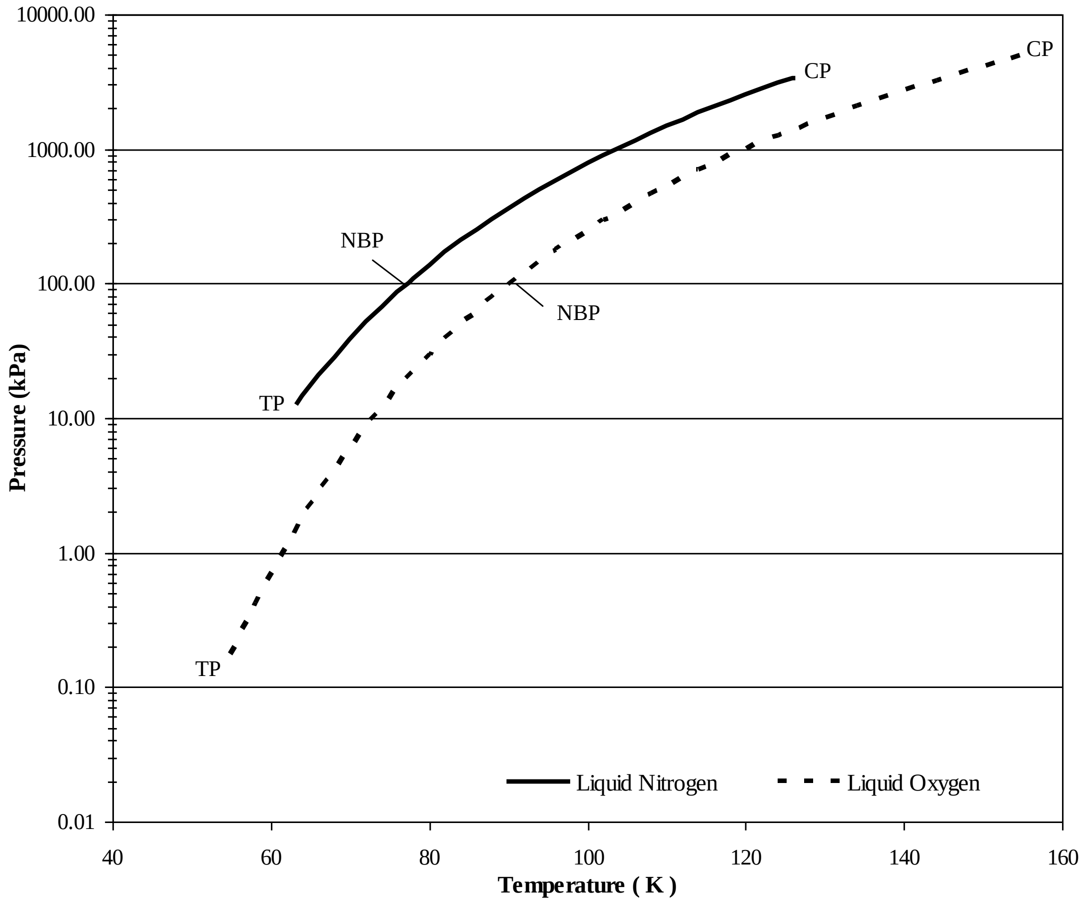


Figure 2.2 Liquid oxygen and nitrogen vapor pressure from TP to CP

2.2 Oxygen Propellant

In liquid propulsion rocket engines, various systems are utilized. Most notable are monopropellant and bipropellant. Monopropellants systems involve a single substance that contains both oxidizer and fuel utilizing a catalyst to decompose the substance. Bipropellant rocket engines require a fuel and oxidizer propellant supply that are mixed and burned in a combustion chamber. Both processes transform the energy contained in the chemical bonds to heat.[21] The completeness of these reactions is pivotal in liberating the highest available thermal energy. This release raises the combustion products to extreme temperatures and increases chamber pressure. Accelerating to high

velocities, the high speed gas escaping the nozzle delivers thrust - functional chemical propulsion to a vehicle.[22] Bipropellant systems generally deliver significant thrust and increased measures of performance as compared to monopropellant systems. In liquid bipropellant propulsion, the major propellant groupings are separated into cryogenic and storable. The characteristics of cryogenic liquids such as LOX have been previously discussed and are fluids with low normal boiling temperatures at atmospheric pressure. A storable propellant is liquid at ambient temperature, and as the name implies can be stored for long periods of time. Table 2.3 depicts thermochemical performance of various propellant combinations. Cryogenic propellants demonstrate the highest performance[23] per propellant weight. LOX/fuel propellant combination presents high measures of I_s representing increased performance.

Table 2.3 Theoretical performance of liquid rocket engine propellant combinations[19,22]

Oxidizer	Fuel	Mixture Ratio By Mass	Mixture Ratio By Volume	Average Specific Gravity	Chamber Temp. (K)	I_s (sec)
Oxygen	75% EtOH	1.30	0.98	1	3178	267
	92.5% EtOH	1.48	1.05	0.98	3308	274
	Hydyne	1.50	1.13	1.01	3489	291
	Methane	3.20	1.19	0.81	3526	296
	H_2	3.40	0.21	0.26	2959	386
	RP-1	2.24	1.59	1.01	3677	286
	NH_3	1.30	0.78	0.88	3042	285
	N_2H_4	0.74	0.66	1.06	3300	301
	UDMH	1.39	0.96	0.96	3542	295
Flourine	NH_3	2.80	1.26	1.14	4405	330
	N_2H_4	1.83	1.22	1.29	4553	334
	H_2	4.54	0.21	0.33	3080	398
RFNA	N_2H_4	1.23	0.79	1.26	3000	277
	UDMH	2.46	1.24	1.22	3117	267
N_2O_4	RP-1	3.46	1.93	1.23	3350	263
	N_2H_4	1.08	0.75	1.2	3130	283
	UDMH	2.12	1.16	1.14	3288	274
Hydrogen Peroxide (90%)	RP-1	7	4.01	1.29	2760	297
Hydrogen Peroxide (95%)	UDMH (50%) N_2H_4 (50%)	2.85	1.81	1.24	2863	274

LOX propellant is significant to historical rocket engine operation. Its ability to provide strong oxidizing media to sustain combustion reactions of an associated fuel is pivotal to increased performance. Bipropellant rocket engines have been consuming LOX as the fuels oxidizer since the inaugural liquid rocket engine (LRE) flight by Robert H. Goddard in 1926 using LOX/gasoline.[24] In 1942, the German V-2 rocket engine confirmed the possibility of achieving orbit under power from LOX and 75% ethyl alcohol/water mixture.[25] The Soviet Union lifted the first orbiting satellite as well as the first human in space on an R-7 multistage engine using LOX/kerosene propellants.[25] The Saturn V Rocket took man to the moon utilizing five LOX/Rocket Propellant 1 (RP-1) F-1 first stage boost engines, five J-2 LOX/ liquid hydrogen (LH_2) second stage boost, and a single J-2 engine for the final stage.[24] The space shuttle operates three space shuttle main engines (SSME) under LOX/LH_2 chemical propulsion.[25] This list reflects few of the significant achievements of LOX/fuel propellant combinations and serves to identify the relevance of LOX propellants application to LRE functionality.

2.3 Oxygen Risk and Safety

The obvious element of risk that accompanies the use of LOX in testing and operational environments is coupled to the fact that LOX is a cryogen and only remains in the liquid phase if kept chilled well below ambient temperature. The cryogenic and volatile nature of this propellant results in complexity in handling and operation. GOX and LOX are commanding oxidizers and their use in an operational system involves a degree of risk.[10] The severity of these risks amplifies in combination with the increased reactivity of oxygen associated with elevated pressure, temperature, and concentration. Engineering materials, including most metals, can react and burn aggressively in enriched

oxygen environments. Engineering facilities are commonly assembled with materials and components that can easily burn in oxygen enriched atmospheres. To illustrate this importance consider a common quarter turn ball valve depicted in Figure 2.3. This ball valve was ignited when the operator rapidly pressurized the component by opening quickly.[26] No definitive ignition mechanism is credited in this example. Slow pressurization of oxygen systems is considered the best practice for removing the high gas velocity inherent to rapid pressurization. In addition, this allows gas compression heating generated during pressurization to safely dissipate out of the system.

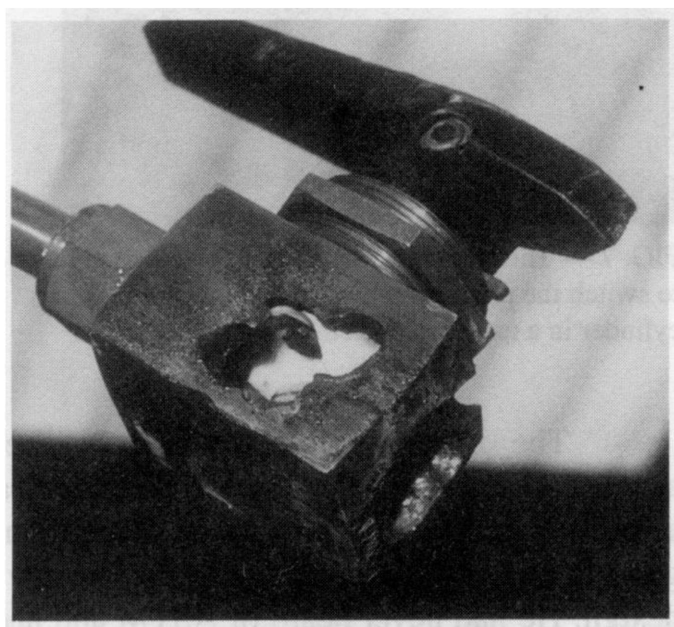


Figure 2.3 Stainless steel ball valve ignition[26]

Flammable components integrated into an oxygen test facility can be operated safely by understanding the potential risks. Minimizing ignition mechanisms through vigilant design and fabrication, selection of burn resistant materials, system operation procedures, cleanliness, and system maintenance contribute to successful operation. Ignition mechanisms leading to sustained combustion in an oxygen system can result in potential loss of testing objectives, equipment damage or destruction, and most severely,

personnel injury. Characteristic elements exist relevant to an oxygen specific ignition mechanism. All elements must be present for the specific ignition mechanism to be active.[10] Introducing a means to remove or reduce ignition mechanism characteristic elements allows for minimization of the potential ignition mechanism. There are multiple ignition mechanisms pertinent to oxygen systems; namely particle impact, heat of compression, flow friction, mechanical friction, mechanical impact, electrical arc, and others. The reader is referred to reference 10 and 11 for an inclusive review of not only the ignition mechanism and its characteristic elements, but the standardized tests used to generate data enabling better oxygen system design, development, and operation. A high degree of respect must be afforded to oxygen systems and the natural presence of potential fuels and ignition sources.

Oxygen safety is important because fires and physical injury can occur. Oxygen is a strong oxidizer that supports combustion but is not flammable by itself. Oxygen hazards are subtle and erratic; ignition is often unpredictable and not repeatable. Fires can occur in high or low pressure, in gaseous or liquid oxygen systems, and in less than 100% oxygen environments. Fire requires a fuel, oxidizer and ignition or heat source. In oxygen systems components become sources of fuel. Two of the three fire characteristics are generally present in oxygen systems. Manage the risks in oxygen systems by maximizing more burn resistant materials, minimizing ignition mechanisms, and utilizing good practices. These principles are illustrated by the ASTM fire triangle[10] in Figure 2.4.

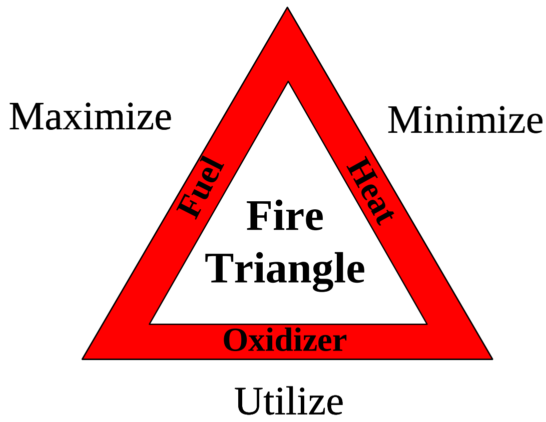


Figure 2.4 ASTM fire triangle[10]

2.4 Injector Performance

Injection processes deliver the propellants, or high pressure chemical media, into the combustion chamber. The injector serves to provide the necessary introduction and mixing of propellants issuing into the combustor. Injector performance relates to both propellant atomization and combustible mixture formation. Atomization is the disintegration of the injected liquid propellant jet into smaller droplets in order to increase surface area. The liquid propellant spray imparted into the combustion chamber break up from the liquid sheet into droplets that evaporate, interact, mix, and combust. Improved atomization increases droplet vaporization, propellant mixing and burning.[27] The injection dynamics must additionally supply the desired mixture ratio of propellant mass distribution uniformly throughout the combustion chamber.[13] This mixing unity is essential to achieve high measures of combustion efficiency relating to injector performance. The injector combined with the chosen propellants, with an associated injection element pressure drop or hydraulic resistance, establishes the propellant droplet spray size, velocity, and mass distribution throughout the combustor. Rocket engine

injectors control both propellant atomization and mixing processes that dictate the maximum realizable combustion efficiency.[28]

High pressure combustion testing distinguishes injector performance by employing operational propellants. This proves significant regarding injector atomization behavior concerning time scales relevant to droplet vaporization and mixing. Higher performance measures of combustion efficiency represent improved atomization to vaporize and evenly mix the propellants in the combustor.

CHAPTER 3

TEST FACILITY OXYGEN COMPATIBILITY ASSESSMENT

This chapter discusses the oxygen propellant systems OCA procedure. The results and changes to achieve LOX – GCH_4 high pressure combustion testing is discussed.

3.1 Rocket Engine Test Facility

The LOX – GCH_4 test facility consists of two independent systems that make engine operation possible. The main propellant system consists of LOX and GCH_4 to feed the oxidizer and fuel to the combustor. The spark driven torch igniter system contains a GOX and gaseous hydrogen (GH_2) feed system to initiate main propellant combustion. The LOX facility system was designed for a maximum flow rate of 1.4 kg/s (3 lbm/s), flow velocities of 4.6 – 9.1 m/s (15 – 30 ft/s) and maximum system pressure of 13.8 MPa (2000 psi). The LOX main feed tank volume has a capacity of 87.1 L (23 gallons) and is cryogenically chilled using a LN_2 outer jacket. LN_2 is bled off of the outer jacket and flows through Teflon tubing, jacketing the LOX delivery lines in order to maintain cryogenic temperatures to keep the oxygen main propellant flow in the liquid state. The GCH_4 fuel main propellant is supplied from a K-bottle gas cylinder manifold, enabling a maximum mass flow of 0.91 kg/s (2 lbm/s). GOX and GH_2 igniter system flows are delivered from a single standard K-bottle gas cylinder of the respective gas.

Mass flow for each system is regulated through critical orifices. Gaseous nitrogen (GN_2) is used as both the pressurant in each system to maintain the necessary propellant and igniter mass flows. Fuel and oxidizer supplies are separated by a reinforced concrete wall, and additionally the rocket engine is separated from the feed system components by a bulkhead. A schematic of the components and configuration of the LOX – GCH_4 testing facility can be seen in Appendix A.

3.2 Oxygen Compatibility Assessment

The PRC LOX facility designers and potential system operators received the ASTM training *Oxygen Systems Operation and Maintenance* in addition to the more inclusive technical and professional training ASTM course *Fire Hazards in Oxygen Systems*. Each provided insight into the fundamental principles for the safe use of oxygen systems stressing that all oxygen systems contain unique characteristics representative of their operation. An ASTM developed approach to manage the inherent oxygen hazard was identified and this introduction resulted in a PRC LOX and GOX test facility individual system level component OCA and hazard review. Standard procedures exist, as established by ASTM, to perform this analysis representing best practices inherent to oxygen system design, materials selection, oxygen cleaning, and oxygen compatibility testing of materials and components. The LOX and GOX OCA analysis was approached from a process of evaluating the current LOX facility operational strategy against requirements to make the system functional for both nominal and any off nominal situations. This attempt to reduce reaction effects of individual components is an efficient way to ensure successful operation in oxygen systems; making the system the most fault tolerant to the unpredictable nature of the reactivity of oxygen.

PRC personnel developed the LOX system OCA as a tool to better recognize and document the chosen components and the potential configuration hazards of the existing system. This analysis revealed LOX system current status hazards as well as perceived operational risks. Even though most had a low probability of occurrence, eliminating all unnecessary risks to the system and operational personnel was deemed the best practice. The OCA provided a means to identify and address component and configuration based hazards. It initiated best practices and recommendations to better serve safe LOX facility operation in order to achieve high pressure combustion testing. Figure 3.1 shows the flow chart used by the PRC to manage the oxygen hazard.

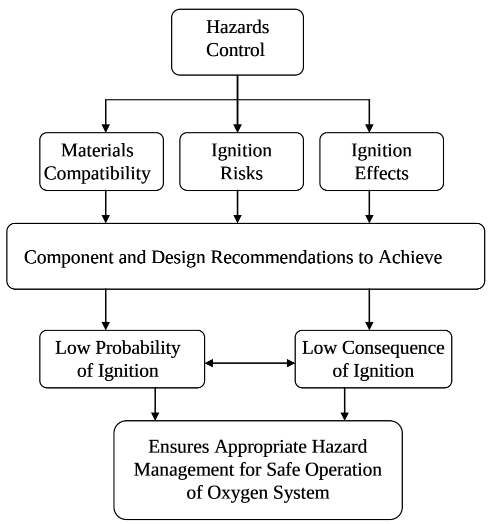


Figure 3.1 Oxygen system risk management

As an additional measure, oxygen safety engineering consultants were contracted to review the PRC findings and conduct an independent audit of the system configuration and proposed operating procedures for the LOX system. Based on the recommendations from the audit, an operational facility tactic was adopted to eliminate flammable materials, ignition mechanisms, procedural control, or implement barriers to reduce risks in the PRC oxygen systems.

3.3 OCA Procedure Development

In accordance with ASTM methodology, PRC personnel completed and documented an OCA analysis for the operational GOX and the developmental LOX systems. The assessment centered on the necessary systems to facilitate LOX – GCH_4 injector testing applications. Specifically the focus of the OCA was system level components in the current configuration of the LOX main propellant system, and the GOX igniter system. The thought process throughout the OCA development as applied to the LOX – GCH_4 system was divided into realizing, identifying, and managing the associated hazards. Figure 3.2 outlines a decision tree relating to the iteration followed in this process.

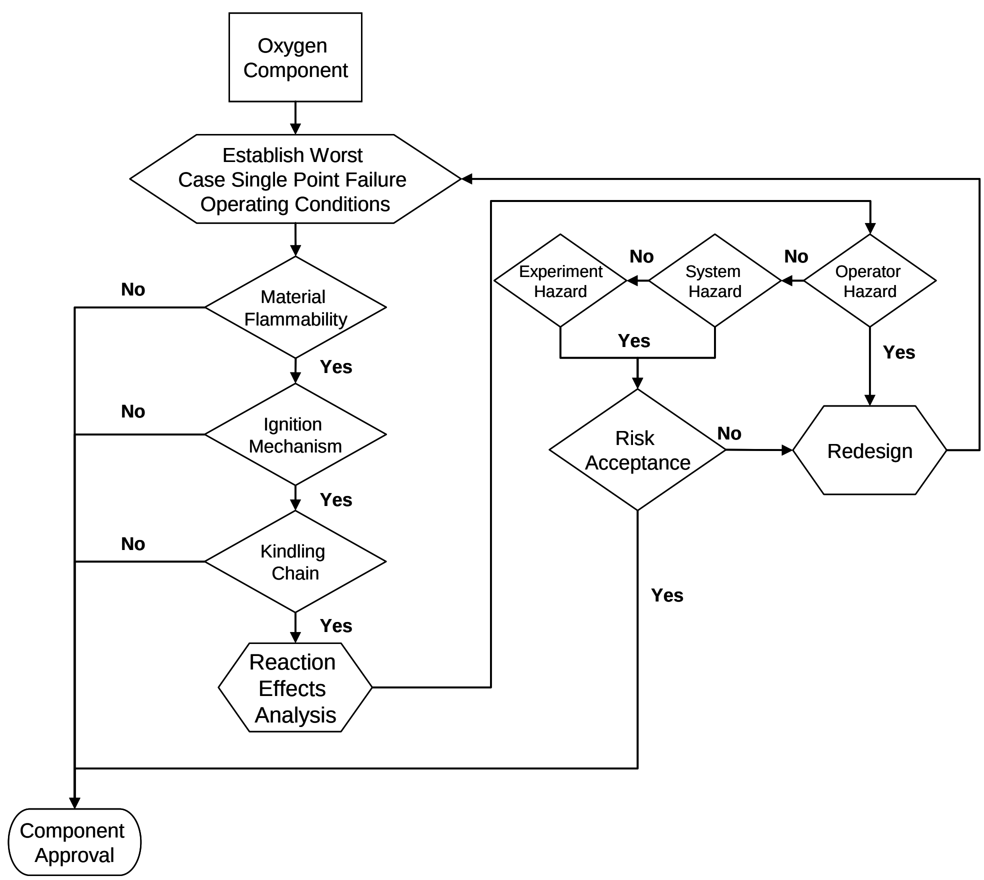


Figure 3.2 OCA decision tree

A worst case operating condition was established in conjunction to any single point failure relating to any individual system component that could potentially fail resulting in unpredictable or catastrophic system operation.[10] This most severe condition addressed the extreme fire hazard relating to oxygen concentration, temperature, pressure, flow rate, and cleanliness level. The OCA procedure establishes worst case operating conditions in order to assess the flammability of the oxygen wetted materials, evaluate the presence and probability of ignition mechanisms, determining reaction effects, and documenting the results pertaining to the specific oxygen system.

All oxygen wetted LOX and GOX system components were identified and individual component flow path cross sections were obtained. The materials of construction for each component were evaluated for oxygen compatibility. This is the first step in managing the oxygen fire hazard risk relating to reactivity of the material in oxygen environments. It would seem logical to judge the materials compatibility simply on flammability; however, other factors such as how easily the material can be ignited, the heat of combustion or heat release per unit mass of the burning material, the minimum oxygen concentration required for the material to react, and the autoignition temperature or minimum temperature in which a material will ignite, are each significant in realizing the compatibility of a component utilized in oxygen systems. ASTM oxygen system standards and reference 10 provide a diverse collection of engineering material test data relevant to all of these compatibility factors. However, this data must be applied using technical judgment. Determining the flammability can be difficult because of configuration dependency. The LOX and GOX system components were evaluated

against potential oxygen ignition mechanisms. These were evaluated with careful consideration of the characteristic elements relevant to a specific ignition mechanism.

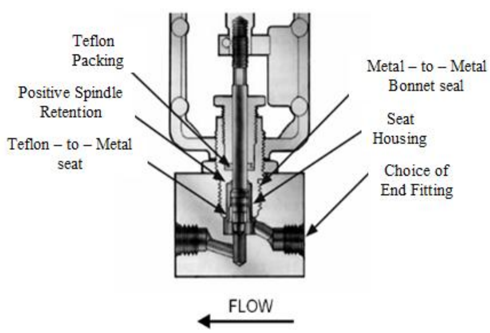
The next step of the OCA is to consider the kindling chain and reaction effect of the LOX and GOX specific system components. This part of the OCA identifies the result of a fire in a system component. Will the fire propagate and burn out the component leading to system failure, non functional system, or simply result in a leaky valve that can be replaced? The reaction effect of a specific component provides an assessment of the consequence of fire in that component relating to test objectives, equipment damage, and test personnel.

The final step of the OCA process is to assess the consequences of component failure and determine if corrective action is required. Any failure that could endanger personnel requires corrective action; however, if the failure does not endanger personnel and the effect of failure has a low consequence to the system or test objective, then no corrective action may be required. When selecting the corrective action, a four tiered approach consistent with the review audit methodology was used. The first approach was to replace flammable material with more burn resistant oxygen compatible material. This could be as simple as replacing O-ring seal material in a valve port connection or more intensive such as replacing the valve itself. The second approach was to eliminate the ignition mechanism from the system. Possible approaches to resolve these mechanisms include adding filters to remove potential particulate, replacing fast opening valves with multi-turn valves, adding distance volume pieces to absorb compression heating, among others. The third approach was to eliminate the possibility and/or reduce the severity of failure through procedural control. This approach involves ensuring that no personnel are

exposed to components during situations which may initiate a failure as well as following test procedures which can eliminate ignition mechanisms. The fourth and final approach was to apply appropriate barriers to protect personnel and equipment from potential failures. Barrier protection is considered a last resort, but can be an effective means to reduce risks in oxygen systems.

3.4 OCA Documentation

A specific component OCA example from the PRC's LOX developmental system is provided below. The component chosen to illustrate the OCA procedure is the LOX main valve. The LOX main valve is a pneumatic globe valve (PGV) and is located immediately downstream of the LOX main propellant feed tank. The valve is used to isolate the tank from the remainder of the system. Figure 3.3 illustrates the LOX main valve oxygen wetted cross section with material callouts.



a) Oxygen wetted flow cross section: source Circle Seal Controls, Inc

b) LOX main valve on facility during LN_2 flow chill operation

Figure 3.3 LOX main pneumatic globe valve

Table 3.1 depicts the LOX main PGV OCA. Footnotes are provided to capture the thought process at the time of OCA analysis. Relevant documentation providing the type of valve, manufacturer, manufacturer part number and corresponding facility label was included for comprehensive facility documentation. All components of the LOX and

GOX systems were analyzed in this manner. The complete OCA document is contained in Appendix A.

Table 3.1 LOX main valve OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Main Valve	**Pneumatic Globe Valve, 1/2" Ports, With Fail Closed Actuator, Cv= 1.7**	**Circle Seal Controls, Inc**	**CES60T1-08B-NC**	**TBD**

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	1[5]	0[6]	0[7]	1[8]	0[9]	2[10]	0[11]	Yes[12]	C[13]
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from single point failure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Particle Impact is not credible ignition source in Liquid Oxygen; however, during filling and chill GOX flow could impact the LOX Main valve seat housing presenting a particle impact ignition hazard. Severe impact geometries internal to valve in the given the flow direction are present. LN_2 Jackets are employed to chill the LOX main flow lines before LOX is pressurized past the Main valve. The LOX is additionally filtered before entering the tank to remove particulate.
[6] Heat of Compression is not a credible ignition source in Liquid Oxygen. Rapid pressurization is controlled by operation; the GOX/LOX filling the system is cold, and a sufficient volume to dissipate any heat of compression results upon pressurization. The cold oxygen and sufficient volume result in a low possibility of ignition.
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is possible but not probable.
[9] The component is not electrically powered.
[10] Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[11] Chatter does not occur in this component.
[12] A kindling chain exists if the Teflon ignites by flow friction and propagates to the stem and body. The probability of ignition by flow friction is low but a kindling chain does exist. Mechanical impact ignition of the Teflon is also possible but not probable. Particle impact could also be a source of ignition during LOX fill.
[13] The valve possesses flammable components, one possible and two remotely possible ignition mechanisms, as well as kindling chain; however the valve is remotely operated minimizing the effect on personnel. Due to importance of LOX main valve in relation to isolation to the LOX Tank, the effect of fire on system objective and functional capability increases. The reaction effect is critical.

3.5 OCA Results

The LOX and GOX system components selected were based on oxygen compatibility, affordability, and commonality with existing hardware. The following section discusses some of the corrective actions implemented to minimize potential oxygen hazards in the PRC's LOX and GOX propellant systems. In depth training, such as the ASTM courses mentioned earlier, in addition to a more thorough review of all components and configurations is always a recommended approach when it comes to the development of a safe and functional oxygen system. Every system must be evaluated using the best available resources, and technical judgment to establish safe system operation. The developmental LOX system contained hardware specific hazards that necessitated facility changes. These changes related to the protection of the hardware and not personnel. The system was designed safely to procedurally control operator risks through remote access of the severe components. The OCA process identified practical engineering fixes to the LOX propellant delivery facility to ensure safe system operation.

3.5.1 System Cleanliness

One of the primary concerns with the PRC oxygen facilities was the lack of traceability to a cleanliness level consistent with oxygen systems. The LOX and GOX main facility components were obtained from reputable manufacturing sources familiar with oxygen cleaning practices. Multiple cleaning processes and best practices in system assembly were undertaken to achieve a clean system necessary for safe and functional oxygen system operation. However, this approach does not guarantee a clean system and post-assembly verification was not performed on either system. This provides no traceable indication of component fittings or tubing cleanliness for oxygen service.

Furthermore, any part of a system connected to an oxygen flow line, such as the GN_2 purge and pressurization must also be cleaned for oxygen service. There exists potential of these connected lines to introduce hazardous unclean material into an oxygen flow line.

Not having established and documented traceability to cleanliness verification creates unknowns. It is essential in any oxygen system to establish and verify the cleanliness level before system operation. In order to establish a baseline of cleanliness, a particulate and non volatile residue (NVR) analysis was performed on multiple sections of each system. Stainless steel flow lines from the LOX and GOX systems were removed from low points or sumps which would inherently collect the most residue and represent the most severe concentrations. This operation allowed for a starting point to confirm the unknowns associated with the LOX and GOX system cleanliness.

The GOX igniter system cleanliness verification analysis established acceptable results for oxygen system operation. The oxygen cleanliness level of the LOX system propellant flow lines sampled were below standard. Numerous green particulates were identified in the LOX propellant flow line from the LOX main tank to the LOX main isolation valve. The largest particle was 3750 microns (0.148 in) which is larger than the LOX propellant flow control orifice diameter. These produced obvious concerns to the cleanliness level of these lines. Functional concerns arose regarding damage to flow component valve seats or plugging the orifice. The top of the LOX main tank employs a Grayloc hub with a Teflon coated seal. The seal color is green and had been utilized in this particular tank for approximately seven years. The deterioration of this seal resulted in erosion of the coating material. These particles collected in the LOX propellant flow

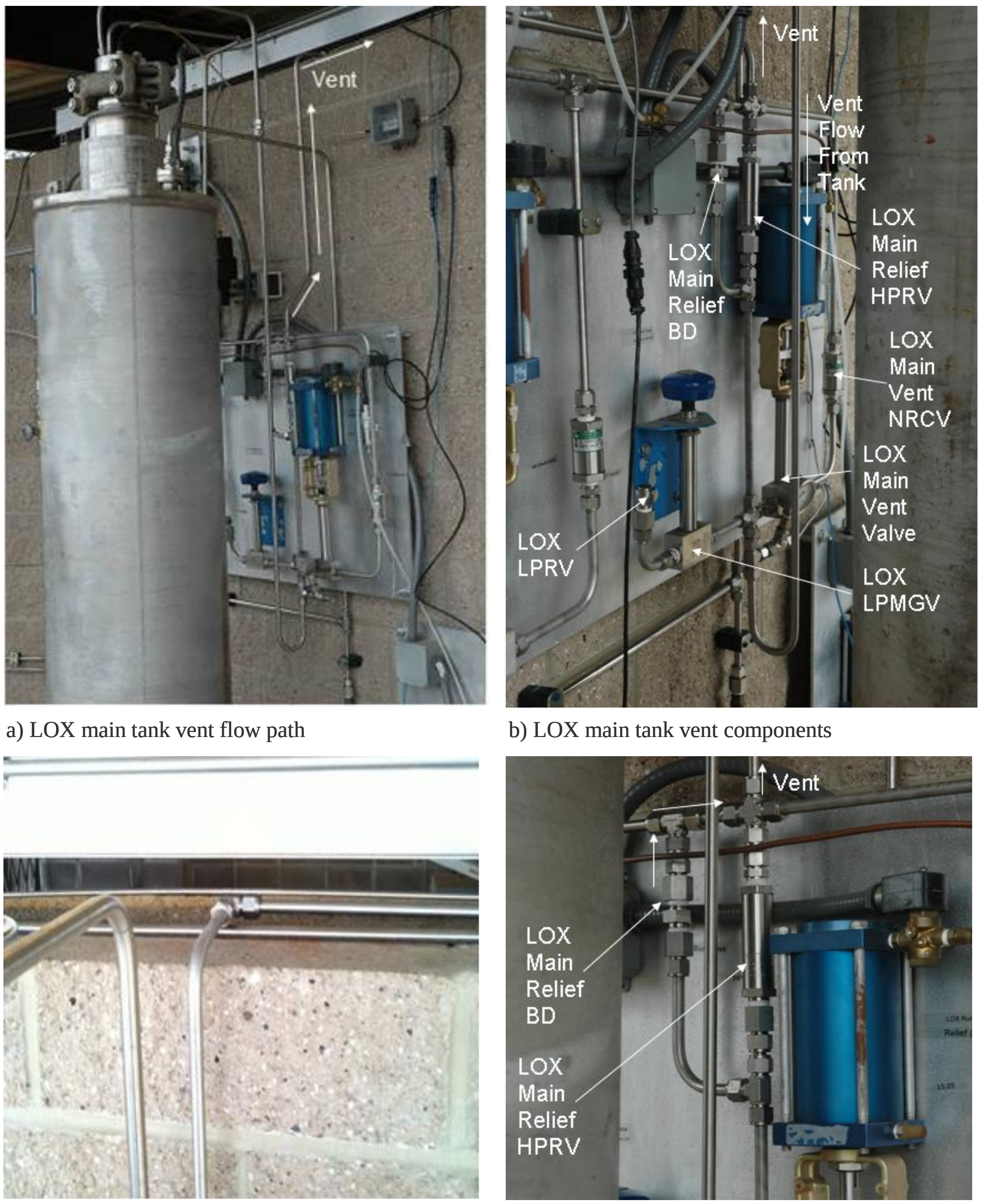
line connecting the LOX tank to the LOX main isolation valve. The second LOX propellant flow line sampled contained particulate as well. This section contained less abundant particles as the former, but still was below acceptable standard for oxygen system operation. The NVR level in both sampled LOX propellant lines was higher than nominal but well within the bands of oxygen cleanliness operational levels. The Grayloc seal was replaced and the LOX propellant system was thoroughly re-cleaned. These two propellant flow lines were then sampled again. The second analysis revealed even lower NVR levels and particulate counts resulting in a cleanliness level appropriate for oxygen system operation. As part of the second analysis green chips were taken from the deteriorated seal and analyzed. These were verified to be the same chemical composition as the green particulates identified in the first LOX propellant flow line oxygen cleanliness analysis.

The NVR and particulate analysis records were added to the OCA documentation. This analysis is found in Section A.6 in the OCA document located in Appendix A. Maintaining meticulous records of the component, system cleaning, and cleanliness level verification institutes long term traceability. This process is relevant to any oxygen system and potentially more significant in this situation. The hazards associated with an unclean system in oxygen service are avoidable. Cleaning, verifying that the system component is clean to the required oxygen service cleanliness level, maintaining system cleanliness inherent to system maintenance best practices, and traceability through documentation can mitigate the hazards associated with an unclean system. The best approach is to start clean, assemble clean, verify clean, and maintain clean.[10]

3.5.2 LOX Facility

The original LOX vent lines were 1.27 cm (0.5 in) stainless steel and contained a multidirectional flow path from the LOX tank main vent valve to the ambient atmosphere away from the test area. Figure 3.4 presents the original configuration for the LOX main tank vent and relief. The vent flow path contained several 90° and 45° bends, elbows, and tees resulting in a complex flow path with numerous flow direction changes. The described configuration illustrated in Figure 3.4a and 3.4c presents probable particle impact ignition sources with flammable components in the flow lines, and valves that could sustain combustion. In order for this ignition mechanism to be active, there must be particles entrained in a high gas velocity flow and a flammable target for the particulate to strike. This situation can generate sufficient energy in an oxygen enriched environment to ignite a flammable component. The vent gas will be a mix of GN_2 pressurant, and GOX vapor from the LOX liquid boil off held in the LOX main tank. Despite the nitrogen concentration in the venting gas flow, the flammable stainless steel lines and components are operated in an oxygen enriched environment. The increased oxygen concentration and high pressure increases the potential oxygen reactivity. The gas flow is venting from a high tank pressure to ambient conditions. The complex flow path and directional changes associated with the original system configuration results in potential flammable particle impingement targets. Even if a system is filtered properly and assembled oxygen clean, particulate can be generated through general maintenance of an oxygen system. Particulate can additionally be generated by flow components such as chattering flow through operation of the non return check valve (NRCV) downstream of the LOX main tank vent valve as seen in Figure 3.4b. The final most notable hazard in

the original LOX main tank vent configuration was a stainless steel tee directly downstream of a stainless steel burst disc. This is a highly probable source of particle impact ignition mechanism and is depicted in Figure 3.4d. The burst disc is a stainless steel material, and if ruptured could generate particulate traveling at high velocity directly into a flammable stainless steel tee.



a) LOX main tank vent flow path

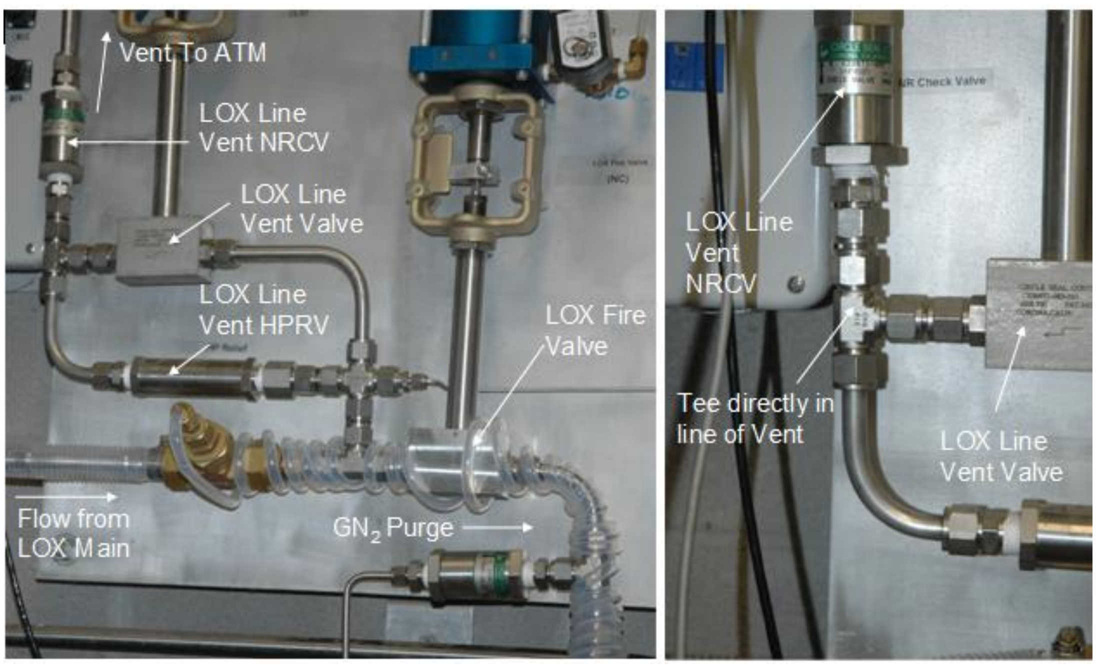
b) LOX main tank vent components

c) Top of wall flow directional change and stainless steel elbow

d) Burst disc and high pressure relief valve

Figure 3.4 LOX main tank vent and relief – original configuration

The LOX line vent configuration included many of the potential component hardware hazards indentified in the LOX main tank vent configuration. The LOX line vent original component arrangement is shown in Figure 3.5a. As displayed in Figure 3.5b a stainless steel flammable tee was placed directly in front of the LOX line vent valve. There was also a NRCV positioned directly down stream of the tee. This configuration increases the potential for a particle impact ignition mechanism to initiate a flammable component and kindle to the remaining flammable materials. The LOX line vent ties directly into the LOX main tank vent lines. Potential particulate generated from the LOX line vent NRCV follows the venting flow path through the directional changes to the ambient atmosphere. This represents the same particle trajectory impingement as seen in the LOX main tank vent configuration flow path with multiple flammable targets.

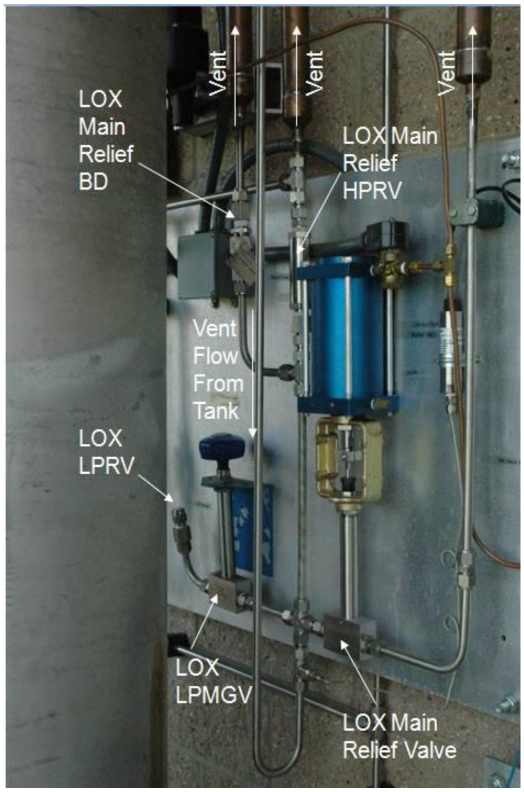


a) LOX line vent components b) LOX line vent ignition hazard

Figure 3.5 LOX line vent and relief – original configuration

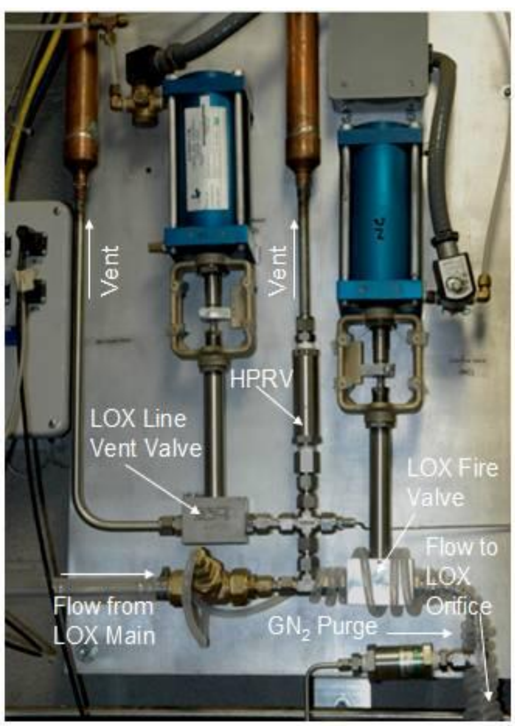
The LOX main vent and LOX line vent configurations were restructured to reduce potential ignition sources. The LOX facility main vent lines were redesigned with larger diameter 3.81 cm (1.5 in.) copper vent lines to reduce the pressure of the venting oxygen flow and additionally maximize the use of more burn resistant copper material. Straighter flow path transitions from the stainless steel flow lines into the copper vent lines minimize the potential risks and reduce particle impact ignition mechanism with the flammable stainless steel material. All stainless steel tubing connecting the main tank relief to the vent lines was given an appropriate flow recovery length of ten diameter's and smooth radii to accomplish changes in the direction of oxygen flow. Figure 3.6 represents the redesigned LOX main tank and LOX line vent configurations on the LOX facility. Figure 3.7 illustrates the venting gas flow path and Figure 3.7b depicts the LOX main tank and LOX line vent line connection, to then provide an oxygen vent path traveling out of the test cell.

GN_2 pressure testing of the LOX system in which certain sections of the facility were filled and held under pressure kept revealing undetectable leaks. The burst disc (BD) utilized in the system weakened in routine system pressure checks leading to small ruptures. This represents one common BD fatigue failure mode. The original LOX facility BD was sized for a low temperature operation. This low temperature design in the BD lowered the requisite burst pressure in ambient temperatures. The BD was replaced with an ambient temperature design. This change prevented disc rupture under pressure in ambient conditions.

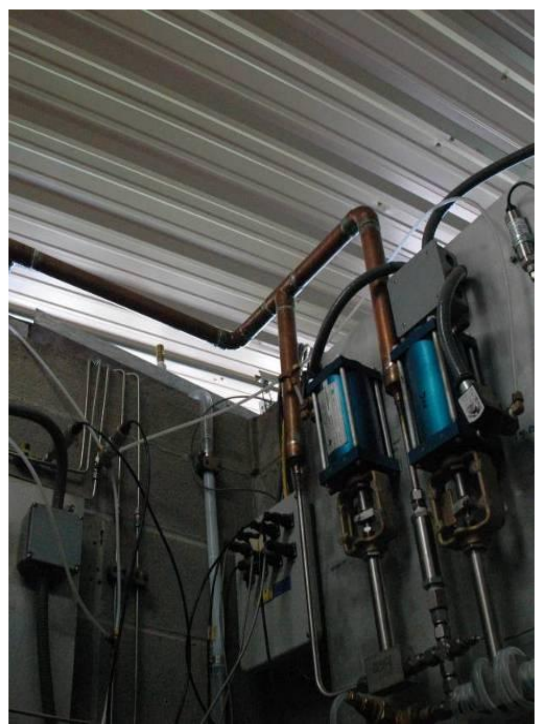


a) LOX main tank vent components

b) LOX main tank flow path

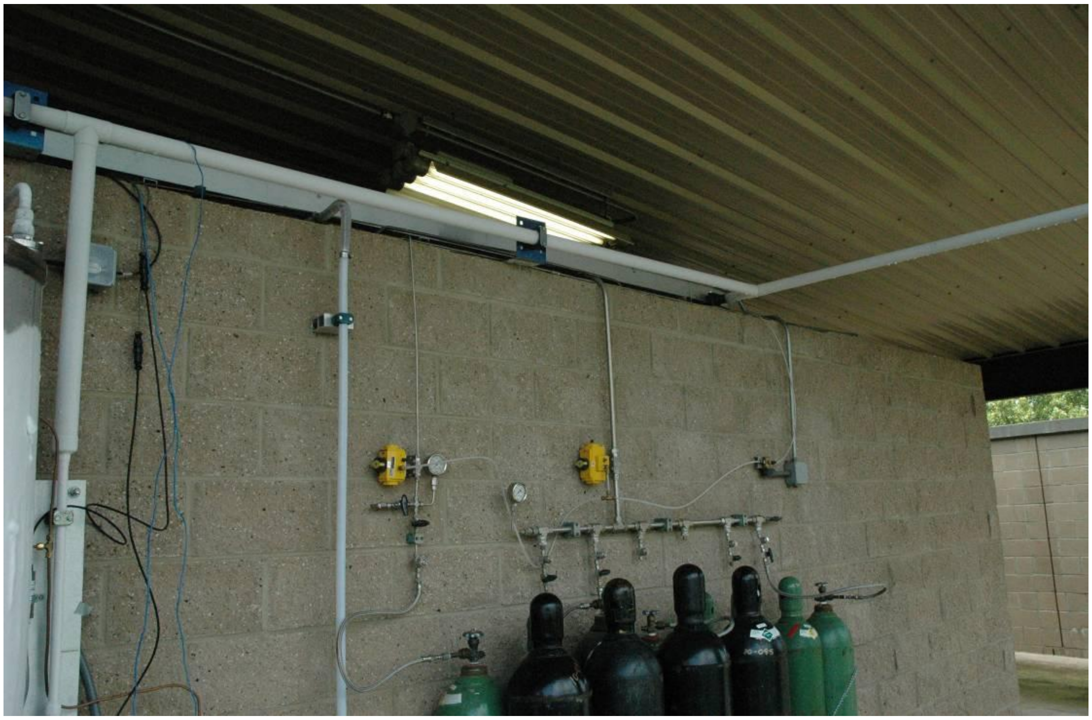


c) LOX line vent components



d) LOX line vent flow path

Figure 3.6 LOX main tank and line vent configuration – redesign



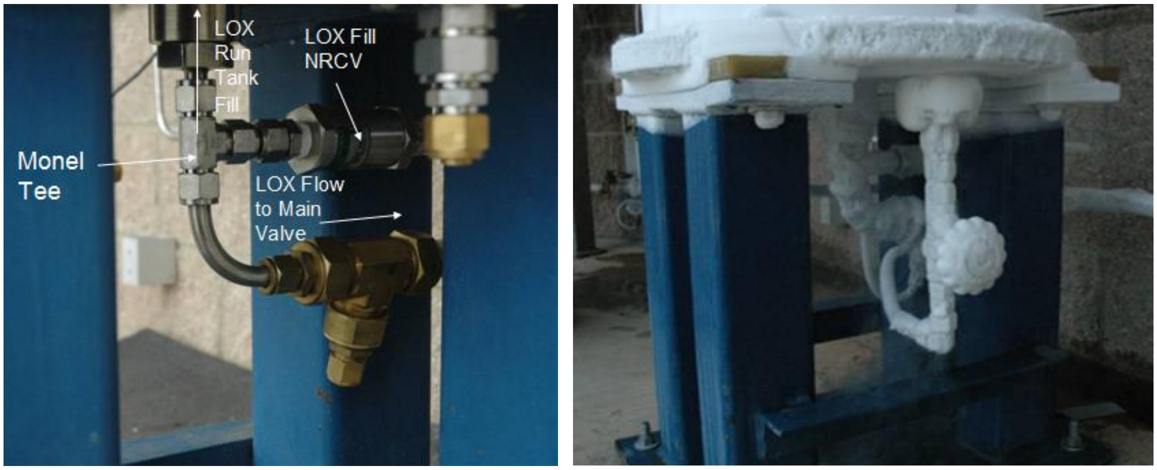
a) LOX facility vent lines during LN_2 checkout fill procedure

b) LOX facility vents away from test area

Figure 3.7 LOX facility vent flow path

In the original configuration, Viton O-rings were used in all situations for port connection sealing from the LOX main tank and system flow component valves to the seamless stainless steel tubing. Viton is not generally serviceable at low temperatures. Concern existed of O-ring material embrittlement leading to leaks through the seals that in turn could result in a potential flow friction ignition source. The Viton O-ring seals were replaced with Teflon for better material compatibility and structural integrity at low cryogenic temperatures.

In situations where particle impact ignition mechanisms were prevalent, stainless steel components were replaced with drop in burn resistant materials. Monel, which is a burn resistant material, tees and fittings were used to replace stainless steel ones to address this ignition mechanism. Directly underneath the LOX main propellant feed tank is one such instance and is shown in Figure 3.8. Particle impact ignition mechanism is not a credible ignition source in LOX due to the required particle or target ignition impact velocities. LN_2 pre-chill shown in Figure 3.8b was utilized in operational procedures to maintain the oxygen fill flow in the liquid state. However, during the LOX chill down transient when filling the LOX main tank, GOX flow is present in the lines. Replacing the stainless steel tee, which is a flammable material, with a more burn resistant material removes the flammable target characteristic element of particle impact ignition. This simple engineering fix minimizes the potential ignition source for the particulate generated from the NRCV directly upstream as seen in Figure 3.8.



a) LOX main tank fill components

b) LOX main tank LN_2 pre-chill

Figure 3.8 LOX main tank fill

The LOX main PGV illustrated in Figure 3.3 contains severe impact points given the flow direction from over the seat to under the seat internal to the valve should particulate be accelerated across the valve at high gas velocities. Even with LN_2 outer jackets to chill the LOX main PGV prior to opening this valve, it is probable that some LOX to GOX flashing will occur across the valve seat creating potential high velocity gas flow that might accelerate particulate. A potential particulate generating source is directly upstream in the fill line if the LOX fill line NRCV chatters. Gravity could pull any generated particulate down into the flow line from the LOX tank to the LOX main PGV. At fill pressures the probability of chatter is low; however, this hazard is identified to better comprehend all risks. In addition, this is the section identified in the cleanliness verification to contain numerous green particles.

The LOX fill PGV contains the same impact points discussed for the LOX main PGV. The LOX fill PGV is not pre-chilled representing even higher risk for LOX to GOX flashing which increases the particle impact ignition mechanism risk. To effectively control this ignition risk two points of filtration were implemented into the

LOX facility as shown in Figure 3.9. The LOX is filtered before entering the LOX fill PGV, flowing through the LOX main NRCV and up into the tank. This filter prevents particulate from entering the system from the LOX fill process. The LOX is filtered again before entering the LOX main PGV and traveling into the main propellant flow lines. In this situation the LOX is filtered before it enters the system, and then again downstream of a potential particle generation source. The filters are thickset brass housings with a sintered bronze 220 micron (0.0087 in) filter element. Both brass and bronze are burn resistant materials and represent a good selection for oxygen system compatibility.

a) LOX fill filter

b) LOX main tank filter

Figure 3.9 LOX facility filtration

3.5.3 GOX Igniter System

The PRC high pressure GOX igniter feed system exhibits a higher degree of hazard potential than the LOX system by reason of increased pressure and flow induced ignition probability. This system is most susceptible to particle impact and heat of compression ignition sources. The igniter system was sized to ensure flow velocities below the recommended maximums which have caused particle ignition events in oxygen tested components. However, during pressurization a high differential pressure between the source (K-bottle gas cylinder) and the system pressure (atmospheric) can result in high velocities and also present adiabatic compression ignition source potential.

Standard gas storage cylinder valves are inherently fast opening components and are incapable of slowly pressurizing closely coupled downstream components. This pressurization time is significant in the potential ignition probability concerning Teflon lined stainless steel flex hoses.[29] Standard cylinder valves contain no mechanical stop other than the nylon seat. Over the operational lifetime the rotating stem valve can wear down and coin the nylon seat. The nylon material exhibits a high heat of combustion that if ignited could burn into downstream system components. This represents a potential hazard with a severe reaction effect considering the manual operation. Simply cracking a cylinder valve to bleed in pressure is not a sufficient method to slowly pressurize the GOX igniter system. This practice increases the potential flow friction ignition mechanism due to the cylinder valve configuration. In addition, the pressurization time could be sufficient to ignite the Teflon lined stainless steel flex hose connecting the oxygen gas cylinder and the GOX ignition fill manual ball valve (MBV). Since the condition of the cylinder valve seat is not known at the time of operation, there exists

potential for nylon fibers resulting from the operational life deterioration of the cylinder valve nylon seat to exist in the flow path. If the cylinder valve is cracked, GOX flow will seep through a small flow area where high surface area nylon fibers could potentially be in the flow path. The heat generated as this GOX flows across the nylon could ignite the nylon fibers. If the seat is ignited, nylons high heat of combustion could further propagate and couple with GOX igniter system flammable components.

Consider the fill section of the GOX igniter circuit shown in Figure 3.10. In this original configuration the GOX fill MBV, GOX vent MBV, and GOX main pneumatic ball valve (PBV) are stainless steel bodied valves. Even though stainless steel is an alloy that is commonly and successfully employed in oxygen service, it is flammable under these operational conditions. Though there are few impact points internal to ball valves if fully open, all characteristic elements of particle impact ignition are present due to the high velocity gas flow inherent to opening the cylinder valve, potential particulate entrained in the flow, and a flammable target in the stainless steel valve bodies for this particulate to impact. In historical GOX igniter system operation, particle impact ignition mechanism has been controlled using filters to reduce or remove particulate from the system. The filters are implemented at connection between the GOX supply and the system interface.

In past operation the heat of compression ignition source has been procedurally controlled. It is standard practice in the GOX igniter system operating procedure to verify the GOX vent MBV is closed, and then fully open the GOX ignition fill MBV and the GOX main PBV before opening the GOX cylinder valve to pressurize the system.

When these two valves are opened before pressurization, a sufficient flow line volume is rendered to safely absorb the heat of compression.

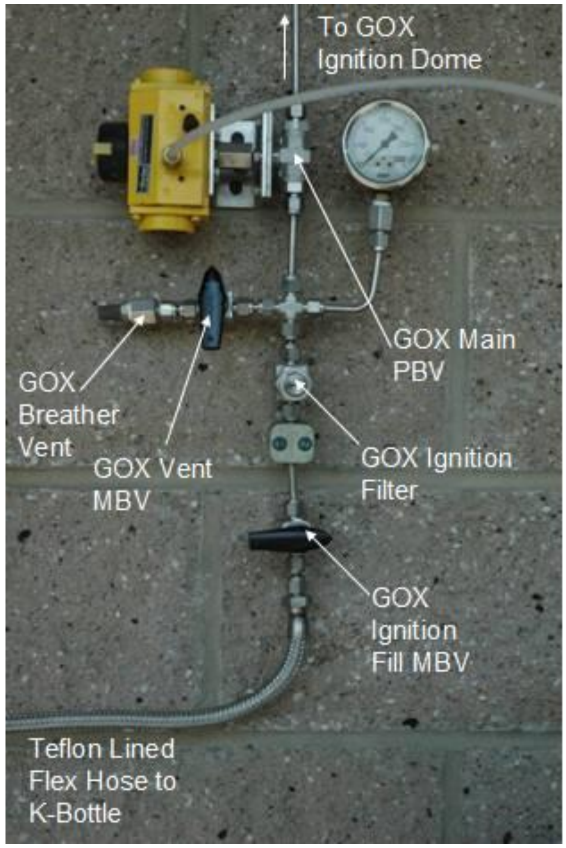


Figure 3.10 GOX igniter fill configuration – original

Consider the off nominal situation that the GOX fill MBV or the GOX main PBV is closed when the oxygen cylinder valve is opened to rapidly pressurize the small volume contained in the stainless steel Teflon lined flex hose. All heat of compression characteristic elements are present. This ignition mechanism is possible due to rapid pressurization, the presence of Teflon exposed near the dead end closed valve flow path, and the significant pressure ratio. The maximum theoretical oxygen gas temperature from isentropic compression is 1010 °C (1850 °F). This presents a final temperature that is well above the autoignition temperature of Teflon which is 435°C (814°F).[10] The GOX cylinder valve could potentially be opened prior to either the GOX fill MBV or

GOX main PBV. This off nominal single point failure will result in rapid pressurization of the fill volume. This situation has severe ignition potential.

To remove the potential for both of these ignition mechanisms in the GOX igniter system the standard GOX cylinder valve has been fitted with an oxygen brass regulator. This configuration is depicted in the re-designed GOX fill configuration shown in Figure 3.11. Using a regulator directly connected to the cylinder valve controls pressurization time of the system. The slower pressurization prevents the high velocity gas flow inherent to particle impact and adiabatic compression heating ignition mechanisms. Such regulators are constructed of a more burn resistant thick walled brass and their use results in increased pressurization time for the system. It is important to note that this is still a procedural fix to these potential ignition sources. To safely operate, the stainless steel GOX fill MBV and GOX main PBV must be opened before system pressurization. Further hazard identification was established using signage to remind operators that the GOX fill MBV and GOX main PBV must be open prior to the GOX cylinder valve. Depicted in Figure 3.11, these measures are an attempt to make test operators more aware of the hazards when indentifying a regulator on the igniter GOX cylinder valve and caution signage in the GOX cylinder fill area. As an additional protection measure, chained restraints were implemented to the GOX ignition flex hose to protect from failure associated with over pressurization and ignition potential.

In order to add a higher level of confidence the GOX ignition filter element was reduced from the original 90 microns (0.0035 in) to 40 microns (0.0016 in) and the stainless steel sintered element was replaced with burn resistant nickel 200. Inline sintered bronze filters in the commercial gas association (CGA) 540 connection fitting to

the GOX cylinder K-bottle are additionally utilized to prevent particle impact downstream, especially concerning impact into the stainless steel GOX ignition filter housing. This configuration ensures the GOX flow entering the system will be filtered in two locations: one directly at the GOX cylinder valve before the flow enters the regulator, and then again before the entrance into the GOX fill MBV.

The original GOX vent MBV in Figure 3.10 was a stainless steel component, and historically had been used as a high velocity component opened under full pressure differential to exhaust the small volume of GOX from the igniter system. Multiple reasons and opinions have been stated why this is not a preferred practice. This venting procedure is a manual process that increases the reaction effect considerably. The GOX fill MBV and GOX main PBV were chosen to facilitate higher flow capacities in the system. This functional capability is not required in this venting situation. The original GOX vent MBV was replaced with a multi-turn needle valve (MTNV) constructed of burn resistant brass. This valve contains a metal to metal seat removing the exposed soft goods in the flow path essential for heat of compression ignition, and the brass body removes the flammable target requisite to particle impact ignition. A flow path to exhaust the oxygen gas away from the operator was built into the GOX igniter vent. The stainless steel tubing that connects the GOX vent MTNV seen in Figure 3.11 was given a smooth radii to accomplish straighter flow path transitions from the stainless steel flow lines into the 1.27 cm (0.5 in) newly implemented GOX ignition copper vent lines maximizing the use of more burn resistant material.

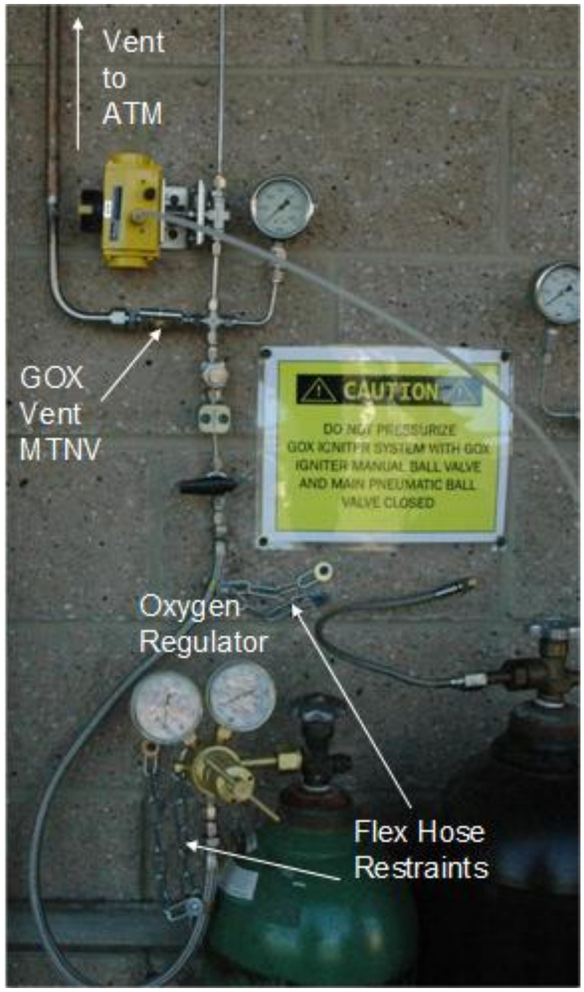


Figure 3.11 GOX igniter fill configuration – redesign

3.6 OCA Summary

The LOX and GOX propellant system OCA documentation procedure supplied a learning environment enabling more thorough realization of the ignition mechanisms prevalent to fires in oxygen systems. Despite best efforts in the design and fabrication stages of the facility development, the review process identified several areas where the system could be adjusted to achieve greater fault tolerance. The identified risks significant to these findings involved relatively simple changes which could decrease the probability of ignition but not reduce system functionality. As an extra measure of

protection an oxygen safety engineering consultant reviewed the findings of this work and performed a system level analysis. The safety review provided an opportunity to engage program management, designers, technicians, graduate and undergraduates students, and operators in creating a safe system which has a low probability of ignition and reduced reliance on procedures to ensure safe operation. The PRC system specific design changes identified represent some but not all of the changes to increase overall system safety. There exists no way to remove all operational risks inherent to oxygen systems. Training and education is the most notable defense against these hazards. These corrective actions are specific to the existing facility and the notion must be stressed that although the described initiatives are the potential fixes to the illustrated situation all oxygen systems are unique. Every oxygen system must be evaluated to establish safe system operation and the actions taken in the PRC facility may not be applicable at other facilities. The practice specifically undertaken in this process was to reduce the chance of operator induced errors relevant to off nominal operation. This results in increasing the fault tolerance of the systems and reducing the severity of reaction effects.

CHAPTER 4

INJECTOR TESTING METHODOLOGY

The LOX – GCH_4 single set point engine operational set up is described in the following sections. The baseline injector, research rocket engine, injector performance measurement configuration, and test procedures are covered.

4.1 MISER Injector

The baseline injector element chosen for high pressure combustion experimentation was designed in accordance with the full scale lunar AME nominal engine specifications. Table 4.1 summarizes these requirements and Table 4.2 describes the expected propellant conditions at the inlet to the injector. The propellant condition labeled standard in Table 4.2 was chosen for the injector design procedure.[1]

Table 4.1 Lunar ascent main engine specifications[1]

Thrust (F)	Engine Burn Time (t_b)	Specific Impulse (I_s)
N (lbf)	Seconds	Seconds
24,465 (5500)	450	355

Table 4.2 Lunar ascent main engine propellant conditions[1]

Propellant	Temperature K (R) Maximum	Standard	Minimum	Pressure MPa (psi) Maximum	Standard	Minimum
Oxygen	124 (223)	103 (185)	91 (164)	2.59 (375)	2.24 (325)	1.90 (275)
Methane	124 (223)	103 (185)	95 (171)	2.59 (375)	2.24 (325)	1.90 (275)

The thrust and specific impulse determined the full scale engine total injector mass flow rate equal to 7.03 kg/s (15.5 lbm/s). The full scale injector design procedure selected an *OF* mass ratio of 3.0 with 65 injector elements. This resulted in a single injector element total mass flow equal to 0.108 kg/s (0.238 lbm/s). The total injector mass flow and the design *OF* ratio determined the LOX mass flow rate ($\dot{m}_{LOX}$) equal to 0.081 kg/s (0.18 lbm/s) and the LCH_4 mass flow rate ($\dot{m}_{LCH_4}$) equal to 0.027 kg/s (0.060 lbm/s). The lunar AME concept specified a bracketed design pressure to the inlet of the injector of 1.90-2.59 MPa (275-375 psi). The MISER injector was designed for a pressure drop (ΔP) equal to 0.34 MPa (50 psi). Using the standard injector pressure of 2.24 MPa (325 psi) the estimated engine chamber pressure was 1.89 MPa (275 psi). The MISER shown in Figure 4.1 in the swirl coaxial arrangement was designed to incorporate swirl swirl, swirl coaxial, and shear coaxial injection schemes through change out hardware implementation.

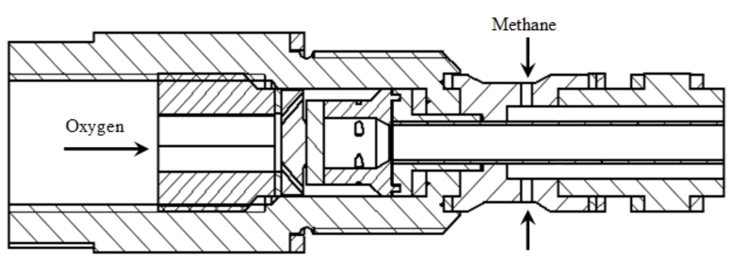
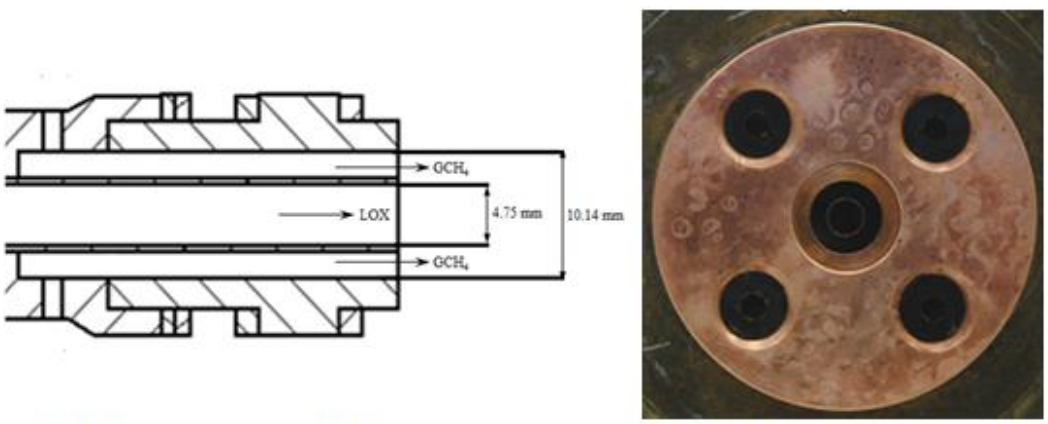


Figure 4.1 MISER injector

For the initial high pressure injector testing, GCH_4 was used in substitution for the LCH_4. In the injector design, an oxygen injection velocity of 25.24 m/s (82.8 ft/s) and a methane injection velocity of 38.35 m/s (127.9 ft/s) were established. This corresponds to a LCH_4/LOX injection velocity ratio 1.545. The GCH_4 injector fuel annulus flow area was adjusted to match the LCH_4 conditions. The GCH_4 fuel mass flow and injection velocity was structured to hold equal measure to the LCH_4 injection propellant flow conditions determined in the injector design. The GCH_4 fuel annulus sizing calculation is presented in Appendix B. Figure 4.2 depicts the MISER injector element tip dimensions and hardware as installed into the injector manifold.



a) MISER injector – element tip dimensions   b) MISER injector – element test hardware

Figure 4.2 MISER injector GCH_4 and LOX annulus

4.2 Research Engine

The small-scale rocket engine is a modular design of individual oxygen-free high conductivity (OFHC) copper rings varying in lengths. These sections are held together by grade 8 steel compression rods. The outer diameter of the engine is 12.7 cm. (5 in) while the inner diameter is 5.4 cm. (2.125 in). The combustor was configured for a single injector element. A depiction of the rocket combustor is shown in Figure 4.3. The

engine has water cooling for the nozzle segment but relies on the copper segment to dissipate heat from the combustion chamber in short duration testing (typically < 5 sec.). The combustor length can be varied by adding or removing engine segments. The engine configuration contains several ports for measuring chamber pressure. Two ports were utilized for chamber pressure measurement. One was located at the injector face and the other at the midpoint of the engine. A small GOX – GH_2 torch igniter was used for main propellant combustion ignition. The igniter is mounted on the upper portion of one ring section as illustrated in Figure 4.3.

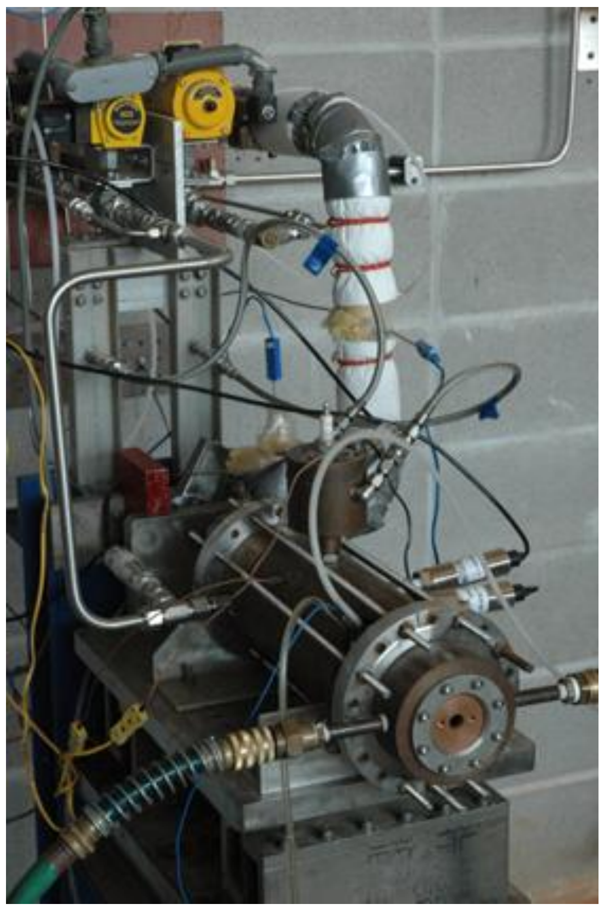


Figure 4.3 Research rocket engine

The combustion chamber length was set at 30.5 cm (12 in). This length was chosen in attempt to match a 2000 Hz transverse mode instability found in the low pressure experiment.[1] The nozzle was sized for the combustion chamber pressure of 1.90 MPa (275 psi) using a theoretical oxygen/methane characteristic velocity (C^*_{th}). This value was determined using Chemical Equilibrium in Excel (Cequel). This combustion products analysis code is based upon the NASA Lewis chemical equilibrium computer program.[30] The LOX – GCH_4 nozzle throat diameter was 1.135 cm (0.447 in) and the sizing calculation is provided in Appendix C.

4.3 Injector Performance

For the rocket engine operation, injector performance was characterized by combustion efficiency. The configuration illustrated in Figure 4.4 depicts the measurement location for the experimental setup. Pressure and temperature measurements were sampled at 500 Hz in the GCH_4 and LOX propellant flow lines directly before the respective flow control orifices. The propellant mass flow rates were determined using the critical mass flow equations. Combustion chamber pressure was also sampled at 500 Hz.

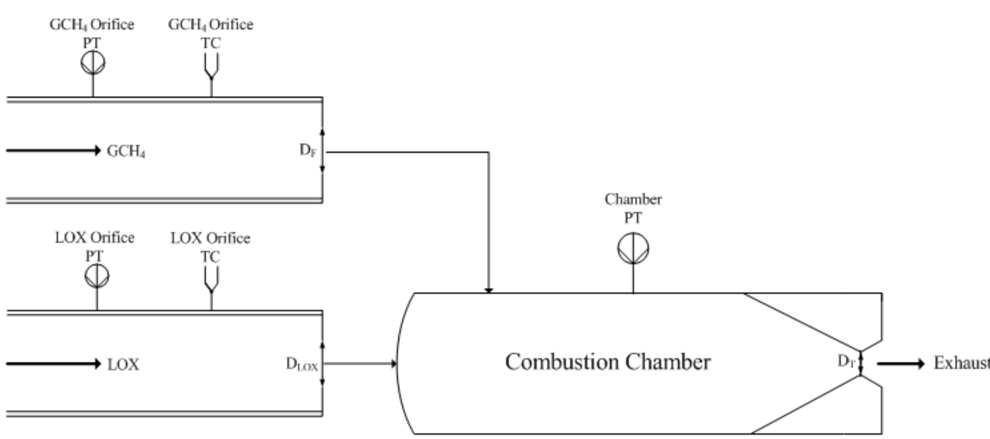


Figure 4.4 Characteristic velocity experimental configuration

Using the measured chamber pressure (P_C), the total mass flow ($\dot{m}_{Tot}$), and the nozzle throat area (A_T), C^* was determined by Equation 4.1.

$$C^* = \frac{P_C A_T}{\dot{m}_{Tot}} \tag{4.1}$$

The $\dot{m}_{Tot}$ is equal to the GCH_4 mass flow ($\dot{m}_{GCH_4}$) plus the $\dot{m}_{LOX}$ represented in Equation 4.2.

$$\dot{m}_{Tot} = \dot{m}_{GCH_4} + \dot{m}_{LOX} \tag{4.2}$$

In the GCH_4 choked flow equation, the variables are the flow control orifice discharge coefficient (C_G), the GCH_4 pressure (P_F) upstream of the orifice, the diameter of the flow control orifice (D_F), the specific heat ratio (γ_F), the gas constant (R_F), and the propellant temperature (T_F). The $\dot{m}_{GCH_4}$ is determined from Equation 4.3 using these parameters.

$$\dot{m}_{GCH_4} = C_G \frac{P_F \frac{\pi D_F^2}{4} \gamma_F \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F + 1}{\gamma_F - 1}}}}{\sqrt{\gamma_F R_F T_F}} \tag{4.3}$$

In the LOX caviating flow equation, the variables are the flow control orifice discharge coefficient (C_D), the LOX pressure (P_{LOX}) upstream of the orifice, the diameter of the flow control orifice (D_{LOX}), the density (ρ_{LOX}), and the LOX vapor pressure (Pv_{LOX}). The ρ_{LOX} and Pv_{LOX} are determined from the LOX saturation vapor pressure data from the National Institute Standards and Technology (NIST). The $\dot{m}_{LOX}$ is determined from Equation 4.4 using these parameters.

$$\dot{m}_{LOX} = C_D \frac{\pi D_{LOX}^2}{4} \sqrt{2\rho_{LOX}(P_{LOX} - Pv_{LOX})} \tag{4.4}$$

Combining the above equations, the C^* data reduction equation (DRE) is shown in Equation 4.5. In the experiment the approximate steady state chamber pressure, the measured mass flow rate, and the nozzle throat area facilitate the C^* experimental determination.

$$C^* = \frac{P_C \frac{\pi D_T^{\ 2}}{4}}{\left(C_G \frac{P_F \frac{\pi D_F^{\ 2}}{4} \gamma_F \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F + 1}{\gamma_F - 1}}}}{\sqrt{\gamma_F R_F T_F}} + C_D \frac{\pi D_{LOX}^{\ 2}}{4} \sqrt{2\rho_{LOX} \cdot (P_{LOX} - Pv_{LOX})} \right)} \tag{4.5}$$

Injector performance was characterized using the experimental C^* from Equation 4.5 and the C^*_{th} calculated from Cequel for the experimentally measured propellant mass flow rates. The characteristic velocity efficiency (η_{C^*}) is defined as the experimental to theoretical C^* ratio yielding a quantitative measure of combustion efficiency and is shown in Equation 4.6.

$$\eta_{C^*} = \frac{C^*}{C^*_{th}} \tag{4.6}$$

In both the GCH_4 and LOX propellant flow equations a discharge coefficient is present. To correctly size the respective propellant orifice supply pressure the discharge coefficient was determined. The GCH_4 orifice discharge was estimated from manufacturer experimental data. Volumetric air flow data existed for supply pressures ranging form 0.108 – 0.791 MPa (15.7 to 114.7 psi) in standard cubic feet per hour (SCFH). Using the choked flow equation shown in Equation 4.3 for supply pressures of 0.584 MPa (84.7 psi), 0.653 MPa (94.7) psi, 0.722 MPa (104.7 psi), 0.791 MPa

(114.7 psi) and air properties, the theoretical mass flow was calculated. Using the ideal gas law, the air density was determined for the pressure and temperature of the supply conditions. The theoretical volumetric air flow was then calculated and converted to SCFH. The GCH_4 discharge coefficient was calculated by comparing the manufacturer experimentally determined air mass flow to the calculated theoretical air mass flow. The GCH_4 discharge coefficient was established to be 0.91. The GCH_4 discharge coefficient calculation can be seen in Appendix D.

To establish the LOX propellant flow control orifice discharge coefficient, a calibration experiment was performed using water. The schematic shown in Figure 4.5 consisted of a water tank with ports for GN_2 regulated pressurization, water fill, and a vent. To isolate the tank pressurization, fill and vent ports, MBV's were used. Pressure and temperature measurements were sampled at 500 Hz and collected directly upstream of the LOX flow control orifice. The water tank was filled to 80% capacity, approximately 2 gallons of water, to allow for sufficient pressurization ullage in the tank. The water run tank was then pressurized with GN_2. The water collection container was weighed before the test and this was recorded. The MBV below the tank was then opened and the water flow through the LOX orifice was collected into a container. The flow time was recorded using a stopwatch, and the container was weighed to establish a measure of mass flow. Six experimental trails were conducted at run feed tank pressures of 3.45 MPa (500 psi), 5.17 MPa (750 psi), 6.21 MPa (900 psi), 7.24 MPa (1050 psi), 9.31 MPa (1350 psi) and 10.34 MPa (1500 psi). For each set pressure, a total of ten tests at 10 seconds was performed. The LOX discharge coefficient was estimated by

comparing the measured water mass flow to the theoretically calculated mass flow using the caviating flow in Equation 4.4 with water properties.

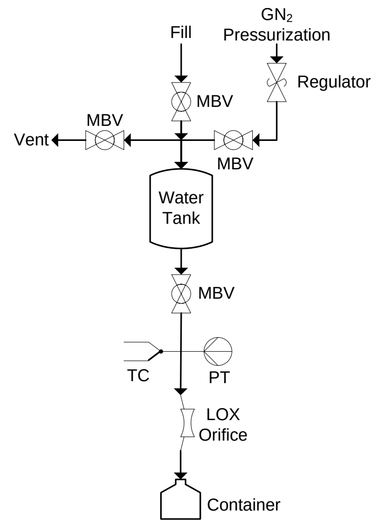


Figure 4.5 LOX orifice calibration configuration

In this calibration, the LOX orifice discharge coefficient was confirmed to remain reasonably constant with increasing mass flow and Reynolds number. Data collected from each set pressure test and C_D versus mass flow and Reynolds number are seen in Appendix E. The LOX orifice discharge coefficient was determined to be 0.65.

4.4 General Uncertainty Analysis

The objective of the general uncertainty analysis is to estimate and predict the associated uncertainty in the C^* experimental determination. It is important in the experimental planning phase to estimate measurement uncertainty[31] to better guide the requisite decisions concerning the planning phase of the summarized experiment in an effort to achieve an acceptable experimental result. Taylor series and Monte Carlo methods facilitate the analysis and each is contained in Appendix F.

The Taylor series method was directly applied to the C^* DRE shown in Equation 4.5. Nominal values of the experimental design conditions and estimated

uncertainties for the individual parameters are supplied in Table 4.3. The LOX Pv_{LOX} and ρ_{LOX} general uncertainty estimates were taken at a percentage of the nominal LOX propellant conditions. These estimates did not directly include the elemental error associated with the T_{LOX} temperature measurement and 10% of Pv_{LOX} and 5% of ρ_{LOX} were chosen.

Table 4.3 C^* experimental - engine operation nominal values

Data Reduction Equation Variables				
Definition	Symbol	Nominal Values	Uncertainty	Units
Chamber Pressure	P_C	1.896 (275)	0.021 (3.0)	*MPa (psi)*
Nozzle Diameter	D_T	1.135 (0.447)	0.0254 (0.001)	*cm (in)*
GCH_4 Orifice Discharge	C_G	0.91	0.015	-
GCH_4 Orifice Pressure	P_F	8.687 (1260)	0.021 (3.0)	*MPa (psi)*
GCH_4 Orifice Diameter	D_F	0.16 (0.063)	0.0254 (0.001)	*cm (in)*
GCH_4 Orifice Temperature	T_F	298 (536.4)	3 (5.4)	*K (R)*
LOX Orifice Discharge	C_D	0.65	0.015	-
LOX Orifice Diameter	D_{LOX}	0.119 (0.047)	0.0254 (0.001)	*cm (in)*
LOX Orifice Pressure	P_{LOX}	6.136 (890)	0.021 (3.0)	*MPa (psi)*
LOX Orifice Temperature	T_{LOX}	103 (185)	3 (5.4)	*K (R)*
LOX Vapor Pressure	Pv_{LOX}	0.324 (46.9)	0.032 (4.7)	*MPa (psi)*
LOX Density	ρ_{LOX}	1081.8 (67.54)	54.1 (3.37)	kg/m^3 (lb/ft^3)

The γ_F and R_F contributes to the C^* DRE equation; however, since these are known to a great degree of certainty, it does not contribute to the general uncertainty estimate. Partial derivatives of the C^* DRE equation are determined with respect to P_C, D_T, C_G, P_F, D_F, T_F, C_D, D_{LOX}, P_{LOX}, ρ_{LOX}, and Pv_{LOX}. Uncertainty magnification factors (UMFs) were determined. The general uncertainty U_{C^*} is then calculated using the evaluated UMFs, supplying the necessary information to attain the uncertainty percentage contributions (UPCs). The general uncertainty equation is stated below in Equation 4.7.

$$\frac{U_{C^*}}{C^*}^2 = \left(\frac{P_C}{C^*}\frac{\partial C^*}{\partial P_C}\right)^2\left(\frac{UP_C}{P_C}\right)^2 + \left(\frac{D_T}{C^*}\frac{\partial C^*}{\partial D_T}\right)^2\left(\frac{UD_T}{D_T}\right)^2 + \left(\frac{C_G}{C^*}\frac{\partial C^*}{\partial C_G}\right)^2\left(\frac{UC_G}{C_G}\right)^2$$
$$+\left(\frac{P_F}{C^*}\frac{\partial C^*}{\partial P_F}\right)^2\left(\frac{UP_F}{P_F}\right)^2 + +\left(\frac{D_F}{C^*}\frac{\partial C^*}{\partial D_F}\right)^2\left(\frac{UD_F}{D_F}\right)^2 + \left(\frac{T_F}{C^*}\frac{\partial C^*}{\partial T_F}\right)^2\left(\frac{UT_F}{T_F}\right)^2 \tag{4.7}$$
$$+\left(\frac{C_D}{C^*}\frac{\partial C^*}{\partial C_D}\right)^2\left(\frac{UC_D}{C_D}\right)^2 + \left(\frac{D_{LOX}}{C^*}\frac{\partial C^*}{\partial D_{LOX}}\right)^2\left(\frac{UD_{LOX}}{D_{LOX}}\right)^2 + \left(\frac{P_{LOX}}{C^*}\frac{\partial C^*}{\partial P_{LOX}}\right)^2\left(\frac{UP_{LOX}}{P_{LOX}}\right)^2$$
$$+\left(\frac{\rho_{LOX}}{C^*}\frac{\partial C^*}{\partial \rho_{LOX}}\right)^2\left(\frac{U\rho_{LOX}}{\rho_{LOX}}\right)^2 + \left(\frac{Pv_{LOX}}{C^*}\frac{\partial C^*}{\partial Pv_{LOX}}\right)^2\left(\frac{UPv_{LOX}}{Pv_{LOX}}\right)$$

A Monte Carlo simulation was conducted to estimate the uncertainty in C^*. Ten thousand simulated random errors are generated using Microsoft Excel for $P_C, D_T, C_G, P_F, D_F, T_F, C_D, D_{LOX}, P_{LOX}, \rho_{LOX}$, and Pv_{LOX}. The simulation reflects a Gaussian error distribution with the standard deviation equal to the individual uncertainty estimate associated divided by two. This approach is necessary to relate the standard deviations for each distribution to the required 95% confidence level. The generated errors are added to the nominal $P_C, D_T, C_G, P_F, D_F, T_F, C_D, D_{LOX}, P_{LOX}, \rho_{LOX}$, and Pv_{LOX}, yielding a new error influenced variable. The C^* DRE equation is then solved using the error influenced parameters. The mean ($\overline{C}^*$) and standard deviation (S_{C^*}) is calculated from the new sample population, and the general uncertainty is estimated at $\approx 2S_{C^*}$. A histogram is configured to cover a range of $\overline{C}^* \pm 4S_{C^*}$ to properly scale the presentation and all 10,000 values are normalized into a histogram and plotted in contrast to a Gaussian distribution. This plot illustrating the Monte Carlo simulation distribution is shown in Figure F.1 and a sample analysis set from the Monte Carlo method is displayed in Tables F.1, F.2, and F.3 contained in Appendix F. The Taylor series and Monte Carlo uncertainty methods yield at 95% confidence that the general uncertainty

associated with the C^* experimental determination to be $\approx 4.4\%$. These results are illustrated in Tables F.4 and F.5 in Appendix F.

In Appendix F, Table F.4 displays the influencing factors associated in the Taylor series general uncertainty. It is important to note the far right two columns presenting the UMFs and UPCs. UMFs specify the influence of the individual variable uncertainty in the resultant uncertainty.[31] It is seen that the D_T UMF is greater than the other independent parameters. This quantity is greater than 1 and thus indicates uncertainty magnification as it propagates through the C^* DRE. The UMFs less than 1 shows the individual uncertainty influence diminishes through the C^* DRE. The P_C UMF equal to 1 specifies the individual uncertainty neither magnifies nor diminishes through the C^* DRE.

Reference 31 defines UPCs for a contributing DRE measurement variable as the "percentage contribution of the uncertainty in that variable to the squared uncertainty in the result." Investigation of the UPCs for each variable demonstrates that parameter D_{LOX} dominates the resultant uncertainty. In fact, $\approx$88% of the 100% total UPC is contributed from C_D, D_{LOX}, and Pv_{LOX}. This signifies the importance of the LOX measured mass flow in the C^* DRE resultant uncertainty. An interesting correlation is noticed recalling the UPC includes the effects of both the UMF and the individual uncertainty of the parameter.[31] The P_C displays the greatest UMF or influence of that independent uncertainty on the resultant uncertainty. However, the principle UPC was from D_{LOX}. This fact validates the relevance of examining UMFs, UPCs, and the individual uncertainties that influence the resultant C^* experimental determination.

4.5 Test Procedures

The LOX –GCH_4 test procedure was produced from previous test experience.[9,32] This checklist was followed in the test operation starting with the pre-test checklist to filling the LOX tank, to firing the engine. It contains general information relating to cryogenic safety, oxygen safety, failure modes and mitigation. In addition, calculations for combustion chamber over pressurization and flex hose chain restraint factors of safety are documented. The rocket engine operation procedure contained pertinent information for test equipment operation, and personnel safety. The test procedure is located in Appendix G.

CHAPTER 5

RESULTS

The research questions posed in this study are addressed in this chapter. The discussion includes LOX facility operations, LOX – GCH_4 engine operation, and evaluated injector performance.

5.1 LOX Facility Operation

LOX facility commissioning involved multiple tests to shakeout operational characteristics. The ultimate objective was LOX – GCH_4 rocket engine injector performance testing. To meet this objective, LOX must be filled into the run tank, the propellant flow line must be chilled, and then the desired LOX mass flow delivered to the rocket engine. The LOX facility was loaded with clean and inert LN_2 to establish and verify procedural operations before the more hazardous LOX propellant was put into the system. LN_2 testing provided experience and confidence into the test operations.

The first facility operational procedure was to fill the tank with a cryogenic liquid. This was performed using the LOX run tank outer jacket to chill the inner tank volume before filling. The outer jacketed volume was filled with LN_2 to bring the tank to low temperatures. In the fill operation, the LN_2 jacket was opened to atmosphere and the outer jacket volume was filled. This was a cumbersome process taking 2.5 hours to perform using approximately 435 liters (115 gallons) of LN_2. Much of the outer jacket

fill LN_2 was lost to atmosphere due to liquid to gas vaporization traveling out the vent lines. The energy required to chill the un-insulated LOX run tank dictated the lengthy outer jacket fill process. When the LN_2 outer jacket was full, the LOX run tank exhibited thick frost covering as illustrated in Figure 5.1. During the fill process the frost served as an approximate indication to the LN_2 level in the outer jacket tank. In facility operation, the frost served as an insulation source for the LOX run tank.

Figure 5.1 LOX tank – frost layer

Once the LN_2 outer jacket was full and the tank was frosted, the LN_2 jacket was closed to atmosphere and held at 0.15 MPa (22 psi) using a pressure relief valve. Multiple LN_2 tests identified that this pressure relief device was insufficient to facilitate the venting nitrogen boil off. The LN_2 vent bypass valve to atmosphere was partially

opened (until the relief valve chattering subsided) to provide an additional vent path. To perform the inner tank fill, the LOX run tank volume was opened to atmosphere and filled. Due to the LN_2 chilled tank, this was a faster process taking approximately 10 to 15 minutes to fill the inner tank. In initial LN_2 checkout fill operations the tank was filled to around 80% capacity, approximately 70 liters (18.5 gallons), of LN_2. The remaining 20% inner tank volume was utilized for GN_2 pressurization.

To maintain the LOX propellant liquid phase, cryogenic flow jackets were employed. LN_2 flow from the LOX run tank outer jacket was used to chill the length of the LOX propellant line to the bulkhead. This was accomplished by opening a LN_2 jacket valve on the bottom of the tank which initiated nitrogen flow. The jacketed lines were constructed of 3.81 cm (1.5 in) Teflon tubing using a metal to Teflon seal. Smaller Teflon tubing with a diameter of 1.27 cm (0.5 in) was used for LN_2 bypass around the LOX propellant flow line connection fittings. This tubing was wrapped around the valves and port connection fittings. These also used a metal to Teflon seal. The variation in shrinkage due to the cryogenic temperatures of the Teflon and stainless steel presented multiple leak paths. Such leaks would slow and eventually stopped due to the frost over of the fitting connections. Considerable LN_2 was expelled in early attempts to shakeout the LOX propellant chill line sequence. Leaks were apparent in all tests performed.

Initial testing to chill the main propellant flow line was unsuccessful due to leaks preventing the LN_2 from traveling upstream to the bulkhead and flow restriction in the jacketed lines. The wrapped Teflon tubing created difficulties in maintenance to the system. Some LOX facility development operations required the wrapped tubing to be removed and then re-wrapped in which tubing fatigue and kinking was easily

accomplished. As a result the LN_2 jacketed flow path was checked for restriction before cryogenic liquid loading to ensure a strong flow path in the cooling jacket from the main tank to the bulkhead.

Large amounts of LN_2 were required to sustain and deliver flow to chill the main propellant line. The LN_2 jacket chill line was insulated; however, LN_2 outer jacket replenishment produced an issue for maintaining the low jacketed temperatures. Little time was required to exhaust the entirety of the LN_2 contained in the outer jacked volume. To successfully accomplish the needed flow for chilling the main propellant line, a 174 L (46 gallon) LN_2 Dewar at 2.41 MPa (350 psi) was utilized for replenishment. This larger volume of LN_2 was connected to the LN_2 fill valve and opened slightly to establish strong nitrogen flow for chilling. A temperature measurement in the LN_2 flow jacket was put in place. This determined the chill jacket temperature far downstream of the LOX run tank and directly before the LOX fire valve. This data point provided a marker to begin the main propellant flow. Figure 5.2 illustrates the time required to chill the LN_2 outer jacket to 90 K (162 R) at approximately 10 – 15 minutes. The time varied slightly due to ambient testing conditions. After the LN_2 jacket temperature measurement was verified to around 90 K (162 R), the LOX main tank was pressurized and main propellant flow initiated. Even with the LN_2 jacket chill line, main propellant cold flow through the engine was necessary to effectively chill the LOX flow line from the bulkhead to the rocket engine and the injector. This was necessary to keep the main propellant as near the liquid phase as possible.

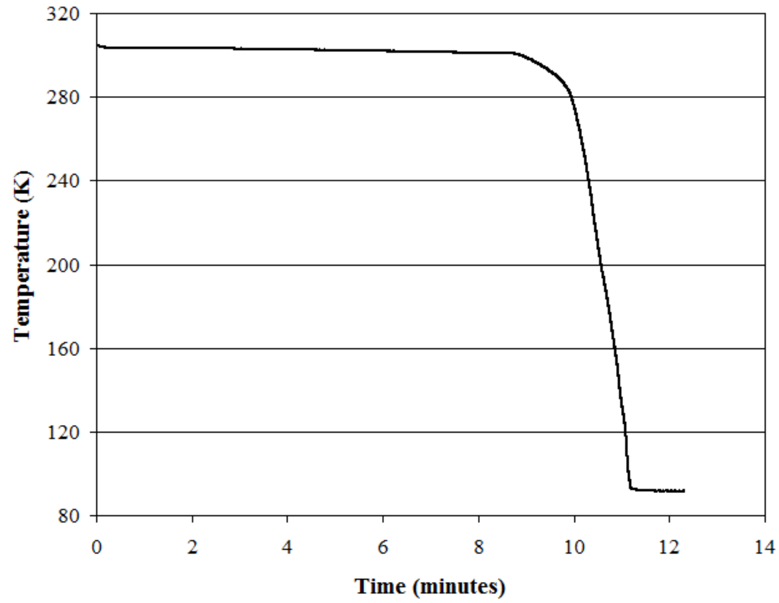


Figure 5.2 LN_2 jacket flow line chill

Three temperature measurements were obtained in the LOX main propellant flow line. Thermocouples were located directly upstream of the LOX main valve, the LOX flow control orifice, and the LOX injector. These provided data points to measure the LOX propellant flow line temperatures. The initial flow line configuration from the bulkhead to the rocket engine was not insulated. In this arrangement the flow line and injector chill down took long transients. The thick frost build up provided some insulation but did not demonstrate the required line chilling for propellant conditioning. To mitigate this loss, the main propellant line from the bulkhead to the rocket engine was insulated. Figure 5.3 illustrates the time required to chill the main propellant flow line using LN_2. This figure includes the LN_2 jacket flow line temperature. To establish low temperatures and chill the remaining portion of the main propellant flow line and injector took around 45 seconds. Figure 5.4 depicts LN_2 cold flow engine operation shutdown illustrating visible LN_2 flowing out of the rocket engine.

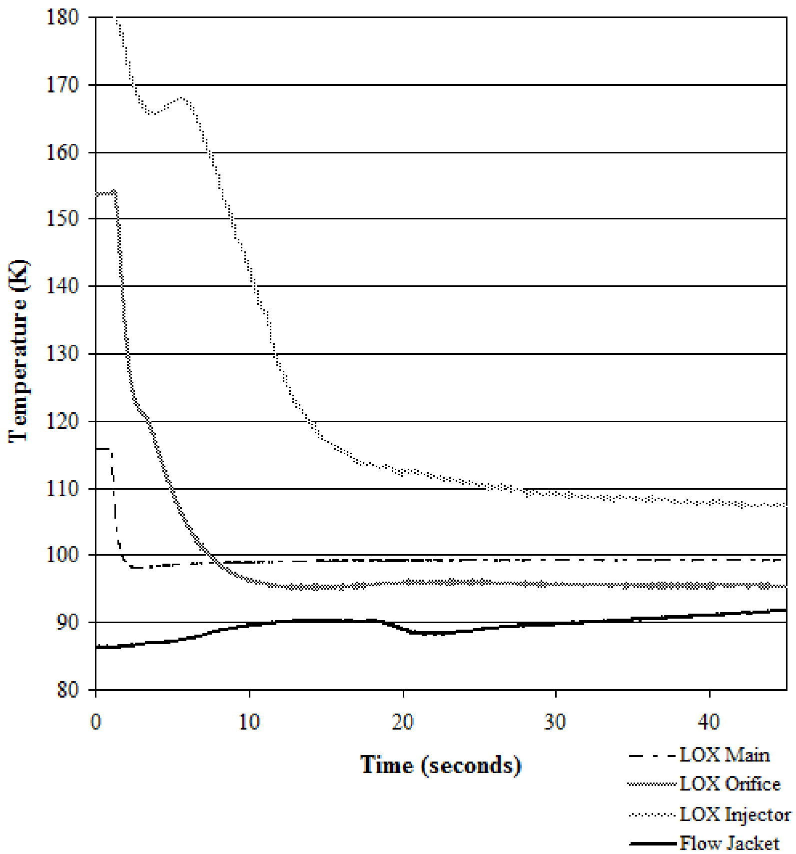


Figure 5.3 LN_2 cold flow main propellant flow line chill down

Figure 5.4 LN_2 cold flow – engine shutdown

Seven simulated firings where performed using LN_2 and GN_2 as final preparation to LOX – GCH_4 rocket engine operation. These tests were executed using mock operational propellants to validate the test procedure. Four of these tests attempted to match the nominal LOX and GCH_4 flow rates. The requisite pressure to deliver 0.082 kg/s (0.18 lbm/s) of LN_2 was around 10.17 MPa (1475 psi). As a precaution to the LOX facility three test where performed at a lower pressure of 6.90 MPa (1000 psi) before increasing the system pressure to the above noted level. After chilling down with the propellant flow line jacket, LN_2 was pushed through the engine. The temperature measurement at the LOX injector was monitored. When the LOX injector temperature had stabilized at the lowest attainable temperature the LN_2 flow was stopped, the engine was briefly purged with GN_2 and then the fire sequence was initiated. In each firing test, four seconds of LN_2 and GN_2 simulated propellant flow was delivered to the engine. Table 5.1 notes the steady state temperature measurements obtained for each pre-chill operation. Table 5.2 presents firing data for measured orifice temperature and pressure, the nominally calculated and measured mass flow, and the measured LN_2/GN_2 ratio. Test 1 (Table 5.1) represents the pre-chill operation prior to test 1 firing in Table 5.2. Obviously, pre-chill is required before initiating the firing sequence to maintain nitrogen liquid phase. Figure 5.5 shows an image of a simulated cold flow firing sequence test operation.

Table 5.1 LN_2 cold flow pre-chill tests

Test	Chill Time seconds	LOX Main K (R)	LOX Orifice K (R)	LOX Injector K (R)	LN_2 Jacket K (R)
1	45	99.4 (178.9)	95.4 (171.7)	107.5 (193.5)	91.5 (164.7)
2	16	99.2 (178.5)	94.9 (170.8)	105.8 (190.4)	94.0 (169.2)
3	24	99.3 (178.7)	92.9 (167.2)	106.4 (191.5)	90.9 (163.6)
4	10	99.3 (178.7)	96.0 (172.8)	114.7 (206.5)	87.2 (157.0)
5	21	102.0 (183.8)	96.2 (173.16)	105.1 (189.2)	91.8 (165.2)
6	38	103.9 (187.0)	96.9 (174.4)	105.3 (189.5)	99.9 (179.8)
7	34	105.9 (190.6)	98.9 (178.0)	108.7 (195.6)	104.5 (188.1)

Table 5.2 LN_2 – GN_2 cold flow firings

Test	LOX Orifice Measured Temperature K (R)	LOX Orifice Measured Pressure MPa (psi)	LN_2 Nominal Mass Flow kg/s (lbm/s)	LN_2 Measured Mass Flow kg/s (lbm/s)	GN_2 Nominal Mass Flow kg/s (lbm/s)	GN_2 Measured Mass Flow kg/s (lbm/s)	LN_2/GN_2 Ratio
1	98.3 (176.9)	6.93 (1004.8)	0.065 (0.144)	0.0694 (0.1531)	0.027 (0.06)	0.0269 (0.0594)	2.58
2	99.8 (179.6)	6.96 (1009.4)	0.065 (0.144)	0.0688 (0.1517)	0.027 (0.06)	0.0267 (0.0589)	2.58
3	96.6 (173.8)	6.82 (989.3)	0.065 (0.144)	0.0697 (0.1536)	0.027 (0.06)	0.0268 (0.0590)	2.60
4	97.7 (175.9)	9.92 (1438.5)	0.082 (0.18)	0.0853 (0.1881)	0.027 (0.06)	0.0268 (0.0590)	3.18
5	99.7 (179.5)	9.71 (1408.1)	0.082 (0.18)	0.0825 (0.1818)	0.027 (0.06)	0.0268 (0.0590)	3.08
6	101.4 (182.5)	9.81 (1422.7)	0.082 (0.18)	0.0829 (0.1828)	0.027 (0.06)	0.0268 (0.0590)	3.09
7	104.1 (187.4)	10.18 (1476.3)	0.082 (0.18)	0.0833 (0.1836)	0.027 (0.06)	0.0268 (0.0590)	3.11

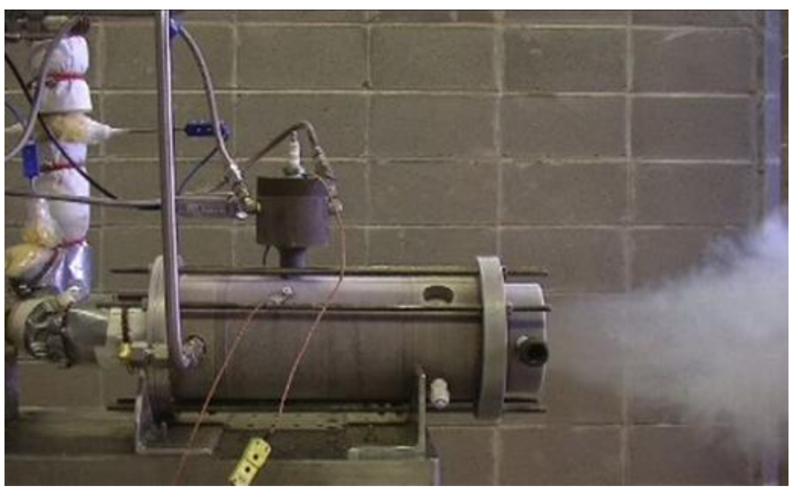


Figure 5.5 LN_2 cold flow firing operation

5.2 LOX – GCH_4 Engine Operation

Rocket engine operation in a high pressure combustion environment was successfully demonstrated using operational propellants. However, the initial LOX – GCH_4 test resulted in missed ignition. Facility dome loaders maintain the GOX and GH_2 ignition pressure. GOX ignition dome loader leaks inhibiting the GOX supply pressure were identified in these tests. To resolve this issue, the GOX ignition pressure was controlled using the regulator implemented into the GOX ignition system for slower pressurization as a result of the OCA facility changes discussed in Section 3.5.3. This configuration operates the GOX ignition line at a lower pressure reducing the reactivity of the oxygen gas with the flammable stainless steel flow line. The regulator added to mitigate an indentified GOX ignition system risk, presented a solution to the ignition problem and successfully contributed to the igniter and engine operation.

The initial firing sequence was configured for 0.5 second of main propellant flow. After verification of ignition the main propellant valve sequencing was adjusted to 1 second, and then 2 seconds. Figure 5.6 displays engine operation with visible plume for a 0.5 second engine operation test. Figure 5.7 captures the 2 second engine operation. The LOX and GCH_4 valve start times were adjusted to open together for this test that achieved sustained high pressure combustion. The chamber pressure trace data for midpoint and injector face pressure transducer measurements is displayed in Figure 5.8. The combustion chamber exhibited an approximate steady state pressure of 1.507 MPa (218.5 psi) for the 2.7 – 3 second duration just prior to engine shutdown. Low frequency oscillations are apparent from the pressure data illustrated in Figure 5.8. The larger oscillations observed in the chamber pressure rise seem to decrease in amplitude as the

chamber pressure approaches steady state. The valve sequence utilized in the 0.5, 1, and 2 second test firings is presented in Appendix H.

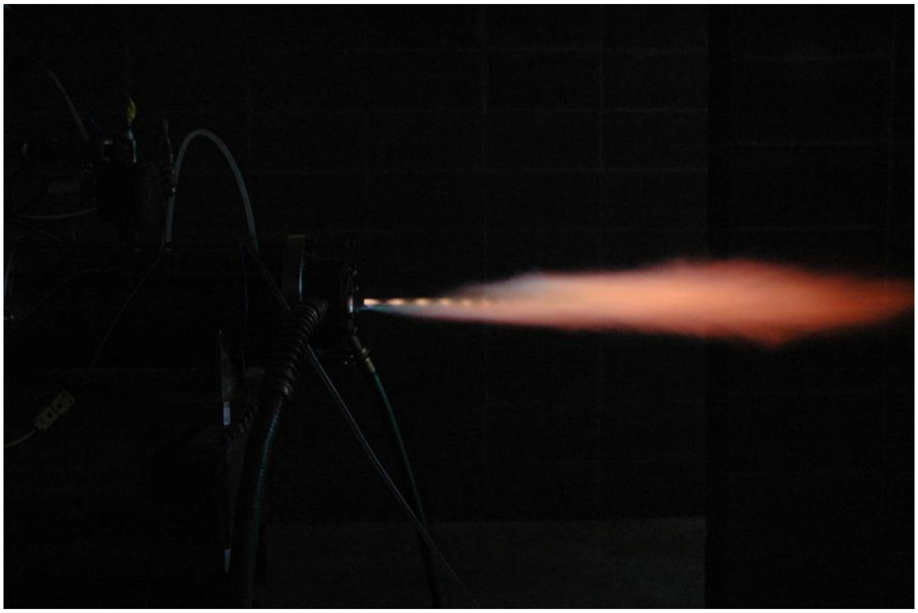


Figure 5.6 LOX – GCH_4 rocket engine operation (0.5 second)

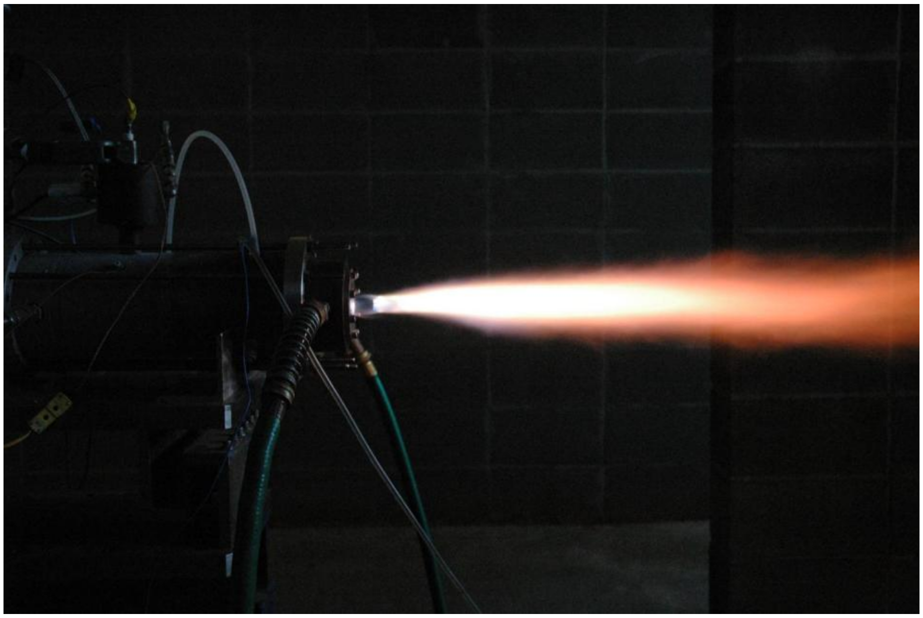


Figure 5.7 LOX – GCH_4 rocket engine operation (2 second)

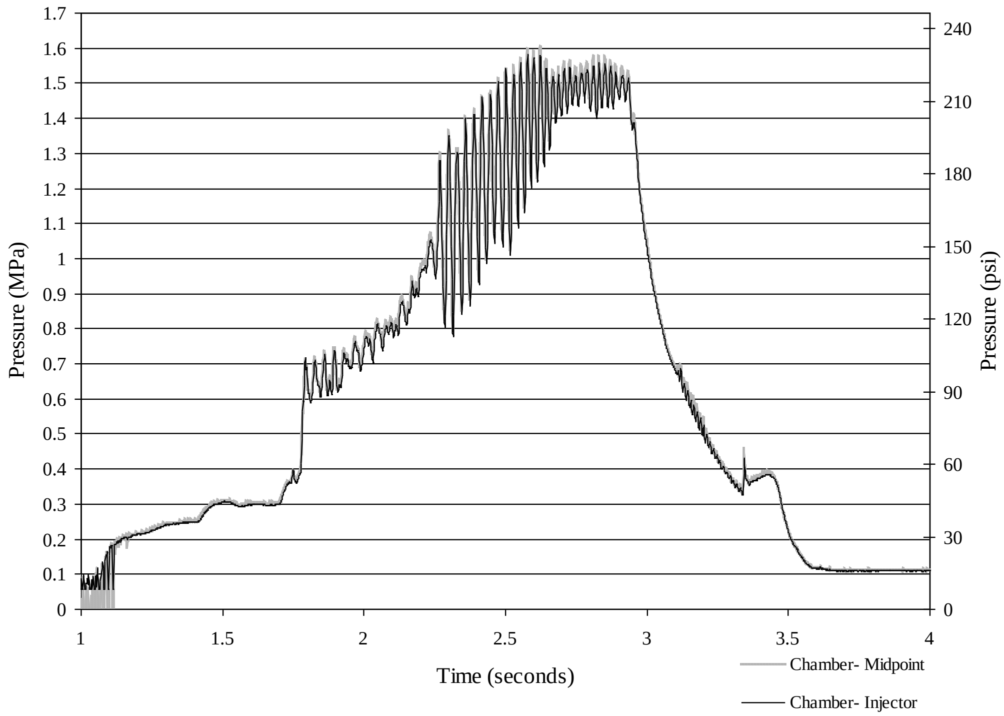


Figure 5.8 Chamber pressure – LOX – GCH_4 rocket engine operation (2 second)

5.3 Injector Performance

A 0.3 second time interval defined the "steady state" during the 2 second sustained high pressure combustion LOX – GCH_4 engine operation was used to evaluate injector performance. Each measurement was the average taken from the 2.7 –3.0 second time interval illustrated in Figure 5.8. In this portion of the test the chamber pressure was steady. The experimental measurements are presented in Table 5.3. Using these measurements and the methodology discussed in Section 4.3, C^* efficiency was determined. The LOX injector pressure (P_{INJ}) and temperature (T_{INJ}) measurements confirm liquid phase oxygen flow through the injector. Table 5.4 shows the measured propellant mass flow and velocity, and LOX injection ΔP. Table 5.5 presents the measured versus theoretical C^* and efficiency.

Table 5.3 C^* DRE LOX – GCH_4 engine operation measured variables

Definition	Symbol	Measured Values	Units
Chamber Pressure	P_C	1.507 (218.5)	*MPa (psi)*
GCH_4 Orifice Pressure	P_F	8.629 (1251.6)	*MPa (psi)*
GCH_4 Orifice Temperature	T_F	301.5 (542.7)	*K (R)*
LOX Orifice Pressure	P_{LOX}	6.272 (909.7)	*MPa (psi)*
LOX Orifice Temperature	T_{LOX}	117.5 (211.5)	*K (R)*
LOX Vapor Pressure	$P_{v_{LOX}}$	0.882 (127.9)	*MPa (psi)*
LOX Density	ρ_{LOX}	1014.3 (63.32)	kg/m^3 (lb/ft^3)
LOX Injector Pressure	P_{INJ}	1.918 (278.2)	*MPa (psi)*
LOX Injector Temperature	T_{INJ}	120.5 (216.9)	*K (R)*

Table 5.4 Measured injection characteristics

$\dot{m}_{LOX}$	$\dot{m}_{GCH_4}$	OF	V_{LOX}	V_{GCH_4}	V_{GCH_4}/V_{LOX}	ΔP_{LOX}
kg/s (lbm/s)		2.83	*m/s (ft/s)*		1.191	*MPa (psi)*
0.0756 (0.167)	0.0268 (0.0581)		25.82 (84.71)	30.75 (100.87)		0.412 (59.7)

Table 5.5 C* Efficiency

C^* Experimental	C^* Theoretical	η_{C^*}
m/s (ft/s)		80%
1488.6 (4883.8)	1864.2 (6116)	

A detailed uncertainty analysis was performed to estimate the associated C^* measurement uncertainty. In this process, the associated systematic and random errors as well as the corresponding uncertainties for each measured variable are considered separately. From the 0.3 second averaged LOX – GCH_4 measurement data, a useful random standard uncertainty (s_{C^*}) estimate can not be quantified since that 0.3 second period effectively defines a single data point. Repeat testing at similar conditions is the proper way to capture the random portion of the uncertainty. The random standard

uncertainty is a necessary component to estimate the total uncertainty. Information is provided to determine the combined standard uncertainty and an expanded uncertainty at a 95 % confidence level when a random standard uncertainty estimate can be attained from multiple tests in the described C^* experimental configuration. The systematic standard uncertainty was estimated using the Taylor series and Monte Carlo methods.

In the C^* DRE, LOX vapor pressure and density are taken from NIST data using the T_{LOX} and P_{LOX} measurements. More comprehensive estimates of the LOX vapor pressure ($b_{P_{V\,LOX}}$) and LOX density ($b_{\rho_{LOX}}$) systematic standard uncertainties were evaluated. These more inclusive estimations include the NIST data, temperature and pressure measurement uncertainties. The $b_{P_{V\,LOX}}$ estimate is shown in Equation 5.1 and the $b_{\rho_{LOX}}$ in Equation 5.2. The partial derivatives were taken from the slopes of the NIST data surrounding the measured data point. This provided a variation in $P_{v_{LOX}}$ and ρ_{LOX} due to temperature and pressure. Table 5.6 contains the systematic standard uncertainty estimates for all variables requisite for the C^* measurement.

$$b_{P_{V\,LOX}} = \sqrt{b_{P_{V\,NIST}}^{\;2} + \left(\frac{\partial P_{v_{LOX}}}{\partial T_{LOX}}\right)^2 b_{T_{LOX}}^{\;2}} \qquad (5.1)$$

$$b_{\rho_{LOX}} = \sqrt{b_{\rho_{LOX}\,NIST}^{\;2} + \left(\frac{\partial \rho_{LOX}}{\partial T_{LOX}}\right)^2 b_{T_{LOX}}^{\;2} + \left(\frac{\partial \rho_{LOX}}{\partial P_{LOX}}\right)^2 b_{P_{LOX}}^{\;2}} \qquad (5.2)$$

Table 5.6 C^* DRE variables systematic uncertainty estimates

Definition	Symbol	Systematic Standard Uncertainty Estimate	Units
Chamber Pressure	b_{Pc}	0.021 (3.0)	*MPa (psi)*
Nozzle Diameter	b_{D_T}	0.0254 (0.001)	*cm (in)*
GCH_4 Orifice Discharge	b_{C_G}	0.015	-
GCH_4 Orifice Pressure	b_{P_F}	0.021 (3.0)	*MPa (psi)*
GCH_4 Orifice Diameter	b_{D_F}	0.0254 (0.001)	*cm (in)*
GCH_4 Orifice Temperature	b_{T_F}	2.5 (4.5)	*K (R)*
LOX Orifice Discharge	b_{C_D}	0.015	-
LOX Orifice Diameter	$b_{D_{LOX}}$	0.0254 (0.001)	*cm (in)*
LOX Orifice Pressure	$b_{P_{LOX}}$	0.021 (3.0)	*MPa (psi)*
LOX Orifice Temperature	$b_{T_{LOX}}$	2 (3.6)	*K (R)*
LOX Vapor Pressure	$b_{P_{V_{LOX}}}$	0.11 (16.01)	*MPa (psi)*
LOX Density	$b_{\rho_{LOX}}$	11.62 (0.725)	*kg/m³ (lb/ft³)*

The Taylor series method was directly applied to the C^* DRE. In Chapter 4, Equation 4.5 reflects the DRE in a more detailed manner; while, Equation 5.3 below illustrates the resultant C^* in a functional representation. Each illustrates the parameters that influence C^*.

$$C^* = C^*(P_C, D_T, C_G, P_F, D_F, T_F, C_D, D_{LOX}, P_{LOX}, \rho_{LOX}, Pv_{LOX})) \tag{5.3}$$

Equation 5.4 represents the overall systematic standard uncertainty propagation (b_{C^*}) concerning the situation in which the three pressure transducers (P_C, P_F, P_{LOX}) were not calibrated to the same standard. Equation 5.5 corresponds to the b_{C^*} for the pressure transducers calibrated to the same standard. Correlated systematic error terms are shown in Equation 5.5 indicating a correlation effect concerning a pair of variables that share an elemental error source.

$$b_{C^*}{}^2 = \left(\frac{\partial C^*}{\partial P_C}\right)^2 b_{Pc}{}^2 + \left(\frac{\partial C^*}{\partial D_T}\right)^2 b_{D_T}{}^2 + \left(\frac{\partial C^*}{\partial C_G}\right)^2 b_{C_G}{}^2 + \left(\frac{\partial C^*}{\partial P_F}\right)^2 b_{P_F}{}^2$$
$$+ \left(\frac{\partial C^*}{\partial D_F}\right)^2 b_{D_F}{}^2 + \left(\frac{\partial C^*}{\partial T_F}\right)^2 b_{T_F}{}^2 + \left(\frac{\partial C^*}{\partial C_D}\right)^2 b_{C_D}{}^2 + \left(\frac{\partial C^*}{\partial D_{LOX}}\right)^2 b_{D_{LOX}}{}^2 \tag{5.4}$$
$$+ \left(\frac{\partial C^*}{\partial P_{LOX}}\right)^2 b_{P_{LOX}}{}^2 + \left(\frac{\partial C^*}{\partial \rho_{LOX}}\right)^2 b_{\rho_{LOX}}{}^2 + \left(\frac{\partial C^*}{\partial P\nu_{LOX}}\right)^2 b_{P\nu_{LOX}}{}^2$$

$$b_{C^*}{}^2 = \left(\frac{\partial C^*}{\partial P_C}\right)^2 b_{Pc}{}^2 + \left(\frac{\partial C^*}{\partial D_T}\right)^2 b_{D_T}{}^2 + \left(\frac{\partial C^*}{\partial C_G}\right)^2 b_{C_G}{}^2 + \left(\frac{\partial C^*}{\partial P_F}\right)^2 b_{P_F}{}^2$$
$$+ \left(\frac{\partial C^*}{\partial D_F}\right)^2 b_{D_F}{}^2 + \left(\frac{\partial C^*}{\partial T_F}\right)^2 b_{T_F}{}^2 + \left(\frac{\partial C^*}{\partial C_D}\right)^2 b_{C_D}{}^2 + \left(\frac{\partial C^*}{\partial D_{LOX}}\right)^2 b_{D_{LOX}}{}^2 \tag{5.5}$$
$$+ \left(\frac{\partial C^*}{\partial P_{LOX}}\right)^2 b_{P_{LOX}}{}^2 + \left(\frac{\partial C^*}{\partial \rho_{LOX}}\right)^2 b_{\rho_{LOX}}{}^2 + \left(\frac{\partial C^*}{\partial P\nu_{LOX}}\right)^2 b_{P\nu_{LOX}}{}^2$$
$$+ 2\left(\frac{\partial C^*}{\partial P_C}\right)\left(\frac{\partial C^*}{\partial P_F}\right) b_{P_C P_F} + 2\left(\frac{\partial C^*}{\partial P_F}\right)\left(\frac{\partial C^*}{\partial P_{LOX}}\right) b_{P_F P_{LOX}} + 2\left(\frac{\partial C^*}{\partial P_{LOX}}\right)\left(\frac{\partial C^*}{\partial P_C}\right) b_{P_{LOX} P_C}$$

Covariance factors were employed in correlated systematic error terms of the Taylor series propagation equation. The systematic standard uncertainty concerning the pressure measurements (P_C, P_F, P_{LOX}) must include the pressure transducer calibration standard (b_{Std}), as well as the installation ($b_{install}$). The installation systematic uncertainty was considered small in comparison to the standard and was not included. Equation 5.6 represents the covariance factor utilized in the situation in which the pressure transducers were calibrated to the same standard. In this case and as shown in Equation 5.5, there are three correlated systematic error terms concerning the shared elemental b_{Std} between the three pressure measurements P_C, P_F, and P_{LOX}. Due to lack of information concerning the systematic uncertainty of the pressure transducer calibration standard, b_{Std} uncertainty estimate was taken as the same value for the b_{Pc}, b_{P_F}, and $b_{P_{LOX}}$.

$$b_{P_C P_F} = b_{Std} b_{Std} \tag{5.6}$$

Experimental measured test data from the 2 second LOX – GCH_4 engine operation as well as the individual parameter systematic standard uncertainty estimates are supplied in Tables 5.3 and 5.6. Partial derivatives of the C^* DRE equation are determined with respect to $P_C, D_T, C_G, P_F, D_F, T_{F,} C_D, D_{LOX}, P_{LOX,} \rho_{LOX}$, and Pv_{LOX}. The detailed systematic standard uncertainty Taylor series analysis is supplied in Appendix I.

Two Monte Carlo simulations are conducted to estimate the systematic standard uncertainty in C^*. In both calibration situations presented, the instrumentation engaged in measuring $D_T, C_G, D_F, T_{F,} C_D, D_{LOX\,,} \rho_{LOX}$ and Pv_{LOX} does not change. In each case, 10,000 simulated errors were generated utilizing a Gaussian error distribution with the standard deviation equal to the $b_{D_T}, b_{C_G}, b_{D_F}, b_{T_F}, b_{C_D}, b_{D_{LOX}}, b_{T_{LOX}}, b_{P_{V_{LOX}}}, b_{\rho_{LOX}}$,and $b_{T_{LOX}}$. The generated error is then added to the experimental measured values $D_T, C_G, D_F, T_{F,} C_D, D_{LOX\,,} \rho_{LOX}$ and Pv_{LOX} yielding a new error influenced variable.

In the situation regarding the pressure transducers not calibrated to the same standard, each temperature measurement is influenced by an individual calibration standard error relevant to the individual temperature measurement (P_C, P_F, P_{LOX}). The calibrated to the same standard situation corresponds to all pressure measurement transducers (P_C, P_F, P_{LOX}) influenced by a single calibration standard error. To properly model each influence, 10,000 simulated errors are generated representing the standard calibration error. One error distribution is produced for each individual pressure transducers, or a single error distribution is sampled for all pressure transducers. Each error uses a Gaussian distribution with a standard deviation b_{Std}. The generated standard

calibration errors are added to measured P_C, P_F, and P_{LOX} for the calibration situations, yielding a new error influenced variable.

The C^* DRE equation is then solved using all contributions from the systematic error influenced parameters. The $\overline{C}^*$ and S_{C^*} is calculated from the new sample population, and the systematic standard uncertainty is estimated as $b_{C^*} \approx S_{C^*}$. A histogram is configured to cover a range of $\overline{C}^* \pm 3S_{C^*}$ to properly scale the presentation. All 10,000 values are normalized into a histogram and plotted in contrast to a Gaussian distribution. Figures I.1 and I.2 illustrate the Monte Carlo simulation distributions.

Table 5.7 displays the detailed uncertainty results concerning the two calibration situations. Inspection of the table reflects only slight differences in the uncertainties calculated through the Taylor series propagation and Monte Carlo methods. This insight illustrates that there is not a considerable effect associated with the correlated terms in Equation 5.4, or 5.5 that represent the two pressure transducer calibration situations. In Taylor series and Monte Carlo systematic standard uncertainty analyses, the correlated effects associated with calibrating the pressure transducers to the same standard lowers the systematic standard uncertainty. This is a small reduction and each method shows b_{C^*} is estimated at 60 m/s (197 ft/s).

Table 5.7 Detailed Uncertainty Results

	Taylor Series Method		**Monte Carlo Method**	
Resultant Uncertainties	**Pressure Transducers Not Calibrated to Same Standard**	**Pressure Transducers Calibrated to Same Standard**	**Pressure Transducers Not Calibrated to Same Standard**	**Pressure Transducers Calibrated to Same Standard**
	m/s (ft/s)			
Systematic Standard Uncertainty b_{C^*}	60.8 (199.5)	59.8 (196.2)	60.3 (196.5)	60.0 (197.5)
$\frac{b_{C^*}}{C^*}$	4.08 %	4.01 %	4.05%	4.03 %

The combined standard uncertainty can be estimated when repeat testing has been performed and a measure of s_{C^*} established. The combined standard uncertainty is determined by Equation 5.7, while the expanded standard uncertainty at the associated 95% confidence level is shown in Equation 5.8.

$$u_{C^*} = \sqrt{{b_{C^*}}^2 + {s_{C^*}}^2} \tag{5.7}$$

$$U_{C^*} = 2\left(\sqrt{{b_{C^*}}^2 + {s_{C^*}}^2}\right) \tag{5.8}$$

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The LOX developmental system is a new operational and successfully demonstrated capability for the Propulsion Research Center. For this reason an extensive review was completed to document the oxygen compatibility and configuration hazards of the rocket engine oxygen propellant test facilities. This documentation procedure supplied an educational experience enabling more thorough realization of the ignition mechanisms prevalent to fires in oxygen systems. Despite best efforts in the design and fabrication stages of the LOX facility development, the review process identified several areas where the system could be made more fault tolerant to oxygen hazard unpredictability. The risks significant to these findings involved corrective actions which decreased the probability of ignition without reducing system functionality.

The oxygen system review reduced reliance on procedures to ensure safe system operation. The system specific design changes identified in this document were implemented to increase the overall system safety and document these facility design decisions. Most notable, the LOX propellant and GOX ignition system cleanliness level consistent with oxygen system design and operation was established. This provides long term traceability to these operational systems. Training and education presented as the

most prominent defense. The practice specifically undertaken reduced the chance of operator induced errors relevant to off nominal operation resulting in increased fault tolerance and reduced severity of reaction effects.

The LOX propellant feed facility delivered liquid phase oxygen successfully to the baseline injector supporting LOX – GCH_4 rocket engine operation. The 2 second high pressure combustion experiment demonstrated safe and successful LOX – GCH_4 engine operation. The measured *OF* and GCH_4/LOX injection velocity were 95% and 77% of the designed conditions measured at 2.85 and 1.191 respectively. This effect is explained by the measured LOX orifice temperature of 117.5 K (211.5 R). This temperature is higher than the injector inlet propellant conditions utilized in the design, creating variations in the LOX density and vapor pressure properties. The LOX injection pressure drop was measured slightly higher than the design at 0.412 MPa (59.7 psi). The baseline injector performance was evaluated at a single engine operating condition resulting in a characteristic velocity efficiency of 80%. Combustion studies at Purdue University and Penn State University have noted comparable or higher efficiencies for similar injectors. For this experiment, procedures were provided to estimate the C^* data reduction equation experimental uncertainty after repeat testing to effectively establish the random standard uncertainty component. The systematic standard uncertainty was established at 4%.

6.2 Recommendations

The LN_2 jacketed main propellant flow line presented numerous difficulties in the conducted testing. This situation corresponded to a significant cost to testing. For future operation it is suggested that the upfront cost to LOX main propellant line insulation be

investigated. The jacketed line conditioning provided LOX within the temperature specifications listed in Table 4.2 but by only by 4 K (6 R). This was acceptable given the variation in the LOX propellant temperature provided in the MISER injector design. However, for lower injection temperatures this could present problems, and require improved insulation to achieve the desired propellant conditioning.

The preliminary investigation of the MISER injector in the swirl coaxial configuration evaluated combustion efficiency for single engine operational combustion chamber arrangement. Losses due to heat or momentum were not included in the calculation of the measured C^*. These effects were not essential to the findings of this research. Testing at different chamber lengths can assist in the design and development of combustion chambers. This procedure facilitates the realization of peak combustion efficiency for a given injector element arrangement.

The LOX facility is now demonstrated capability for the Propulsion Research Center's rocket engine test facility. The final recommendation is to test the MISER injector using LOX – LCH_4 operational propellants. As noted earlier, the MISER injector can be configured in multiple injection schemes. The variability of injection arrangement employing operational propellants offers a wealth of experimental research to investigate injector design through high pressure injector performance rocket engine testing.

APPENDICES

APPENDIX A

Oxygen Compatibility Assessment

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The following report represents an oxygen compatibility assessment (OCA) of the existing hardware for the GOX ignition system and the LOX system for the Propulsion Research Center rocket test stand. All components in each system can be located in the LOX-GCH_4 facility diagram located in Section A.2 of this document. The flammability of the component and the associated possible ignition sources are examined against materials, configuration, and operation.

A.1 UAH Propulsion Research Center Rocket Test Facility

UAHuntsville Propulsion Research Center has a hot fire rocket test facility for small scale liquid, gaseous, and solid rocket testing. Figure A.1 shows a photograph of the test facility. The facility is located on the UAHuntsville campus behind the Johnson Research Center. The test facility consists of two test cells and an instrumentation room. Experiments in the test facility are remotely operated from a control room in the adjacent JRC. The facility is enclosed by a fence with controlled gated access. Security cameras are located around the facility to monitor activity in the test cells and in the surrounding area. Rocket engines are tested on a single axis thrust stand capable of supporting thrust levels up to 2.24 kN (500 lbf). The PRC has successfully tested hybrids, solids, liquids, gels and gaseous rocket motors on this stand. Data acquisition equipment is located in an adjacent instrumentation cell. Existing DAQ capability provides for thermocouple and voltage measurements at high speed (1.25Msamples/sec) or high resolution (16 bit) with programmable low pass filter. The instrumentation is expandable as needed for more measurement requirements. The test cell is prewired for instrumentation connections which feed through the instrumentation cell into the JRC control room.

Figure A.1 PRC propulsion test stand

The test stand and the primary engine used for liquid and gaseous testing are shown in Figure A.2. The engine is a modular heat sink design for a single injector element. The engine has water cooling for the nozzle segment but relies on the copper segment to dissipate heat from the combustion chamber in short duration testing (typically < 5 sec.). The combustor length can be varied by adding or removing engine segments. Various nozzles can be used in the engine to change the chamber pressure/flow rate/ expansion properties. General facility specifications are provided below.

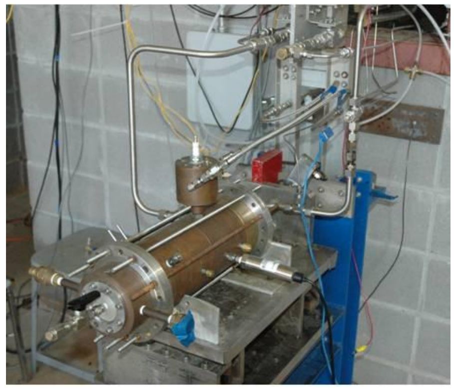


Figure A.2 PRC rocket test stand

TEST STAND

Gaseous and liquid propellant delivery systems
Single axis thrust measurement: max thrust = 2.24 kN (500 lbs)
Prewired instrumentation inputs
- 8 Type K thermocouple channels
- 8 Type T thermocouple channels
- 12 Four pin powered channels
- 8 Unpowered BNC channels

A/D: All voltages can be recorded on either
- High Speed: 12 Bit 1.2Msamples/sec
- Low Speed: 16 Bit 333 ksamples/s with programmable low pass filter
- Easily upgradable for more capability

Remote operation via an Omron programmable logic controller
Video surveillance of test cells and surrounding area

STANDARD ENGINE

- Single injector element configuration
- Heat sink chamber design with a water cooled nozzle
- Interchangeable copper rings to modify chamber length
- Windowed segments for optical access to chamber
- Chamber O.D. = 0.127 m (5 inch), I.D. = 0.054m (2.125 inch).
- Spark driven torch igniter (Hydrogen/GOX)
- Max chamber pressure 6.9 MPa (1000 psi)
- Modular nozzle segment (designed per task)

PROPELLANTS
Existing Capabilities

Gaseous Oxygen
K– Bottle Manifold
Sonic Venturi Mass Flow Regulation
Mass Flow up to 0.91 kg/s (2 lbm/s)

Gaseous Methane
K – Bottle Manifold
Sonic Venturi Mass Flow Regulation
Mass Flow up to 0.91 kg/s (2 lbm/s)

Planned Capabilities

Liquid Oxygen
Maximum mass flow rate 1.4 kg/s (3 lbm/s)
Maximum system pressure 13.8 MPa (2000 psi)
Main feed tank: 87.1 L (23 gallon) capacity
System initialization (Summer 2010)

Liquid Methane
Maximum mass flow rate 1.4 kg/s (3 lbm/s)
Maximum system pressure 13.8 MPa (2000 psi)
Main feed tank: 56.8 L (15 gallon) capacity
System initialization (Summer 2010)

A.2 LOX - GCH$_4$ Facility

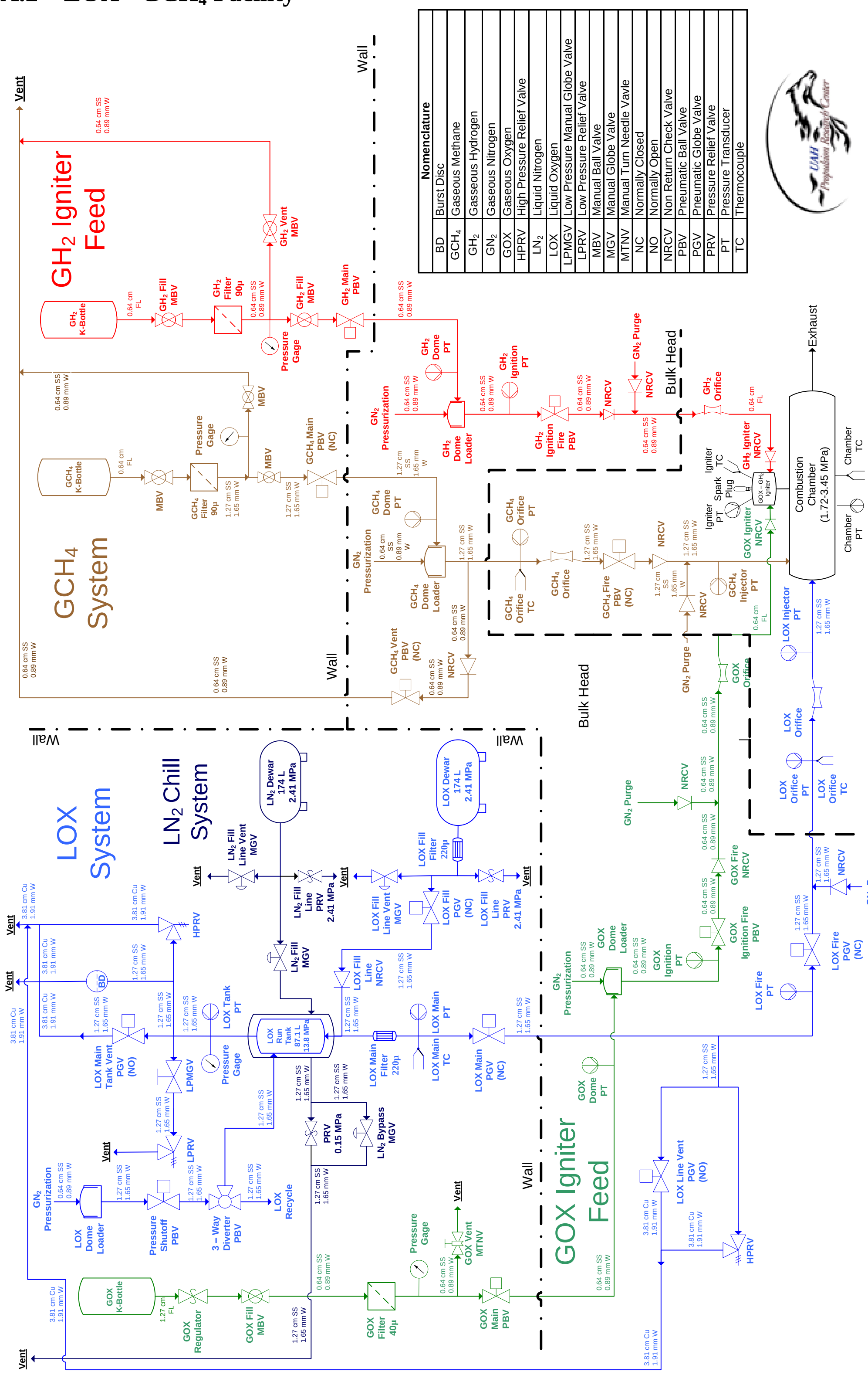


Figure A.3 LOX – GCH$_4$ facility

A.3 System Cleanliness

The GOX ignition and LOX main propellant system were sampled to establish a baseline of cleanliness. A particulate and non volatile residue (NVR) analysis in accordance to SN-C-0005\Level 300A was performed on multiple sections of each system. This analysis was conducted by the chemistry team at NASA Marshall Space Flight Center (MSFC) materials test branch. Stainless steel flow lines from the LOX and GOX systems were removed from low points or sumps which inherently would collect the most residues and represent the most severe concentrations. Two sections were removed from both the GOX and LOX systems. This operation allowed for a starting point to confirm the unknown associated with the LOX and GOX system cleanliness. This analysis was performed twice. The first on August 6, 2010, presented acceptable for the sampled GOX flow lines. It however, identified below standard levels requisite for oxygen system operation from the sampled LOX flow lines. Large green particulate too numerous to count was observed in on section of the LOX flow lines. This was a result from a Teflon coated deteriorating seal in the top of the LOX run tank. This seal was replaced and the LOX system was re-cleaned. The identical LOX flow lines were sampled again on September 1, 2010 to verify oxygen system cleanliness. The official reports representative of the analyses are located in Section A.6.

A.4 Gaseous Oxygen Ignition System

The PRC uses a gaseous hydrogen and gaseous oxygen spark driven igniter to initiate combustion in the rocket. The gaseous oxygen ignition system uses a single 17.24 MPa (2500 psi) K-bottle for the oxygen supply. The primary components of the GOX ignition system are a sintered metal filter, manual isolation ball valve, a dome loaded pressure regulator, and remotely actuated main and fire valves, non return check valves, and a flow control orifice.

A.4.1 GOX Ignition Regulator

The GOX ignition regulator is located immediately downstream of the GOX ignition K-bottle. The primary function is to control rapid pressurization inherent to gas cylinder valves and closely coupled components.

APPLICATION & USES
SR 4 Series
- High Pressure.
- Ideally suited for pressure vessel testing.
- Dead-end testing.
- Delivery pressures up to 4500 PSIG on some models.
- May be panel mounted.
- Single Stage design.

Dimensions: 6" W x 6-1/2" H x 6-1/4" D
(15 cm x 16 cm x 15.5 cm)
Weight: .... 4 lb. (1.8 kg)

OTHER DATA
- All SR 4 series regulators have 1/4" swaged lock type stainless steel outlet fittings.

Panel Mounting Details
- All SR 4 series regulator models may be panel mounted. (1-3/4" hole required in panel for mounting) For a flush panel mount installation order one (1) panel mount nut 1409-0093. For an adjustable panel mount installation order two (2) panel mount nuts 1409-0093.

DESIGN/CONSTRUCTION
- Piston type actuation
- Machined body and cap
- 2-1/2" gauges brass
- Cartridge type seat assembly with PCTFE seat
- Delrin® cap bushing for smooth adjustments
- External adjustable relief valves on F and G range models
- Hydrogen models have ventable relief valves *J Series Does Not
- Sintered inlet filter
- CGA 680, 677 &347: Inlet Port 5/8 20 UNF - all others 1/4 NPT (F)

SPECIFICATIONS PERFORMANCE
MAXIMUM INLET
7500 PSIG with CGA 677
6000 PSIG without Inlet Fitting
5500 PSIG with CGA 701, 680, 347
4000 PSIG with CGA 577
3000 PSIG with CGA 540, 580, 346, 350
Adapter: 5/8 20 M UNF x 1/4 NPTF 0912-0094

NOTE: Regulators will deliver at least the stated upper range at no flow and in some cases may exceed the stated upper range.

MATERIALS
Body................................Machined Brass
Piston..Brass
Housing Cap ....Machined Brass
Inlet Filter ....Bronze

Figure A.4 GOX ignition regulator information

Model No.	Delivery Range	CGA Inlet Connection
SR 4	F	580

Gas Service	Model No.	Delivery Range (PSIG)	Part No.
Oxygen	SR 4F-540 SR 4G-540 SR 4J-540	50-750 100-1500 200-3000	0781-1405 0781-1425 0781-1445

Figure A.5 GOX ignition regulator nomenclature

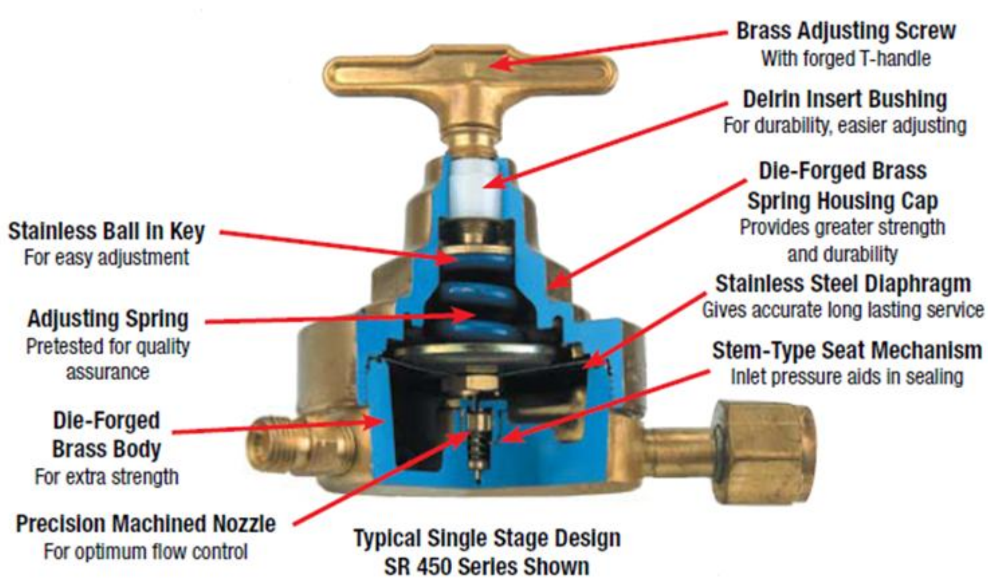


Figure A.6 GOX ignition regulator cross section

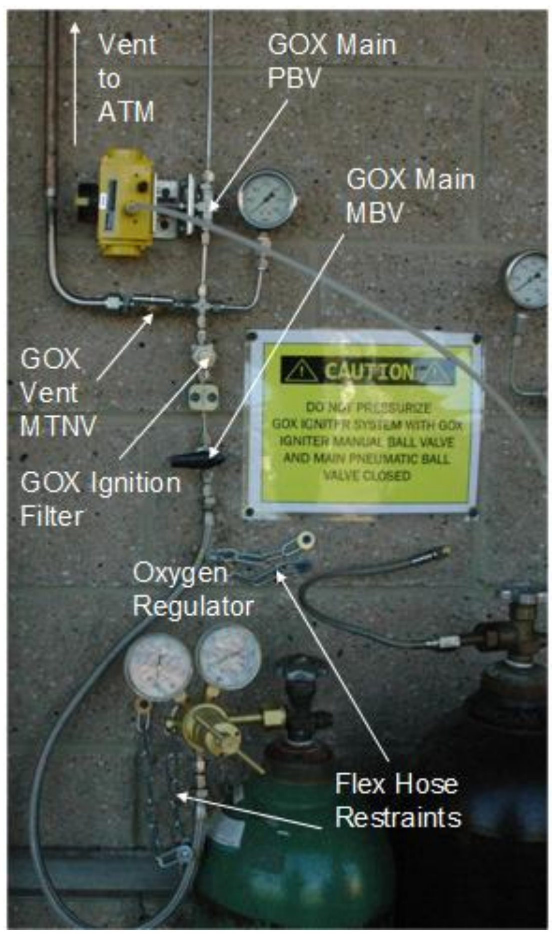


Figure A.7 GOX ignition fill regulator configuration on facility

Table A.1 GOX ignition regulator OCA

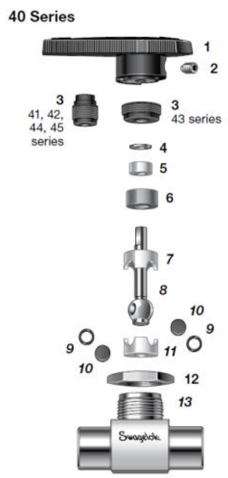
Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Ignition Regulator	Brass Bodied High Pressure Welding Regulator	Victor	SR4J-540 0781-1445	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	Brass			No[3]									
Piston	Brass			No									
Housing Cap	Brass			No									
Inlet Filter	Bronze			No[4]									
Nozzle	Brass	Ambient[1]	2500[2]	No	1[7]	3[8]	0[9]	0[10]	0[11]	0[12]	0[13]	No[14]	B[15]
Stem	Brass			No									
Stem Spring	Stainless Steel			Yes[5]									
Seat	PCTFE			Yes[6]									
Diaphragm	Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure
[2] Worst case operating pressure from max k-bottle pressure
[3] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[4] Bronze is not considered flammable at the worst case operating conditions stated above Bronze does not burn until experiencing pressures > 10,000 psi. (Manual 36, Table 3.1, pg 18)
[5] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[6] PCTFE is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[7] Particle Impact is remotely possible due to stainless steel diaphragm and spring material in the regulator; however the utility of the brass stem and body minimizes the characteristic element of a flammable target reducing the possible ignition source. Transitional gas velocities will be high upon opening gas cylinder. However, K-bottle in upright position has low likelihood of particulate emission. The CGA-540 connection contains a bronze filter element to diminish particulate entering the regulator.
[6] All characteristic element of heat of compression are present; this ignition mechanism is possible due the presence of PCTFE exposed in the flow path and possible dead end when the regulator is closed. The significant pressure ratio achieves a final temperature of 1850 °F if the regulator is closed during gas cylinder valve opening to rapidly pressurize the regulator. This final temperature is well above the AIT of PCTFE (730°F). Even with this ignition source, due to the thick walled brass body the combustion cannot propagate. The closely coupled downstream PTFE stainless steel flex hose is flammable and can burn violently. The regulator must be procedurally closed upon gas cylinder valve pressurization.
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] Mechanical impact is not possible without a nonmetal. This component experiences no impacts.
[9] The component is not electrically powered.
[10] Flow friction is possible in the situation where the GOX ignition regulator was leaking past the PTCFE seat. Even with this ignition source, due to the thick walled brass body the combustion cannot propagate.
[11] Chatter does not occur in this component.
[12] A kindling chain does not exist. If the stainless steel diaphragm or spring ignites by particle impact or heat of compression the burn resistant brass body serves as a fire break to extinguish combustion.
[13] Due to the proximity to personnel when the GOX ignition regulator is opened (hand operated), there is a moderate risk of personnel injury should the regulator ignite. Even with ignition of the flammable regulator components the brass body serves as a fire break. The controlled and slower pressurization of the regulator also helps to mitigate the risk. The reaction effect is marginal. If the regulator is not closed and fully open when gas cylinder valve is opened the reaction effect is higher. If this situation presents when the GOX main PBV or GOX main MBV are closed the reaction effect is catastrophic.

A.4.2 GOX Fill Manual Ball Valve

A manual ball valve is located downstream of the K-bottle and GOX ignition regulator. The valve is used as an isolation valve for the GOX ignition supply. Procedurally the GOX ball valve is opened prior to opening the GOX K-bottle and regulator.



Component	Valve Body Materials: Stainless Steel	Brass	Alloy 400
	Material Grade/ASTM Specification		
1 Handle	Nylon with brass insert		
2 Set screw	S17400 SS/A564		
3 Packing bolt	Powdered metal 300 series SS or 316 SS/A276, A479	Brass CDA 360/B16	Alloy 400/B164
4 Upper gland	316 SS/A240	41, 42, 45 series: brass 260/B36; 43, 44 series: 316 SS/A240	Alloy 400/B127
5 Bushing	PTFE/D1710		
6 Lower gland	Powdered metal 300 series SS	Brass CDA 360/B16	Alloy 400/B164
7 *Upper packing*	*PTFE/D1710*		
8 *Ball stem*	*316 SS/A276*	*Brass CDA 360/B16*①	*Alloy 400/B164*
9 *Side rings* 10 *Side discs*	*Fluorocarbon-coated powdered metal 300 series SS/B783*	*Fluorocarbon-coated brass powdered metal*①	*Fluorocarbon-coated alloy 400 powdered metal*
11 *Lower packing*	*PTFE/D1710*		
12 Panel nut	Powdered metal 300 series SS/B783	Brass CDA 360/B16	Powdered metal 300 series SS/B783
13 *Body*②	*316 SS/ A276, A479*	*Brass CDA 360/B16*	*Alloy 400/B164*
Wetted lubricant	*41, 42, 43 series: silicone-based; 44, 45 series: silicone- and fluorinated-based*		
Nonwetted lubricant	Molybdenum disulfide with hydrocarbon binder coating		

Wetted components listed in *italics*.
① 4-way, 5-way, 6-way, and 7-way valves contain stainless steel stem, rings, and discs.
② Bodies with VCO end connections have fluorocarbon FKM O-rings.

Figure A.8 GOX fill MBV component materials

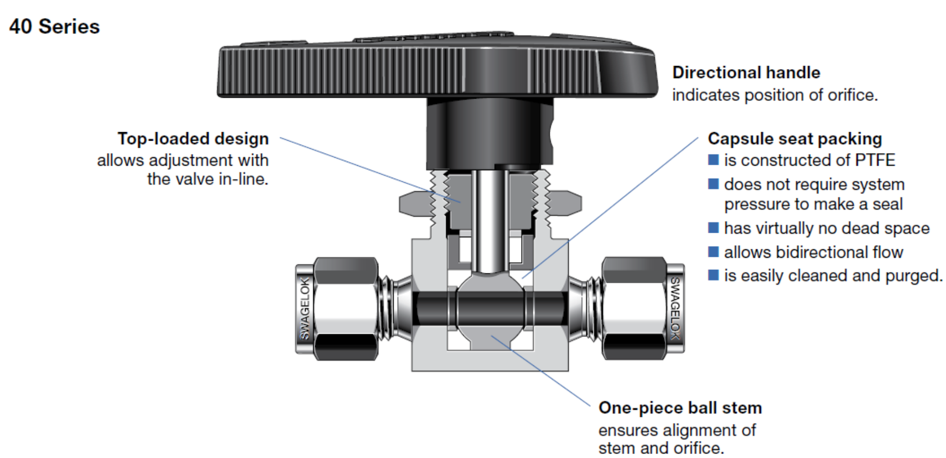


Figure A.9 GOX fill MBV cross section

Table A.2 GOX fill MBV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Fill MBV	Stainless Steel Ball Valve, ¾" Swagelok Port Connections	Swagelok	SS-43S4	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Handle	Nylon with brass insert	Ambient[1]	2300[2]	Yes[3]	1[9]	2[10]	0[11]	0[12]	0[13]	1[14]	0[15]	Yes[16]	C[17]
Set Screw	17-4 Stainless Steel			Yes[4]									
Packing Bolt	Powdered 316 Stainless Steel			Yes									
Upper Gland	316 Stainless Steel			Yes									
Bushing	PTFE			Yes[5]									
Lower Gland	Powdered 316 Stainless Steel			Yes									
Upper Packing	PTFE			Yes									
Ball Stem	316 Stainless Steel			Yes									
Side Rings	Fluorocarbon coated 300 series powdered Stainless Steel			Yes[6]									
Side Discs	Fluorocarbon coated 300 series powdered Stainless Steel			Yes									
Lower Packing	PTFE			Yes									
Panel Nut	Powdered 300 series Stainless Steel			Yes									
Body	316 Stainless Steel			Yes									
Wetted Lubricant	Silicone-based			Yes[7]									
Nonwetted Lubricant	Molybdenum disulfide with hydrocarbon binder coating			Yes[8]									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Nylon is flammable in 23 -28 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[4] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg19)
[5] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[6] Fluorocarbon film coating is considered flammable in 77% oxygen. (ASTM G63-99, Table X1.6, pg 22)
[7] Silicone grease must be considered flammable in 26% oxygen. (ASTM G63-99, Table X1.6, pg 22)
[8] Hydrocarbon's are flammable.
[9] Particle Impact is a remotely possible ignition source due to the rapid pressure transient even with the few impact points internal to valve. The controlled pressurization with the GOX ignition regulator, of this component mitigates high transitional flow velocities.
[10] All characteristic element of heat of compression are present; this ignition mechanism is possible due to rapid pressurization, the presence of PTFE exposed in the flow path and significant pressure ratio achieving a final temperature of 1850 °F. This final temperature is well above the AIT of PTFE (814°F). In the LOX_GCH4 Test SOP the heat of compression ignition mechanism is procedurally controlled by opening the GOX Main Valve and the GOX Fill MBV before opening the GOX k-bottle to slowly pressurizing the GOX Ignition line using the GOX ignition regulator.
[11] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the $1.5x10^6$ psi x ft/min requisite to ignite stainless steel (Manual 36, pg 23, Table 3.5)
[12] Mechanical impact cannot occur due to the hand operated stem.
[13] The component is not electrically powered.
[14] All characteristic elements of flow friction are present; however the configuration is unlikely to produce erosion, friction, and/or vibration.
[15] Chatter does not occur in this component.
[16] A kindling chain exists if the PTFE or valve body ignites by particle impact, compression heating or flow friction and propagates.
[17] The valve possesses flammable components, one possible ignition mechanism and one remotely possible, as well as kindling chain. The valve is hand operated increasing risk effects on personnel. The reaction effect is critical

A.4.3 GOX Ignition Filter

The GOX ignition filter is located immediately downstream of the GOX ignition MBV. The primary function is to filter out particulate entering the GOX ignition System. The filter element is a drop in sintered Nickel 200 cup with a 40 micron rating. There is an additional sintered bronze filter in the CGA 540 regulator to K-bottle connection.

Materials of Construction

Component	Filter Series	Filter Body Materials	
		Brass①	316 SS
		Material Grade/ASTM Specification	
Bonnet nut	TF	Brass/B16	316 SS/A479
Bonnet	*TF*	*Brass/B16*	*316 SS/A479*
Retainer screens (2)	*FW*	—	*316 SS*
Element	*FW*	—	*0.5 µm size—316L SS*
			2, 7, and 15 µm size—316 SS
	F, TF	*Sintered—316 SS*	
		Strainer—316 SS with silver solder	
Spring	*F, TF*	*302 SS*	
Gasket	*F, TF*	*Aluminum/B209*	*Silver-plated 316 SS/A240*
Body	*All*	*Brass/B16*	*316 SS/A479*
Retaining ring	TF	PH 15-7 Mo® SS	
Lubricant	*F*	*Silicone-based*	

Wetted components listed in *italics*.
① FW series filters not available in brass.

Figure A.10 GOX filter component materials

Pressure-Temperature Ratings

Ratings are based on standard materials of construction. Ratings for TF series filters with PCTFE gaskets are limited to 200°F and 3000 psig (93°C and 206 bar). See page 8.

Filter Series	FW, TF	2F, 4F	6F, 8F	F	TF
Material	316 SS			Brass	
Temperature, °F (°C)	Working Pressure, psig (bar)				
–20 (–28) to 100 (37)	6000 (413)	3000 (206)	2500 (172)	1000 (68.9)	2000 (137)
200 (93)	5160 (355)	2580 (177)	2150 (148)	780 (53.7)	1730 (119)
300 (148)	4660 (321)	2330 (160)	1940 (133)	680 (46.8)	1470 (101)
400 (204)	4280 (294)	2140 (147)	1780 (122)	—	—
500 (260)	3980 (274)	1990 (137)	1660 (114)	—	—
600 (315)	3760 (259)	1880 (129)	1560 (107)	—	—
650 (343)	3700 (254)	1845 (127)	1540 (106)	—	—
700 (371)	3600 (248)	1800 (124)	1500 (103)	—	—
750 (398)	3520 (242)	1760 (121)	1460 (100)	—	—
800 (426)	3460 (238)	1725 (118)	1440 (99.2)	—	—
850 (454)	3380 (232)	1690 (116)	1410 (97.1)	—	—
900 (482)	3280 (225)	1640 (112)	1360 (93.7)	—	—

Figure A.11 GOX filter pressure – temperature ratings

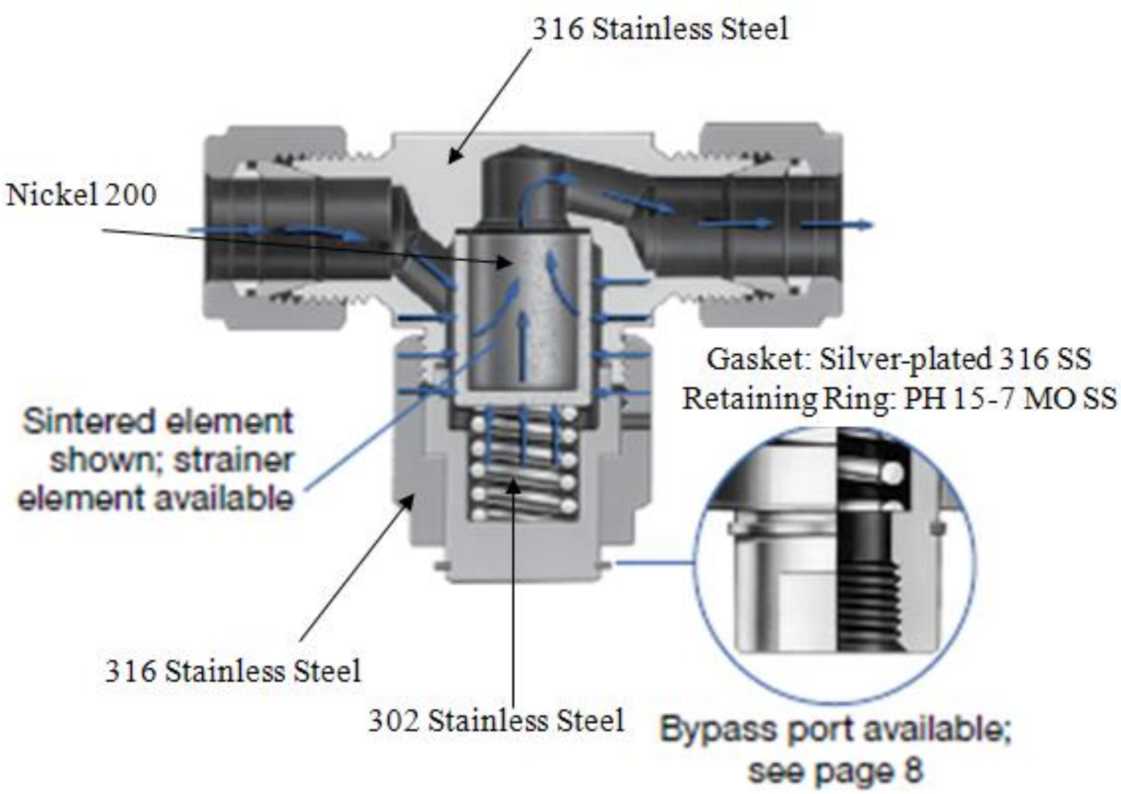


Figure A.12 GOX filter cross section

Table A.3 GOX filter OCA

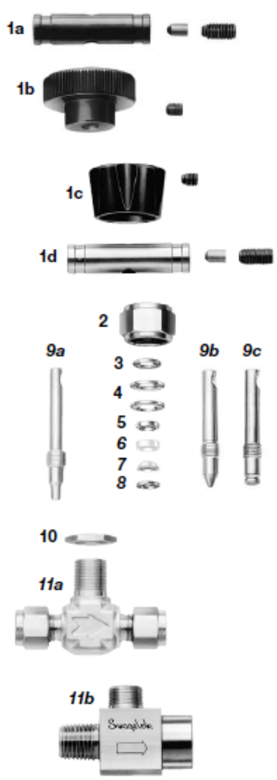
Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Filter	Nickel 200 Sintered Element Filter, ¼" Swagelok Port Connections	Swagelok, Applied Porous (Filter)	SS-4TF-90	TBD

Component	Material	Worse-Case Operating Condition		Material Flammable?	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)	Yes/No	Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/Chatter		
Body	Stainless Steel			Yes[3]									
Bonnet Nut	Stainless Steel			Yes									
Bonnet	Stainless Steel			Yes									
Element	Sintered Nickel 200 40 Micron	Ambient[1]	2,500[2]	No[4]	1[5]	0[6]	0[7]	0[8]	0[9]	0[10]	0[11]	Yes[12]	B[13]
Spring	Stainless Steel			Yes									
Gasket	Silver Plated Stainless Steel			Yes									
Port Seal	Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Sintered Nickel 200 filters are not flammable. Nickel 200 won't burn as a wire mesh at 10,000 psi, it certainly won't burn as a sintered element at 10,000 psi. (Manual 36, Table 3.2, pg 21)
[5] Particle Impact is remotely possible due to stainless steel body impact point, however the utility of the Nickel 200 sintered element removes the characteristic element of a flammable target reducing the possible ignition source. Transitional gas velocities will be high upon opening gas cylinder. However, K-bottle in upright position has low likelihood of particulate emission.
[6] Heat of compression is low probability due to missing the characteristic element of exposed dead-end at the filter.
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] Mechanical impact is not possible without a nonmetal. This component experiences no impacts.
[9] The component is not electrically powered.
[10] Flow friction is not considered to be possible without a nonmetal, Swagelok metal to metal port connection seals
[11] Chatter does not occur in this component.
[12] A kindling chain exists if the stainless steel body ignites by particle impact into the housing and propagates.
[13] Due proximity to personnel when the manual ball valves are opened (hand operated valve) and the possible particle impact ignition source, there is a moderate risk of personnel injury should the filter ignite. The reaction effect is marginal.

A.4.4 GOX Vent Multi-Turn Needle Valve

A vent branch is located between the GOX ignition manual ball valve and the GOX ignition pneumatic main valve. On shutdown, the fire valve is closed which traps GOX between the fire valve and the K-bottle. After the K-bottle is closed the manual vent valve is opened to discharge the gas trapped between the fire valve and the K-bottle. Then the GOX ignition regulator is closed.



Component	Series	Valve Body Materials — Material Grade/ASTM Specification: 316 SS	Brass	Steel	Alloy 400
1a Bar handle	18	Anodized aluminum 2024/B221 or A209			
Handle pin		Steel/A108			
Set screw		Nickel cadmium-plated steel			
1b Round handle	O and 1	Phenolic with brass insert			
Set screw		Nickel cadmium-plated steel			
1c Knob handle	20K	Anodized aluminum 7129/B221	—		
Set screw		Nickel cadmium-plated steel			
1d Bar handle	20V and 26	316 SS/A276	—		
Handle pin, set screw		S17400/A564			
2 Packing nut	All	316 SS/A276	Brass 360/ B16	12L14/ A108	Alloy 400/ B164
3 Gland	O, 1,① and 20	304 SS/A240, A167			
4 Packing springs	All②	S17700/A693			
5 Packing gland	All	316 SS/A240, A276, B783			
6 *Upper packing*	All	*PFA/D3307*			
7 *Lower packing*					
8 *Lower gland*	All	*316 SS/A240*			*Alloy 400/ B127*
9a *Regulating stem*	O, 1, and 18	*Chrome-plated③ 316 SS/A276*	*316 SS/A276*		*Alloy 400/ B164*
9b *Vee stem*	All				
9c *Soft-seat stem*	All				
Stem tip		*PCTFE/D1430*			
10 Panel nut	O, 1, and 18	316 SS	Brass 360/ B16	316 SS	
11a *Body*	O, 1, and 18	*316 SS/A182*	*Brass 377/ B283*	*Cadmium-plated 11L17/ A108*	*Alloy 400/ B564*
11b *Body*	20 and 26	*316 SS/A479*	—		
Lubricant	All	*Tungsten disulfide- and fluorocarbon-based*			

Wetted components listed in *italics*.
Valve series listed with standard handles. For handle options, see **Handles,** page 8.
① 1 series valves with orifice of 0.172 in. (4.4 mm).
② O, 20 and 1 series with orifice of 0.172 (4.4 mm)—2 springs; 18, 26, and 1 series with orifice of 0.250 (6.4 mm)—3 springs.
③ Regulating and vee stem tip and threads; soft-seat stem threads.

Figure A.13 GOX vent MTNV component materials

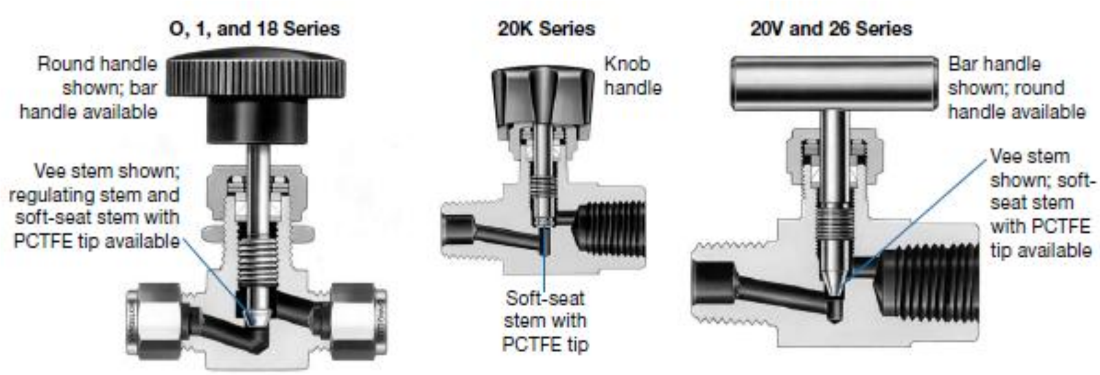


Figure A.14 GOX vent MTNV cross section

Table A.4 GOX vent MTNV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Vent MTNV	Stainless Steel Ball Valve, ¼" Swagelok Port Connections,	Swagelok	B-1VS4-SC11-SH	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Bar Handle	316 Stainless Steel	Ambient[1]	2900[2]	Yes[3]	2[7]	0[8]	0[9]	0[10]	0[11]	0[12]	0[13]	No[14]	B[15]
Set Screw	17-4 Stainless Steel			Yes									
Packing Nut	Brass			No[4]									
Gland	304 Stainless Steel			Yes									
Packing Springs	17-7 Stainless Steel			Yes									
Packing Gland	316 Stainless Steel			Yes									
Lower Gland	316 Stainless Steel			Yes									
Packing	Teflon PFA			Yes[6]									
Vee Stem	316 Stainless Steel			Yes									
Stem Tip	316 Stainless Steel			Yes									
Body	Brass			No									
Lubricant	Krytox			No[5]									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[5] Krytox is not considered flammable in oxygen and is an approved oxygen system lubricant. (ASTM G63-99, Table X1.6, pg 22)
[6] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[7] All characteristic element of particle impact are present. This ignition mechanism low probability due to GOX filtration and additionally the multi-turn actuation of the GOX vent MTNV. The type of valve actuation allows for slower pressurization which limits the particulate flow velocities.
[8] Heat of compression is not possible due to the missing characteristic element of the exposed nonmetal close to a dead end.
[9] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the 1.5×10^6 psi x ft/min requisite to ignite stainless steel. (Manual 36, pg 23, Table 3.5)
[10] Mechanical impact can not occur due to the hand operated multi-turn stem.
[11] The component is not electrically powered.
[12] Flow friction is not possible due to missing an exposed nonmetal in the flow path
[13] Chatter does not occur in this component.
[14] A kindling chain does not exist. If the stainless steel stem ignites by particle impact the burn resistant brass body serves as a fire break to extinguish combustion.
[15] The valve possesses flammable components, one remotely possible ignition mechanism, and no kindling chain. The valve is hand operated increasing risk effects on personnel. The reaction effect is marginal.

A.4.5 GOX Ignition Main Valve

This component is used to isolate the GOX ignition system flow lines, GOX dome loader, and GOX ignition fire valve from the high pressure oxygen gas ignition tank K-bottle.

Materials of Construction

Item #	Part Description	Stainless Steel	Brass
*1	Connector O-Ring	PTFE**	
*2A	Seat Retainer	ASTM A 276 Type 316	ASTM B 16 Alloy C36000
*2B	Seat	PTFE, PCTFE, PEEK	
*3	Retainer Seal	PTFE**	
*4	Ball	316 Stainless Steel	
*5	Body	ASTM A 351 Grade CF3M	ASTM B 283 Alloy C37700
*6A	Stem	ASTM A 276 Type 316	
*6B	Stem Seal	PTFE**	
*6C	Stem Washer	316 Stainless Steel	
7	Packing Nut	ASTM A 479 Type 316	ASTM B 453 Alloy C34000
8	Handle	Nylon 6/6	
9	Handle Set Screw	Stainless Steel	
10	Panel Nut	316 Stainless Steel	
*11	End Connector	ASTM A 479 Type 316	ASTM B 16 Alloy C36000

* Wetted Parts.
** Optional stem seal and body seal materials are described in the How to Order section.
Lubrication: Perfluorinated Polyether.

Figure A.15 GOX main PBV component materials

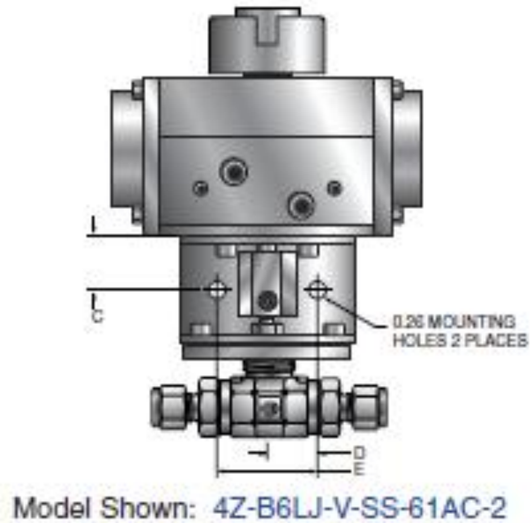


Figure A.16 GOX main PBV shown with actuator

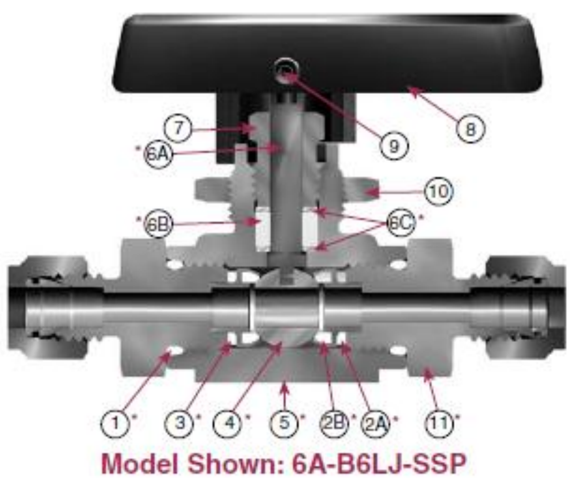


Figure A.17 GOX main PBV cross section

Table A.5 GOX main PBV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Main PBV	Stainless Steel Pneumatically Actuated Ball Valve, ¼" fittings	Parker	4Z(A)-B6LJ2-SSP-61AC-2	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Connector O-Ring	PTFE			Yes[3]									
Seat Retainer	316 Stainless Steel			Yes[4]									
Seat	PTFE			Yes									
Retainer Seal	PTFE			Yes									
Ball	316 Stainless Steel			Yes									
Body	316 Stainless Steel			Yes									
Stem	316 Stainless Steel	Ambient[1]	2500[2]	Yes	0[6]	2[7]	0[8]	0[9]	0[10]	1[11]	0[12]	Yes[13]	C[14]
Stem Seal	PTFE			Yes									
Stem Washer	316 Stainless Steel			Yes									
Packing Nut	316 Stainless Steel			Yes									
Handle	Nylon 6/6			Yes[5]									
Handle Set Screw	300 series Stainless Steel			Yes									
Panel Nut	316 Stainless Steel			Yes									
End Connector	316 Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[4] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[5] Nylon 6/6 is flammable in 21- 38 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[6] Particle Impact is a remotely possible ignition source due to the rapid pressure transient even with the few impact points internal to valve. The controlled pressurization with the GOX ignition regulator, of this component mitigates high transitional flow velocities.
[7] All characteristic element of heat of compression are present; this ignition mechanism is possible due to rapid pressurization, the presence of PTFE exposed in the flow path and significant pressure ratio achieving a final temperature of 1850 °F. This final temperature is well above the AIT of PTFE (814°F). In the LOX_GCH4 Test SOP the heat of compression ignition mechanism is procedurally controlled by opening the GOX Main Valve and the GOX Fill MBV before opening the GOX k-bottle to slowly pressurizing the GOX Ignition line using the GOX ignition regulator.
[8] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the $1.5x10^6$ psi x ft/min requisite to ignite stainless steel. (Manual 36, pg 23, Table 3.5)
[9] Mechanical impact cannot occur due to the ball valve.
[10] The component is not electrically powered.
[11] All characteristic elements of flow friction are present; however the configuration is unlikely to produce erosion, friction, and/or vibration.
[12] Chatter does not occur in this component.
[13] A kindling chain exists if the PTFE ignites by compression heating or flow friction and propagates to the valve body
[14] The valve possesses flammable components, one possible and one remotely possible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. Due to importance of main valve, effect of fire on system objective and functional capability is more critical. The reaction effect is critical.

A.4.6 GOX Dome Loader

This component is used to regulate the operational pressure upstream of the GOX flow control orifice. Hand regulated Gaseous nitrogen is used as the ullage gas for the dome loaded pressure regulator. In the PRC oxygen facility, the Buna-N O-rings and diaphragm were replaced with Viton.

❑ **Media Contact Materials**

body	303 SST, 316 SST, Aluminum or Brass
diaphragm	Buna-N
o-rings	Buna-N
back-up rings	PTFE
seat	CTFE
retaining ring	15-7 SST
valve cap	17-4 SST
remaining parts	300 Series SST

For other materials or modifications, please consult TESCOM.

Figure A.18 GOX ignition dome loader component materials

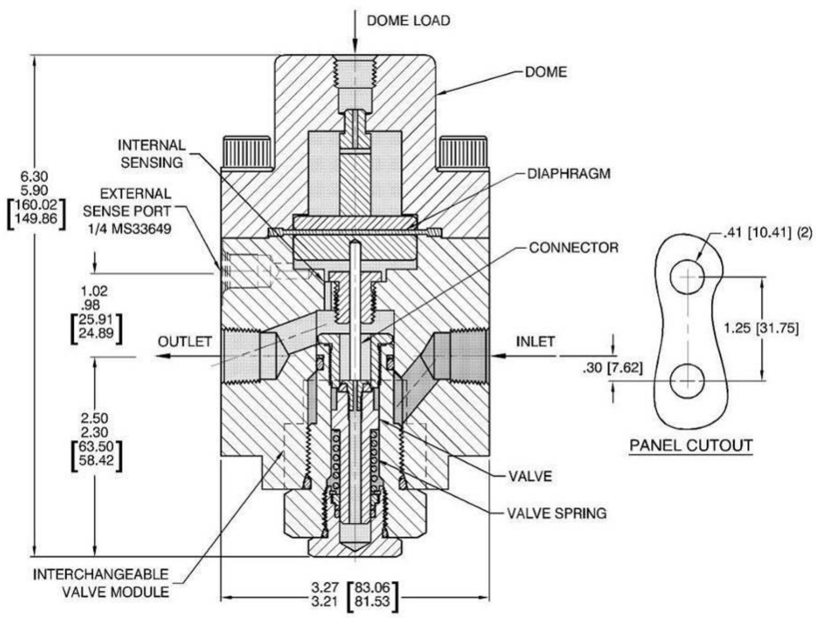


Figure A.19 GOX ignition dome loader cross section

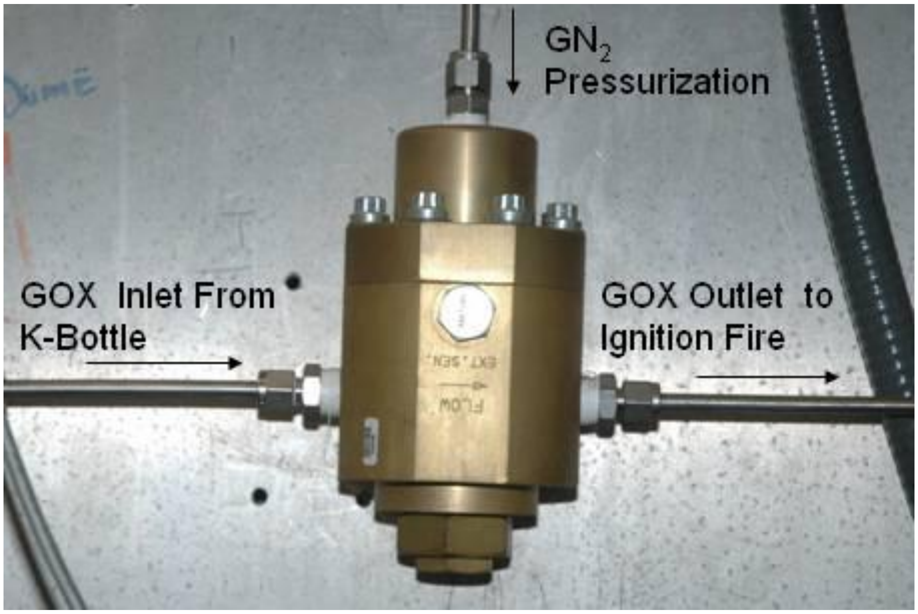


Figure A.20 GOX ignition dome loader on facility

Table A.6 GOX ignition dome loader OCA

Nomenclature	**Description**	**Manufacturer**	**Part Number**	**Facility Label**
GOX Igniter Dome Loader	**Brass Body Dome Loader**	**Tescom**	**26-1111-269**	**TBD**

Component	**Material**	**Worse-Case Operating Condition** Temp (°F)	**Worse-Case Operating Condition** Press (psi)	**Material Flammable?** Yes/No	**Ignition Mechanism Ratings (0-4)** Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	**Kindling Chain?** Yes/No	**Reaction Effect** (A-D)
Body	Brass	Ambient[1]	2500[2]	No[3]	1[8]	2[9]	1[10]	0[11]	0[12]	2[13]	0[14]	Yes[15]	B[16]
Diaphragm	Buna-N			Yes[4]									
O-rings	Buna-N			Yes									
Back-up rings	PTFE			Yes[5]									
Seat	CTFE			Yes[6]									
Retaining Ring	15-7 Stainless Steel			Yes[7]									
Valve Cap	17-4 Stainless Steel			Yes									
Remaining Parts	300 series Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Brass is not considered flammable in Oxygen. (Manual 36, Table 3.1, pg 18)
[4] Buna-N must be considered flammable in 22% oxygen. (Manual 36, Table 3.12, pg 34)
[5] PTFE is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[6] CTFE is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[7] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[8] Particle Impact is remotely possible due to particulate impact trajectories > 45° into stainless steel components. Due to the filtration of the GOX flow entering the GOX dome loader and additionally the slower pressurization using the GOX ignition regulator, this ignition mechanism is considered less severe.
[9] All characteristic elements of heat of compression are present; this ignition mechanism is possible due to rapid pressurization, the presence of PTFE and Buna-N exposed in the flow path and significant pressure ratio achieving a final temperature of 1850 °F. This final temperature is well above the AIT of PTFE (814°F) and Buna-N (331°F). In the LOX_GCH4 Test SOP the heat of compression ignition mechanism is procedurally controlled by opening the GOX Main Valve and the GOX Fill MBV before opening the GOX k-bottle and pressurizing the GOX Ignition line. This is a procedural fix to a probable heat of compression ignition mechanism. Using the procedural control is simply a Distance Volume/Piece (DVP) utilized to contain the hot compressed gas slug that can form during pressurization and to safely absorb its heat of compression (ASTM G88-05, Section 7.7.2.6, note 42, pg 17).
[10] Friction ignition is remotely possible due to the rubbing surfaces; however the load producing Pv much lower than the $1.5x10^6$ psi x ft/min requisite to ignite stainless steel. (Manual 36, Table 3.5, pg 23)
[11] Mechanical impact can not occur in this dome loader.
[12] The component is not electrically powered.
[13] All characteristic elements of Flow friction are present; this ignition mechanism is remotely possible with any dome loader in oxygen service. Since the dome load is GN_2 this situation is less severe. The GOX dome loader will be monitored to remove/repair if leakage initiates
[14] Chatter does not occur in this component.
[15] If ignition of soft goods occurs, kindling chain does exist to SS trim and potentially has sufficient fuel load to melt through brass if conditions are right. However, brass body is thick and the fire would most likely burn out at the non flammable brass body.
[16]The Dome loader possesses flammable and non flammable components, one probable, one possible, and two remotely possible ignition mechanisms. Flow friction is a primary concern with the Buna-N soft good components in the GOX dome loader. There is a kindling chain, and the dome loader is remotely operated minimizing the risk effects on personnel. If contaminant or soft seat ignites, stainless steel trim will burn and potentially melt through brass body (lower) due to fuel load however, GN_2 is on dome load, thus less severe. The reaction effect is marginal.

A.4.7 GOX Fire Valve

The GOX fire valve is a remotely actuated pneumatic ball valve. When opened, GOX flow is allowed to enter the igniter, mix with GH_2 and establish ignition of the main propellants. The GOX fire valve is a spring return normally closed valve that is only operational during the test sequence, for a short duration (typically around 0.5 seconds). The GOX fire valve material components, configuration with actuator, and cross-sectional diagram is the same as the GOX main valve. This information is found in Section A.4.5.

Figure A.21 GOX fire PBV on facility

Table A.7 GOX fire PBV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
GOX Fire Valve	Stainless Steel Pneumatically Actuated Ball Valve, ¼" fittings	Parker	4Z(A)-B6LJ2-SSP-61AC-2	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Connector O-Ring	PTFE			Yes[3]									
Seat Retainer	316 Stainless Steel			Yes[4]									
Seat	PTFE			Yes									
Retainer Seal	PTFE			Yes									
Ball	316 Stainless Steel			Yes									
Body	A351 Stainless Steel			Yes									
Stem	316 Stainless Steel			Yes									
Stem Seal	PTFE	Ambient[1]	2500[2]	Yes	2[6]	0[7]	0[8]	0[9]	0[10]	1[11]	0[12]	Yes[13]	B[14]
Stem Washer	316 Stainless Steel			Yes									
Packing Nut	316 Stainless Steel			Yes									
Handle	Nylon 6/6			Yes[5]									
Handle Set Screw	316 Stainless Steel			Yes									
Panel Nut	316 Stainless Steel			Yes									
End Connector	Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[4] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[5] Nylon 6/6 is flammable in 21- 38 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 29)
[6] Particle Impact is a possible ignition source. Though system is filtered, this valve is operated under a differential pressure where high gas velocity will occur during transient. Presence of particulate is low, sustained high velocity is low, remote operation justifies use of stainless steel valve material.
[7] Heat of compression is not possible due to the characteristic element of the exposed nonmetal close to a dead end.
[8] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the 1.5×10^6 psi x ft/min requisite to ignite stainless steel. (Manual 36, pg 23, Table 3.5)
[9] Mechanical impact cannot occur due to the ball valve.
[10] The component is not electrically powered.
[11] All characteristic elements of flow friction are present; however the configuration is unlikely to produce erosion, friction, and/or vibration. Flow friction is possible and leaks must be monitored to safely control this ignition mechanism.
[12] Chatter does not occur in this component.
[13] A kindling chain exists if a nonmetal ignites flow friction and propagates to the valve body
[14] The valve possesses flammable components, one remotely possible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. Due to importance of fire valve, effect of fire on system objective and functional capability increases. The reaction effect is marginal.

A.4.8 GOX Fire (Ignition) Non Return Check Valve

Non return check valves are used to prevent back flow through the system in the event of an over pressure event, and to prevent gaseous nitrogen from the igniter purge lines from entering GOX ignition lines. Purge pressure is typically set well below the GOX ignition line pressure. The common check valve used has a cracking pressure of 0.3 psi.

Materials of Construction

Item #	Part	Stainless Steel Valve	Brass Valve
1	Cap	ASTM A 276, TYPE 316	ASTM B 16 Alloy C36000
2	Seat*	Fluorocarbon Rubber*	
3	Poppet	ASTM A 479, TYPE 316	ASTM B 16 Alloy C36000
4	Spring	316 Stainless Steel	
5	Body	ASTM A 276, TYPE 316	ASTM B 16 Alloy C36000

* Optional seat materials are available. See How to Order section.
Lubrication: Silicone Paste

Note: PTFE seated valves employ an additional PTFE coated 316 SS gasket between the seat and the body and are distinguishable from elastomeric seated valves by the gap designed between the body and cap.

**See Pressure Rating note on page 4.

Figure A.22 GOX fire NRCV component materials

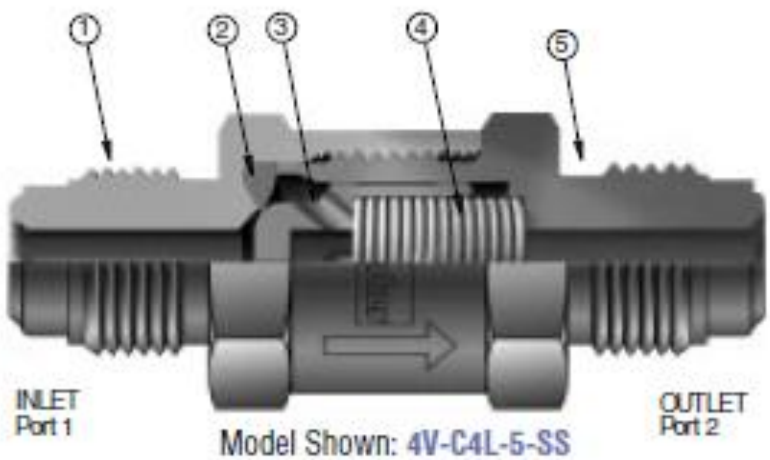


Figure A.23 GOX fire NRCV cross section

① Inlet Port	② Outlet Port	③ Body Size	④ Crack Pressure	⑤ Seat Material	⑥ Body Material
2A, 2F, 2F5, 2G5, 2KF, 2KM 2M, 2TA, 2Z, M3A, M3Z,	2A, 2F, 2F5, 2G5, 2KF, 2KM 2M, 2TA, 2Z, M3A, M3Z,	C2L	1/3 psi 1 psi 5 psi 10 psi 25 psi 50 psi 75 psi 100 psi	Blank - Fluorocarbon Rubber BN - Buna-N Rubber EPR - Ethylene Propylene Rubber NE - Neoprene Rubber T - PTFE* KZ - ** Highly Fluorinated Fluorocarbon	B - Brass SS - 316 Stainless Steel
4A, 4F, 4F5, 4G5, 4KF, 4KM, 4L, 4M, 4Q, 4TA, 4V, 4Z, M6A, M6Z,	4A, 4F, 4F5, 4G5, 4KF, 4KM, 4L, 4M, 4Q, 4TA, 4V, 4Z, M6A, M6Z,	C4L			
6A, 6F, 6F5, 6G5, 6KF, 6KM, 6L, 6M, 6Q, 6TA, 6Z, M8A, M8Z, M10A, M10Z,	6A, 6F, 6F5, 6G5, 6KF, 6KM, 6L, 6M, 6Q, 6TA, 6Z, M8A, M8Z, M10A, M10Z,	C6L			
8A, 8F, 8F5, 8G5, 8KF, 8KM, 8L, 8M, 8Q, 8TA, 8V, 8Z, M12A, M12Z,	8A, 8F, 8F5, 8G5, 8KF, 8KM, 8L, 8M, 8Q, 8TA, 8V, 8Z, M12A, M12Z,	C8L			
12A, 12F, 12F5, 12G5, 12KF, 12KM, 12L, 12M, 12Q, 12TA, 12V, 12Z, M20A, M20Z, M22A, M22Z,	12A, 12F, 12F5, 12G5, 12KF, 12KM, 12L, 12M, 12Q, 12TA, 12V, 12Z, M20A, M20Z, M22A, M22Z,	C12L			
16A, 16F, 16F5, 16G5, 16KF, 16KM, 16L, 16M, 16TA, 16Z, M25A, M25Z,	16A, 16F, 16F5, 16G5, 16KF, 16KM, 16L, 16M, 16TA, 16Z, M25A, M25Z,	C16L			

*Available only with stainless steel valves.
** Not available on C2 series

Figure A.24 GOX fire NRCV part number specifications

Table A.8 GOX fire NRCV OCA

<table>
<tr><th colspan="2">Nomenclature</th><th colspan="3">Description</th><th colspan="4">Manufacturer</th><th colspan="4">Part Number</th><th>Facility Label</th></tr>
<tr><td colspan="2">GOX Fire NRCV</td><td colspan="3">Stainless Steel Check Valve, ¼" fittings</td><td colspan="4">Parker</td><td colspan="4">4Z(A)-C4L-1/3-SS</td><td>TBD</td></tr>
<tr><th rowspan="2">Component</th><th rowspan="2">Material</th><th colspan="2">Worse-Case Operating Condition</th><th rowspan="2">Material Flammable? Yes/No</th><th colspan="7">Ignition Mechanism Ratings (0-4)</th><th rowspan="2">Kindling Chain? Yes/No</th><th rowspan="2">Reaction Effect (A-D)</th></tr>
<tr><th>Temp (°F)</th><th>Press (psi)</th><th>Particle Impact</th><th>Comp. Heating</th><th>Friction/Galling</th><th>Mechanical Impact</th><th>Elec. Arc/Spark</th><th>Flow Friction</th><th>Other/Chatter</th></tr>
<tr><td>Cap</td><td>316 Stainless Steel</td><td rowspan="5">Ambient[1]</td><td rowspan="5">2500[2]</td><td>Yes[3]</td><td rowspan="5">1[5]</td><td rowspan="5">0[6]</td><td rowspan="5">0[7]</td><td rowspan="5">0[8]</td><td rowspan="5">0[9]</td><td rowspan="5">1[10]</td><td rowspan="5">1[11]</td><td rowspan="5">Yes[12]</td><td rowspan="5">B[13]</td></tr>
<tr><td>Seat</td><td>Fluorocarbon Rubber</td><td>Yes[4]</td></tr>
<tr><td>Poppet</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Spring</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Body</td><td>316 Stainless Steel</td><td>Yes</td></tr>
</table>

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Fluorocarbon Rubber is flammable in 31.5 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 33)
[4] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[5] Particle Impact is remotely possible due to particulate impact trajectories > 45° into stainless steel components and high gas velocities during the opening transient. Due to the filtration of the GOX flow entering the GOX Dome loader this ignition mechanism is considered remotely possible, but still possible.
[6] Heat of compression is not possible due to the missing characteristic element of the exposed nonmetal close to a dead end.
[7] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the $1.5x10^6$ psi x ft/min requisite to ignite stainless steel. (Manual 36, pg 23, Table 3.5)
[8] Mechanical impact can not occur in this valve configuration. In mechanical impact test data Flurocarbon Rubber experienced 0/20 reactions/tests at 2000 psi. (ASTM G63-99, Table X1.4, pg 20).
[9] The component is not electrically powered.
[10] All characteristic elements of flow friction are present; however the configuration is unlikely to produce erosion, friction, and/or vibration
[11] Chatter does occur in this component. The chatter could generate particulate that could present a particle ignition mechanism downstream in the GOX ignition Orifice.
[12] A kindling chain exists if the steel poppet ignites by particle impact or if a nonmetal fluorocarbon rubber ignites by flow friction and propagates to the body.
[13] The valve possesses flammable components, three remotely possible credible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. Due to position proximity of check valve to igniter fire valve and the flow control orifice, potential damage effect on system objective and functional capability increases. The reaction effect is marginal.

A.4.9 GOX Flow Control Orifice

The GOX ignition flow control orifice is used to meter the igniter GOX flow rate. The upstream pressure is set so that a sonic choke exists at the orifice producing a steady flow rate through to the igniter.

General Specifications

Maximum Operating Pressure –

Brass 2000 psig

303 SS 4000 psig

Type DEL

Brass 200 psig

Flow – See flow chart for air on pages 20 and 21.

Orifice Diameters – .004" to .125" standard. Consult factory for other sizes.

Orifice Diameter Accuracy – ±.0005"

C_v Range – .00035 to .37 See pages 20 and 21.

Fluid Media – Air, Water, Gases and Liquids compatible with materials of construction.

Dimensions – See drawings on page 9.

Figure A.25 GOX flow control orifice specifications

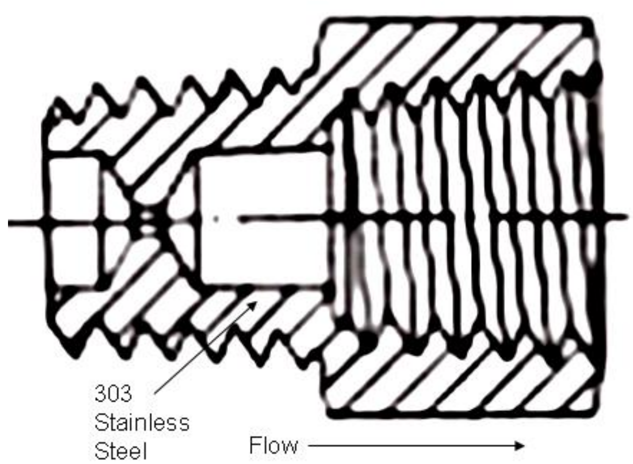


Figure A.26 GOX flow control orifice cross section

Table A.9 GOX flow control orifice OCA

Nomenclature		Description			Manufacturer					Part Number			Facility Label
GOX Orifice		Stainless Steel Flow Control Orifice, ¼ " NPT Port Connections			(McMaster)					2822T15			TBD
Component	Material	Worse-Case Operating Condition		Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter		
Body	303 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	3[4]	0[5]	0[6]	0[7]	0[8]	0[9]	0[10]	Yes[11]	C[12]

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] All characteristic element of particle impact are present; This ignition mechanism is probable due to the configuration of the check valve upstream of the flow control orifice. The GOX Fire NRCV in operation will inherently generate particulate presenting a particle impact ignition hazard to the GOX flow control orifice. Although all characteristic elements are present and some are severe, this configuration has been fired multiple times without problem. For this reason the ignition mechanism rating is 3 instead of 4. However, there is still a potential ignition hazard in this configuration.
[5] Heat of compression is not possible due to the lack of an exposed non metal in the flow close to a dead end.
[6] Friction heating in a flow orifice is not possible.
[7] Mechanical impact is not possible due to the lack of an impact on a polymer.
[8] The component is not electrically powered.
[9] Flow friction is not possible due to missing an exposed nonmetal in the flow path. Orifice is welded onto metal to metal seat fittings.
[10] Chatter does not occur in this component.
[11] A kindling chain exists if the steel ignites by particle impact or if the Teflon tape seat ignites by flow friction and spreads to the body.
[12] The valve possesses flammable component, one probable and one remotely possible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. Due to position proximity of check valve the flow control orifice, potential damage effect on system objective and functional capability is critical.

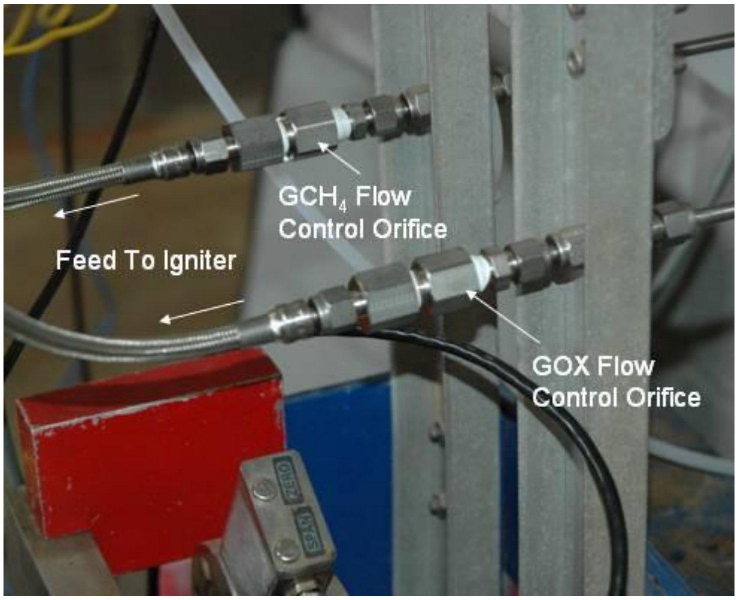


Figure A.27 GOX ignition flow control orifice on facility

A.4.10 GOX Igniter Non Return Check Valve

A non return check valve is located immediately upstream of the igniter. This component prevents back flow of combustion gas into the GOX ignition system flow lines. The GOX igniter NRCV component materials, configuration with actuator, cross-sectional diagram, and part number specifications are the same as the GOX fire NRCV. This information is found in Section A.4.8.

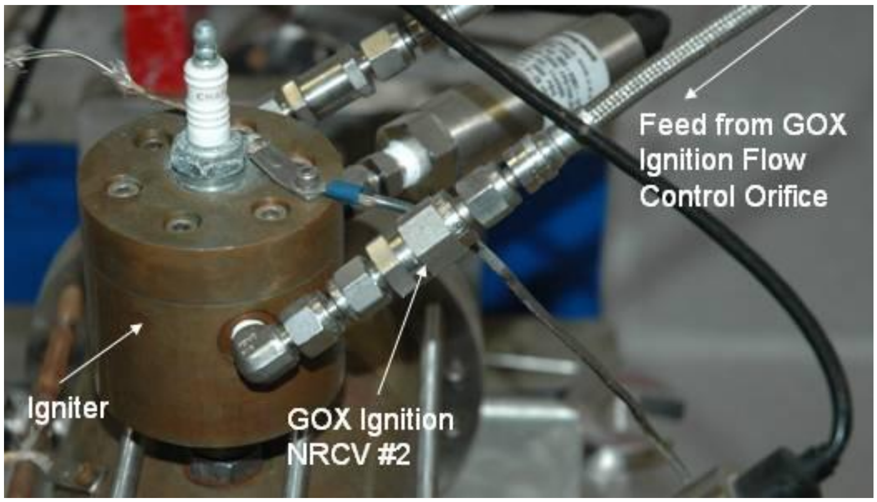


Figure A.28 GOX igniter NRCV

Table A.10 GOX igniter NRCV OCA

Nomenclature	**Description**	**Manufacturer**	**Part Number**	**Facility Label**
GOX Igniter NRCV	**Stainless Steel Check Valve, ¼" fittings**	**Parker**	**4Z(A)-C4L-1/3-SS**	**TBD**

Component	**Material**	**Worse-Case Operating Condition**		**Material Flammable?**	**Ignition Mechanism Ratings** (0-4)							**Kindling Chain? Yes/No**	**Reaction Effect (A-D)**
		Temp (°F)	Press (psi)	Yes/No	Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter		
Cap	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[5]	0[6]	0[7]	0[8]	0[9]	1[10]	1[11]	Yes[12]	B[13]
Seat	Fluorocarbon Rubber			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Spring	316 Stainless Steel			Yes									
Body	316 Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Fluorocarbon Rubber is flammable in 31.5 % Oxygen at ambient pressure. (Manual 36, Table 3.12, pg 33)
[4] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[5] All characteristic element of particle impact are present due to a potential particulate source form the upstream check valve, high velocity from transient delivery of oxygen, impact points internal to the valve and flammable stainless steel body. This ignition mechanism is possible, however due to the configuration of the check valve upstream of the flow control orifice.
[6] Heat of compression is not possible due to missing the characteristic element of an exposed non metal in the flow path near a dead end.
[7] Friction ignition is not possible due to the rubbing speed and load producing a Pv much lower than the 1.5×10^6 psi x ft/min requisite to ignite stainless steel. (Manual 36, pg 23, Table 3.5)
[8] Mechanical impact cannot occur in this valve configuration. In mechanical impact test data Flurocarbon Rubber experienced 0/20 reactions/tests at 2000 psi. (ASTM G63-99, Table X1.4, pg 20).
[9] The component is not electrically powered.
[10] All characteristic elements of flow friction are present; however the configuration is unlikely to produce erosion, friction, and/or vibration.
[11] Chatter could occur in this component. The chatter could generate particulate; the particulate could present particle impact ignition hazard since there is a stainless steel elbow directly downstream of the GOX Igniter NRCV. However, this ignition hazard is considered controllable due to the remote operation.
[12] A kindling chain exists if the steel poppet ignites by particle impact or if the seat ignites by flow friction and spreads to the body
[13] The valve possesses flammable components, three possible credible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. The reaction effect is negligible.

A.5 LOX System

The liquid oxygen system is used to deliver LOX to the main engine. The system is supplied from a LN_2 jacketed, 23 gallon, 3000 psi run tank. The system was designed to support up to 3 lbm/s of LOX flow to the test article. The system uses 0.5 inch seamless stainless steel tubing with a 1.25 inch outer jacket for liquid and gaseous nitrogen flow to keep the temperature of the lines low. Tube joints have either stainless steel or monel bodies, depending on the assessed hazard at the joint. The system uses a gaseous nitrogen purge and has 1.5 inch copper vent lines. Throughout the system relief valves and burst disks were added at any location where liquid oxygen could be trapped through valve closures. The body of each component is wrapped with 0.25 inch Teflon tubing through which liquid nitrogen can flow to keep the component body temperature low enough to sustain liquid oxygen in the component. The primary components of the LOX system are the LOX run tank, remotely actuated pneumatic globe valves, a burst disk, non return check valves, relief valves, and a metering flow control orifice.

A.5.1 LOX Run Tank

The LOX dual jacketed, stainless steel, 23 gallon tank was fabricated at NASA MSFC by surrounding a single tank with a 2.5 ft diameter stainless steel pipe. Stainless flanges with pass through ports are welded on the end of the outer pipe. The tank was designed to support a pressure of 3000 psi. The outer jacket is operationally filled with liquid nitrogen which boils off at a low pressure to help chill the liquid oxygen inner tank. The tank is filled from the bottom through a 1 inch NPT fitting sealed to the tank using a Teflon O-ring. A relief valve and burst disk are attached to the top of the tank to prevent over-pressurization of the tank.

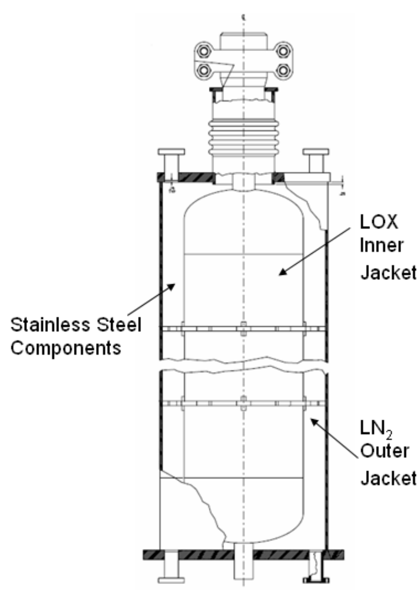


Figure A.29 LOX run tank cross section

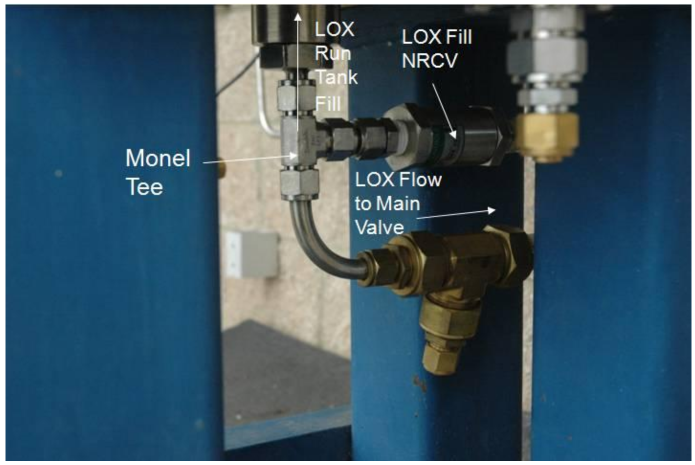


Figure A.30 LOX fill and main flow on facility

Table A.11 LOX run tank OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Run Tank	**23 Gallon LOX Inner Tank, LN_2 Outer Jacket**	**NASA Marshall**	-----	**TBD**

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	0[4]	0[5]	0[6]	0[7]	0[8]	1[9]	0[10]	Yes[11]	C[12]
O-ring	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. This ignition mechanism is not possible due to missing the characteristic element of the high velocities requisite for particle impact ignition.
[5] Heat of compression is not possible due to the lack of an exposed non metal in the flow.
[6] Friction heating in a flow orifice is not possible.
[7] Mechanical impact is not possible due to the lack of an impact on a non metal.
[8] The component is not electrically powered.
[9] Flow friction is not a credible ignition source for Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[10] Chatter does not occur in this component.
[11] A kindling chain exists if the steel ignites by Teflon port seal or tape ignites by flow friction and spreads to the body.
[12] The tank possesses flammable components, one possible ignition mechanism, as well as kindling chain. The tank is remotely operated at high pressure minimizing the risk effects on personnel. Due to sheer volume of LOX that will be pressurized in the operation of the system potential damage effect on system objective and functional capability is critical. The reaction effect is critical.

A.5.2 LOX Main Filter

The LOX main filter is located immediately downstream of the LOX run tank and directly upstream of the LOX main isolation pneumatic globe valve. The primary function is to filter out particulate entering the LOX main propellant flow system. The filter element is sintered bronze with a 220 (0.0087 in) micron rating. There is an additional LOX fill filter discussed in Section A.5.11 stationed directly before LOX fill pneumatic globe valve. These filters provide two points of filtration before LOX enters the LOX run tank and again before entering the main propellant flow line.

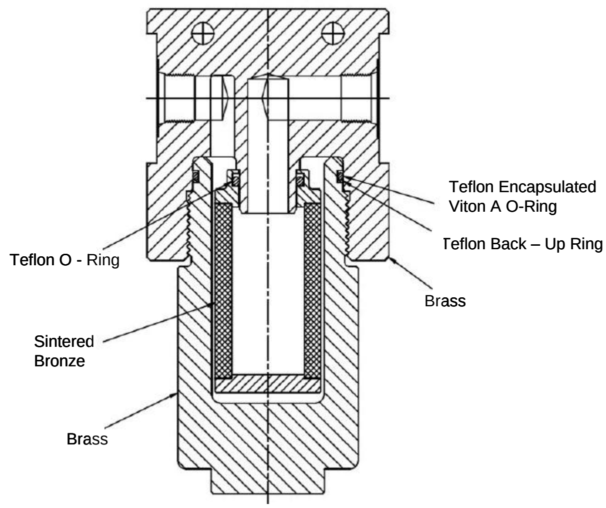


Figure A.31 LOX main filter cross section

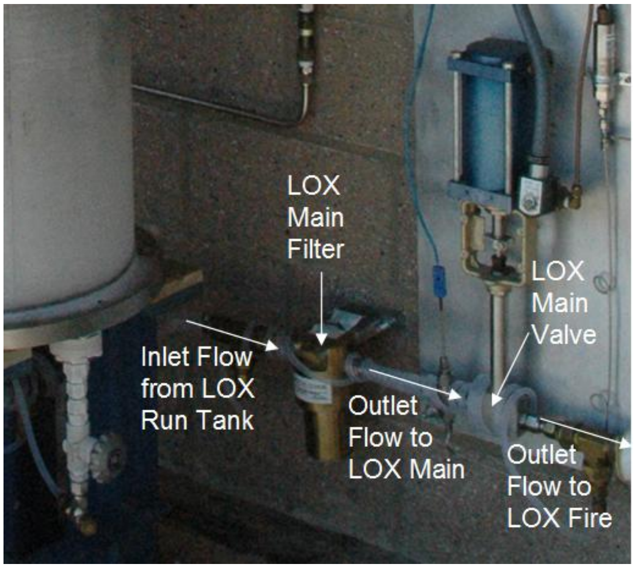


Figure A.32 LOX main filter on facility

Table A.12 LOX main filter OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Main Filter	**Tee Filter assembly, 220µ filter element**	**Chase Filter & Components.**	**50B-8S8S-2P2**	**TBD**

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Head	Brass	Ambient[1]	2500[2]	No[3]	0[6]	0[7]	0[8]	0[9]	0[10]	2[11]	0[12]	No[13]	A[14]
Bowl	Brass			No									
Element	Sintered Bronze			No[4]									
O - Ring	Teflon			Yes[5]									
O - Ring	Teflon Encap. Viton A			Yes									
Back – Up Ring	Teflon			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[4] Bronze is not considered flammable at the worst case operating conditions stated above Bronze does not burn until experiencing pressures > 10,000 psi. (Manual 36, Table 3.1, pg 18)
[5] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[6] Particle Impact is not probable in this valve due to missing the characteristic element of a flammable target.
[7] Heat of compression is not possible due to the lack of an exposed non metal in the flow.
[8] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[9] Mechancal impact cannot occur in this component.
[10] The component is not electrically powered.
[11] Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[12] Chatter does not occur in this component.
[13] A kindling chain does not exist. If the Teflon ignites by flow friction and propagates to the burn resistant brass body will extinguish the combustion. The probability of ignition by flow friction is low and no kindling chain exists.
[14] The valve possesses flammable components, one possible remotely possible ignition mechanism, as well as no kindling chain. Personnel are present at the time of operation of this component; however, this component presents low risk of ignition. The reaction effect is negligible.

A.5.3 LOX Main Pneumatic Globe Valve

The LOX main pneumatic globe valve is located immediately downstream of the run tank. The valve is used to isolate the run tank from the remainder of the system. The valve is a spring return normally closed valve actuated using 100 psi (0.69 MPa) compressed air.

CIRCLE SEAL CONTROLS, INC.

CMV/CES 12 & 60 Series

0–12,000 psi & 0–6000 psi DYNAFLOW® Pneumatically Operated Patented Shutoff Valves

Features

- Zero leakage
- Three operating modes
- Bi-directional
- Positive spindle retention
- Extended stem for extreme temperatures
- Field tested at 1 × 10⁻⁷ torr to 12,000 psi with zero leakage

Technical Data

Body Construction Materials	• Valve body: 303 or 316 stainless steel • Actuator body: aluminum
Seat & Packing Material	Teflon®
Operating Pressures	• CMV12 & CES12: 0 to 12,000 psi (828 bar) • CMV60 & CES60: 0 to 6000 psi (414 bar)
Proof Pressures	• CMV12 & CES12: 18,000 psi (1,241 bar) • CMV60 & CES60: 9000 psi (621 bar)
Burst Pressures	• CMV12 & CES12: 48,000 psi (3,310 bar) minimum • CMV60 & CES60: 24,000 psi (1,655 bar) minimum
Operating Temperatures	• CMV12 & CMV60: −65° F to +250° F (−54° C to +121° C) • CES12 & CES60: −452° F to +450° F (−269° C to +232° C)
Connection Sizes	⅜″–1″
Cylinder Air Service:	• Operating pressure: 50 to 150 psig (3 to 10 bar) • Proof pressure: 225 psig (16 bar) • Burst pressure: 600 psig (41 bar)
Leakage	All series and actuators: bubble-tight

Note: Proper filtration is recommended to prevent damage to sealing surface.

Figure A.33 LOX main PGV technical data

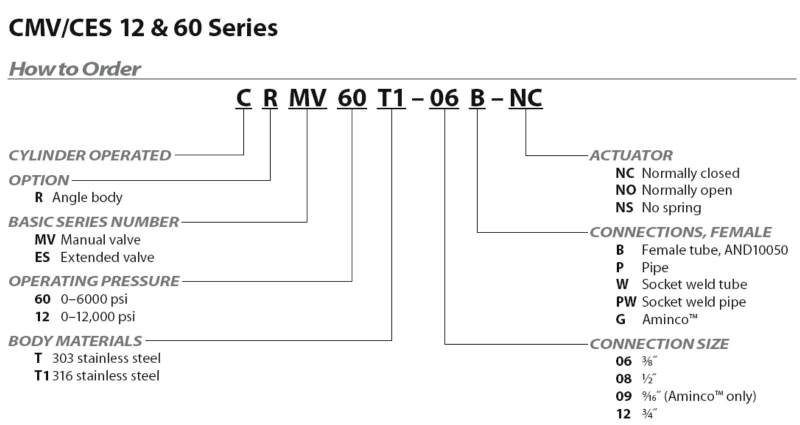


Figure A.34 LOX main PGV nomenclature

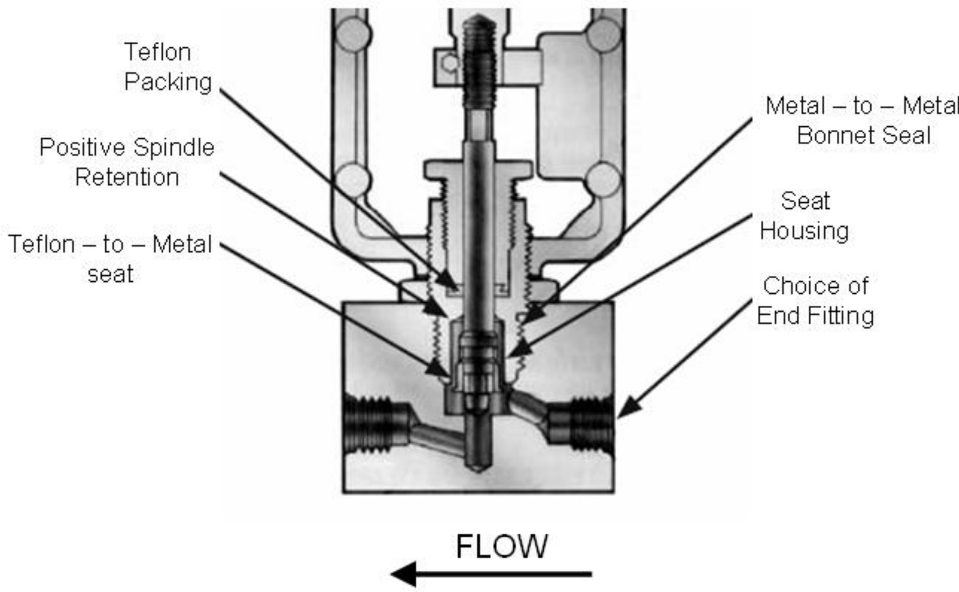


Figure A.35 LOX main PGV cross section

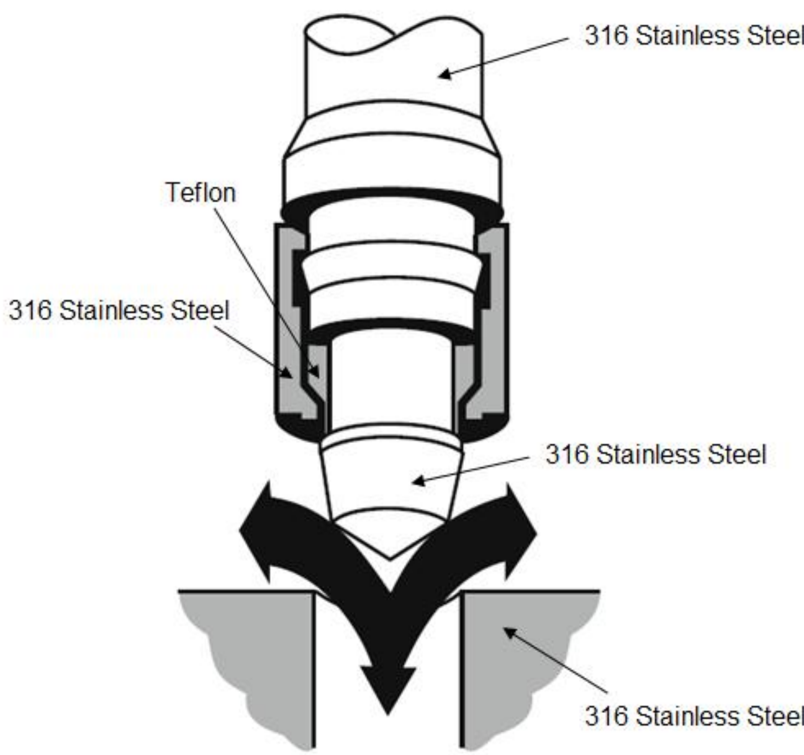


Figure A.36 LOX main PGV oxygen wetted flow path

Table A.13 LOX main PGV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Main Valve	**Pneumatic Globe Valve, 1/2" Ports, With Fail Closed Actuator, Cv= 1.7**	**Circle Seal Controls, Inc**	**CES60T1-08B-NC**	**TBD**

Component	Material	Worse-Case Operating Condition		Material Flammable?	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)	Yes/No	Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/ Chatter		
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	1[5]	0[6]	0[7]	1[8]	0[9]	2[10]	0[11]	Yes[12]	C[13]
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. This ignition mechanism is low probability due to missing the characteristic element of the high velocities requisite for particle impact ignition. LN_2 Jackets are employed to chill the LOX main flow lines before LOX is pressurized past the main valve. The LOX is additionally filtered before entering the tank and directly upstream of the LOX main valve to remove particulate.
[6] Heat of compression is not possible due to the slow controlled pressurization of this component.
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is possible but not probable.
[9] The component is not electrically powered.
[10] Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[11] Chatter does not occur in this component.
[12] A kindling chain exists if the Teflon ignites by flow friction and propagates to the stem and body. The probability of ignition by flow friction is low but a kindling chain does exist. Mechanical impact ignition of the Teflon is also possible but not probable. Particle impact could also be a source of ignition during LOX fill.
[13] The valve possesses flammable components, one possible and two remotely possible ignition mechanisms, as well as kindling chain; however the valve is remotely operated minimizing the effect on personnel. Due to importance of LOX main valve in relation to the LOX Tank, effect of fire on system objective and functional capability increases. The reaction effect is critical.

A.5.4 LOX Fire Pneumatic Globe Valve

The LOX fire valve is a pneumatically actuated, spring return, normally closed, globe valve. It is used to allow LOX to flow into the test article where it will mix with the fuel and combust. The LOX fire valve technical data, nomenclature, cross-sectional diagram, and oxygen wetted flow path is the same as the LOX main valve. This information is found in Section A.5.3.

Table A.14 LOX fire PGV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Fire Valve	Pneumatic Globe Valve, 1/2" Ports, With Fail Closed Actuator, Cv= 1.7	Circle Seal Controls, Inc	CES60T1-08B-NC	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	1[5]	0[6]	0[7]	1[8]	0[9]	2[10]	0[11]	Yes[12]	C[13]
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure; Boiling point temperature of Oxygen is -297.4°F.

[2] Worst case operating pressure from max k-bottle pressure.

[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)

[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)

[5] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. This ignition mechanism is low probability due to missing the characteristic element of the high velocities requisite for particle impact ignition. LN_2 Jackets are employed to chill the LOX main flow lines before LOX is pressurized past the main valve. The LOX is additionally filtered before entering the tank and directly upstream of the LOX main valve to remove particulate. This ignition source is controlled by filtration and remote operation.

[6] Heat of Compression is not possible in Liquid Oxygen.

[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.

[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is possible but not probable.

[9] The component is not electrically powered.

[10] Flow friction is not a credible ignition source for in Liquid Oxygen. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.

[11] Chatter does not occur in this component.

[12] A kindling chain exists if the Teflon ignites by flow friction and propagates to the stem and body. The probability of ignition by flow friction is low but a kindling chain does exist. Mechanical impact ignition of the Teflon is also possible but not probable.

[13] The valve possesses flammable components, one remotely possible and one possible ignition mechanisms, as well as kindling chain; however the valve is remotely operated minimizing the effect on personnel. Due to importance of LOX Fire valve, effect of fire on system objective and functional capability is more critical. The reaction effect is critical.

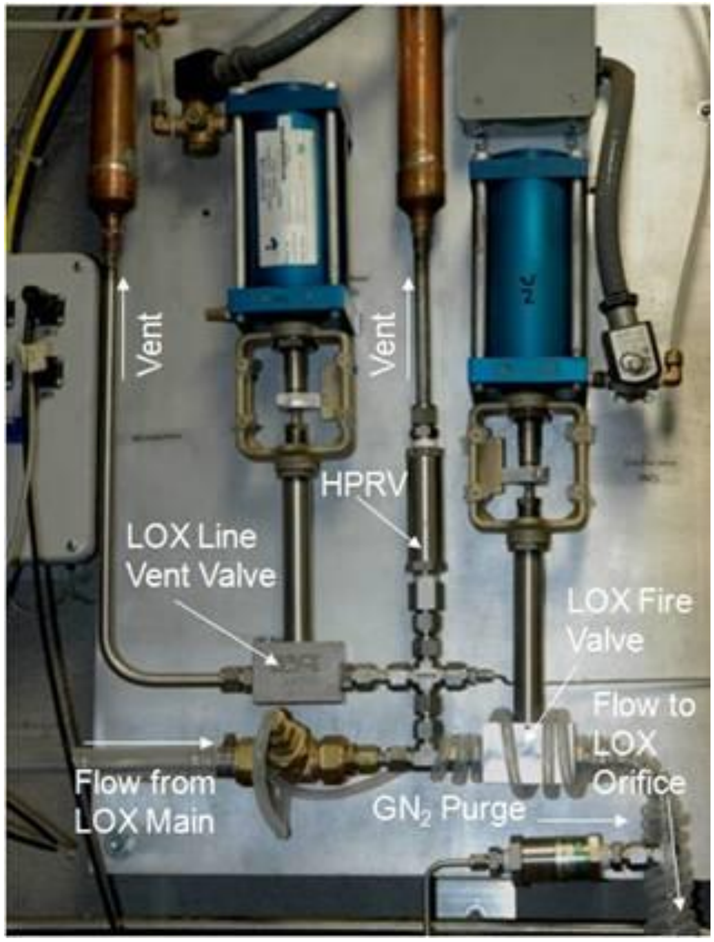


Figure A.37 LOX fire and line vent on facility

A.5.5 LOX Flow Control Orifice

This component is used to meter the LOX flow to the desired mass flow setting. The LOX flow control orifice technical data, nomenclature, cross-sectional diagram, and oxygen wetted flow path is the same as the GOX flow control orifice. This information is found in Section A.4.9.

Table A.15 LOX flow control orifice OCA

Nomenclature		Description			Manufacturer				Part Number			Facility Label	
LOX Orifice		Stainless Steel Flow Control Orifice, ¼ " NPT Port Connections			(McMaster)				2822T15			TBD	
Component	Material	Worse-Case Operating Condition		Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/Chatter		
Body	Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[4]	0[5]	0[6]	0[7]	0[8]	1[9]	0[10]	Yes[11]	B[12]

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. The initial flow from the fire valve to the flow control orifice is not jacketed with cryogenic nitrogen however it is insulated. GOX could be present in the initial flow from the LOX fire valve to the LOX flow control orifice providing all the characteristic elements of particle impact ignition mechanism. This ignition source is controlled by filtration and remote operation.
[5] Heat of compression is not possible due to the lack of an exposed non metal in the flow.
[6] Friction heating in a flow orifice is not possible.
[7] Mechanical impact is not possible due to the lack of an impact on a polymer.
[8] The component is not electrically powered.
[9] Flow friction is only possible is flow leaks through the threads across the Teflon tape used to seal. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[10] Chatter does not occur in this component.
[11] A kindling chain exists if the stainless steel ignites by particle impact or Teflon tape seal ignites by flow friction and spreads to the stainless steel body.
[12] The component is flammable, and contains one possible and one remotely possible ignition mechanism, as well as kindling chain. The valve is remotely operated minimizing the risk effects on personnel. The reaction effect is marginal.

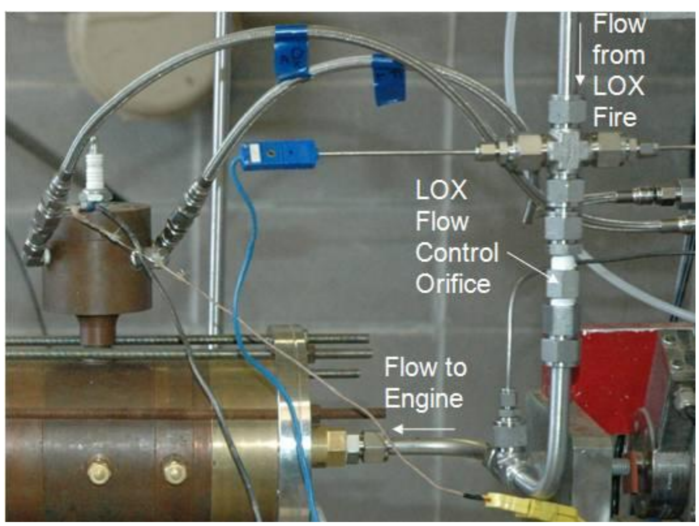


Figure A.38 LOX flow control orifice on facility

A.5.6 LOX Main Vent Valve

This component is the active source of pressure relief for the LOX run tank. The valve is a pneumatically actuated, spring return, normally open, globe valve. The valve is connected to the top of the run tank and when open will relieve pressure from the tank. The LOX main vent valve technical data, nomenclature, cross-sectional diagram, and oxygen wetted flow path is the same as the LOX Main valve. This information is found in Section A.5.3.

Table A.16 LOX main vent PGV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Main Relief Valve	Pneumatic Globe Valve, 1/2" Ports, With Fail Open Actuator, Cv=1.7	Circle Seal Controls, Inc	CES60T1-08B-NO	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[5]	0[6]	0[7]	1[8]	0[9]	2[10]	0[11]	Yes[12]	B[13]
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure.(Manual 36, pg 29, Table 3.12)
[5] All characteristics of particle impact are present; as a vent valve, this is a high-velocity gas component whenever it functions. Plus the valve geometry has severe internal impact points. GOX flow could impact the LOX Main valve seat housing presenting a particle impact ignition hazard. The LOX is filtered before entering the tank to remove particulate introduced into the system in the filling process mitigating this ignition source. In addition, the risk of particulate is low given flow out of the top of the tank. Further this is a remotely operated component.
[6] Heat of compression is not possible due to the lack of an exposed non metal in the flow.
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is remotely possible.
[9] The component is not electrically powered.
[10] All characteristic elements of flow friction are present; GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[11] Chatter does not occur in this component.
[12] A kindling chain exists if the Teflon stem seal or seat seal ignites by particle impact, or flow friction and propagates to the stem and body. The probability of ignition by mechanical impact is low; however particle impact and flow friction present more critical ignition sources.
[13] The valve possesses flammable components, one remotely possible and one possible ignition mechanisms, as well as kindling chain. The valve is remotely operated minimizing the effect on personnel. The reaction effect is marginal

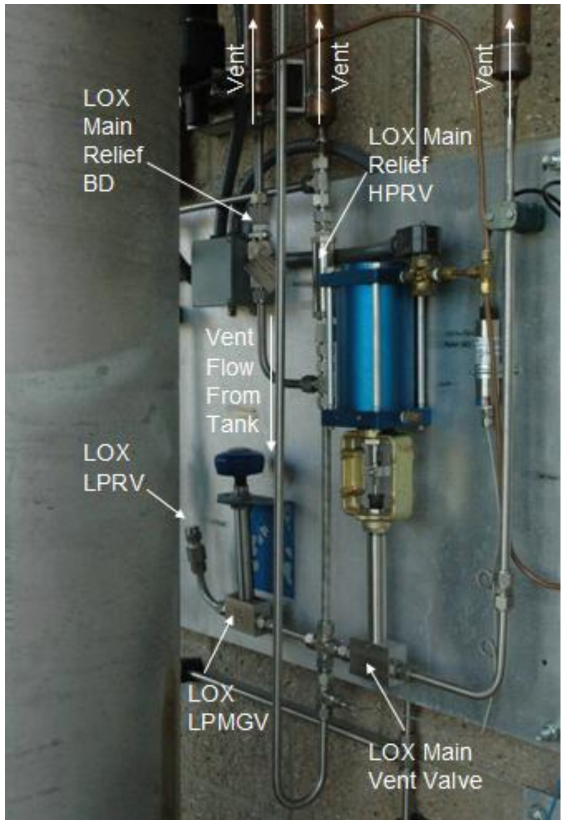


Figure A.39 LOX main vent and relief on facility

A.5.7 LOX Main Relief Burst Disc

This component is a passive source of pressure relief for the LOX run tank. The disk is connected to the top of the run tank along with the LOX main relief valve, and a LOX high pressure relief valve. The disk has a burst pressure of 3000 psi at temperature of 72°F. This is also a redundancy measure to maintain pressures less than the maximum operational pressure of the LOX tank and flow lines.

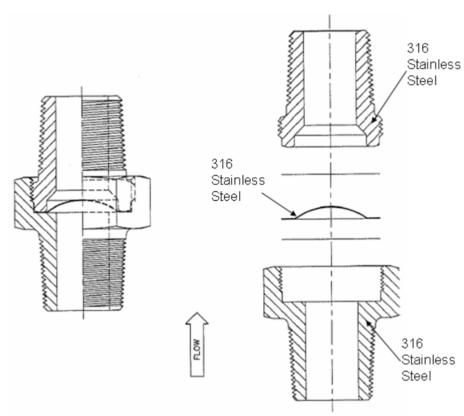


Figure A.40 LOX main relief burst disc cross section

Table A.17 LOX main relief burst disc OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
Burst Disc (BD)	**Rupture Disk, 3000psig, @ 72°F**	**ZOOK, Inc**	0.5"-PB Metal Rupture Disk, ST4-2-00 Holder Rupture Disk Holder	**TBD**

Component	Material	Worse-Case Operating Condition		Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter		
Upper Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	0[4]	0[5]	0[6]	0[9]	0[8]	1[9]	0[10]	Yes[11]	B[12]
Lower Body	316 Stainless Steel			Yes									
Burst Disc	316 Stainless Steel			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Particle impact is remotely possible. The burst disc is a fragmenting style; fragments of the disc can become particles blown downstream at high velocities. There are no direct impingement points in SS vent lines; however, it is important to understand how the disc fails. The preferred BD for oxygen systems is one that pedals rather than fragments. This ignition source is controlled using a straight line flow path with larger copper burn resistant vent lines.
[5] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
[6] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[7] Mechanical impact is not possible due to missing the characteristic elements of large impacts and a non metal at the point of impact
[8] The component is not electrically powered.
[9] All characteristic elements of flow friction are present; flow could leak past the Teflon sealing surface however the configuration is unlikely to produce a vibrating or chafed Teflon sliver in the flow path.
[10] Chatter does not occur in this component.
[11] A kindling chain exists if the stainless steel body ignites by particle impact or Teflon sealing tape ignites by flow friction and propagates to body.
[12] The BD possesses flammable components, one remotely possible ignition mechanisms, as well as kindling chain. The component is autonomously operated (passive relief device). The reaction effect is marginal.

A.5.8 LOX Main Relief High Pressure Relief Valve

This component is a passive source of pressure relief for the LOX run tank. The relief valve is connected to the top of the run tank along with the LOX main vent valve, and the LOX main burst disk. The relief valve is set to a relief pressure of 17.24 MPa (2500 psi). This component is a second order redundancy relief mechanism for the LOX run tank.

Technical Data

- Set Pressure Range: 10 to 2400 Psig (0.7 to 166 bar)
- Set Pressure Tolerance: Factory Preset +/– 5% on increasing pressure
- Reseal: Elastomer Seals 90% - 95% of Actual Crack Pressure
  Teflon™ may be slightly lower
- Inline Valves *(Series HPRV)*:
  Proof Pressure: 3700 Psig (225 bar)
  Burst Pressure: >5000 Psig (345 bar)
- Temperature Range: -320°F to 400°F (-220°C to 205°C)

Based on seal selection, see ordering information

Materials of Construction

Component	Valve Body Material			
	Brass	**Carbon**	**303 Stainless Steel**	**316 Stainless Steel**
Inlet Body, Outlet Cap, Spring Chamber, Spring Retainer, O'ring Spreader	Brass, ASTM B16	Brass, ASTM B16	303 SS, ASTM A582[1]	316 SS, ASTM A479[1]
Poppet	303 SS, ASTM A582			
Spring	302 SS/ 17-7 PH ASTM A313			
Locking Screw	18 - 8 SS			
Seals[2]	As Specified, see ordering information			
Pull Stud	Brass, ASTM B16	303 SS, ASTM A582		316 SS, ASTM A479
Pull Ring	Plated Steel			

1 PTFE dry lubricant applied to threads
2 Lubricated with Krytox™ GPL 202

Figure A.41 LOX main relief HPRV technical data

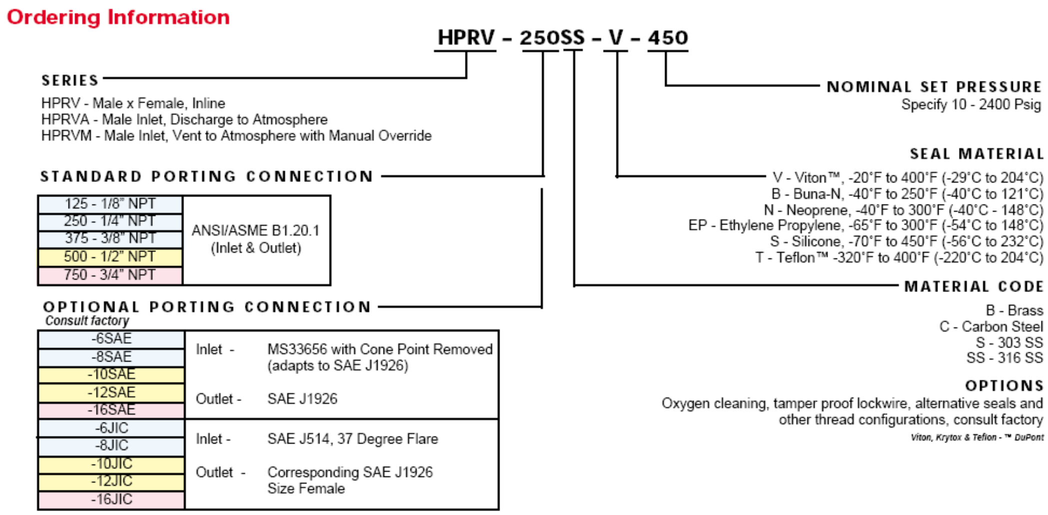


Figure A.42 LOX main relief HPRV technical data

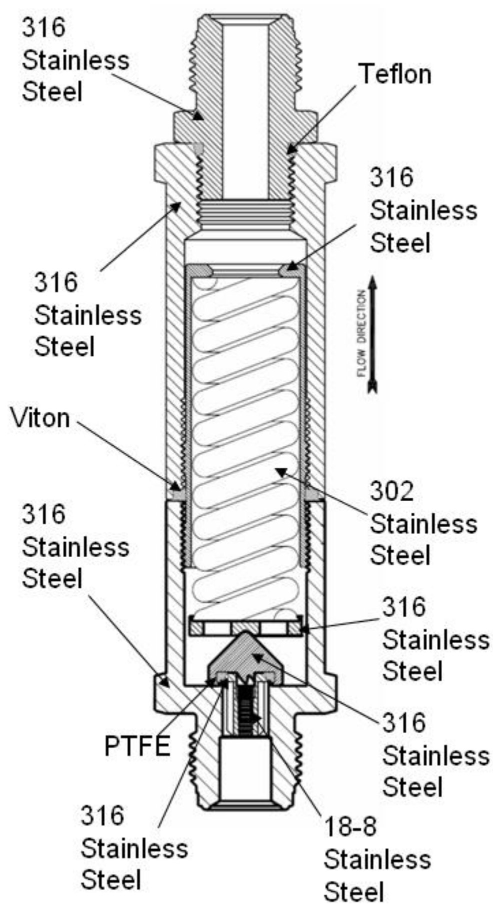


Figure A.43 LOX main relief HPRV cross section

Table A.18 LOX main relief HPRV OCA

<table>
<tr><th colspan="2">Nomenclature</th><th colspan="3">Description</th><th colspan="4">Manufacturer</th><th colspan="3">Part Number</th><th colspan="2">Facility Label</th></tr>
<tr><td colspan="2">LOX Main Relief HPRV</td><td colspan="3">2400 psig, 1/2" Port</td><td colspan="4">Generant</td><td colspan="3">HPRV-500SS-T-2400</td><td colspan="2">TBD</td></tr>
<tr><th rowspan="2">Component</th><th rowspan="2">Material</th><th colspan="2">Worse-Case Operating Condition</th><th rowspan="2">Material Flammable?
Yes/No</th><th colspan="7">Ignition Mechanism Ratings (0-4)</th><th rowspan="2">Kindling Chain? Yes/No</th><th rowspan="2">Reaction Effect (A-D)</th></tr>
<tr><th>Temp (°F)</th><th>Press (psi)</th><th>Particle Impact</th><th>Comp. Heating</th><th>Friction/Galling</th><th>Mechanical Impact</th><th>Elec. Arc/Spark</th><th>Flow Friction</th><th>Other/ Chatter</th></tr>
<tr><td>Upper Body</td><td>316 Stainless Steel</td><td rowspan="9">Ambient[1]</td><td rowspan="9">2500[2]</td><td>Yes[3]</td><td rowspan="9">1[6]</td><td rowspan="9">0[7]</td><td rowspan="9">0[8]</td><td rowspan="9">1[9]</td><td rowspan="9">0[10]</td><td rowspan="9">1[11]</td><td rowspan="9">1[12]</td><td rowspan="9">Yes[13]</td><td rowspan="9">C[14]</td></tr>
<tr><td>Lower Body</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Spring Chamber</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Spring Retainer</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Spring</td><td>302 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Poppet</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Poppet O-ring Seal Outlet Seal</td><td>PTFE</td><td>Yes[4]</td></tr>
<tr><td>Body Seal</td><td>Viton</td><td>Yes[5]</td></tr>
<tr><td>Locking Screw</td><td>18-8 Stainless Steel</td><td>Yes</td></tr>
</table>

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Viton A is flammable in 31.5 -57.5 % Oxygen at ambient pressure. (Manual 36, pg 33, Table 3.12)
[6] All characteristics of particle impact are present in the relief valve; however, the LOX is filtered before entering the tank to remove particulate and the configuration of vent flow path is straight. This ignition source is remotely possible.
[7] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
[8] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[9] In operation this valve will experience chatter (repeated impacts) on the check valve seat. In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is remotely possible.
[10] The component is not electrically powered.
[11] All characteristic elements of flow friction are present; flow could leak past the Teflon sealing surface however the configuration is unlikely to produce a vibrating or chafed Teflon sliver in the flow path.
[12] In operation this valve will experience chatter (repeated impacts) on the check valve seat. In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is remotely possible. This is not a significant ignition source.
[13] A kindling chain exists if the stainless steel body ignites by particle impact or Teflon sealing tape ignites by flow friction and propagates to body.
[14] The valve possesses flammable components, four remotely possible ignition mechanisms, as well as kindling chain. The component is autonomously operated (passive relief device). Though the probability of ignition is low, any ignition could lead to burn-out at these pressures. The reaction effect is critical.

A.5.9 LOX Low Pressure Manual Globe Valve

A manual globe valve is connected to the top of the LOX run tank. The valve is used to isolate the LOX low pressure relief valve from the tank when the tank is pressurized to operating conditions. This component is only opened between tests when LOX is in the tank.

CIRCLE SEAL CONTROLS, INC.

MV/ES 12 & 60 Series

0 12,000 psig & 0 6000 psig DYNAFLOW® Globe & Angle Shutoff Valve

Features

- Zero leakage
- Throttling control without wire drawing
- Spindle threads external to packing
- Positive spindle retention
- Metal-to-metal bonnet seal
- Extended stem for extreme temperatures\
- Bi-directional
- Field tested at 1×10^{-7} torr to 12,000 psi with zero leakage

Technical Data

Body Construction Materials	303 or 316 stainless steel
Seat & Packing Material	Teflon®
Operating Pressures	MV12 & ES12: 0 to 12,000 psi (827 bar) MV60 & ES60: 0 to 6000 psi (414 bar)
Proof Pressures	MV12 & ES12: 18,000 psi (1,241 bar) MV60 & ES60: 9000 psi (621 bar)
Burst Pressures	MV12 & ES12: 48,000 psi (3,310 bar) minimum MV60 & ES60: 24,000 psi (1,655 bar) minimum
Operating Temperatures	MV12 & MV60: –65° F to +250° F (–54° C to +121° C) ES12 & ES60: –452° F to +450° F (–269° C to +232° C)
Connection Sizes	⅛"–1"
Leakage	All series and actuators: bubble-tight

Note: Proper filtration is recommended to prevent damage to sealing surface.

Figure A.44 LOX low pressure MGV technical data

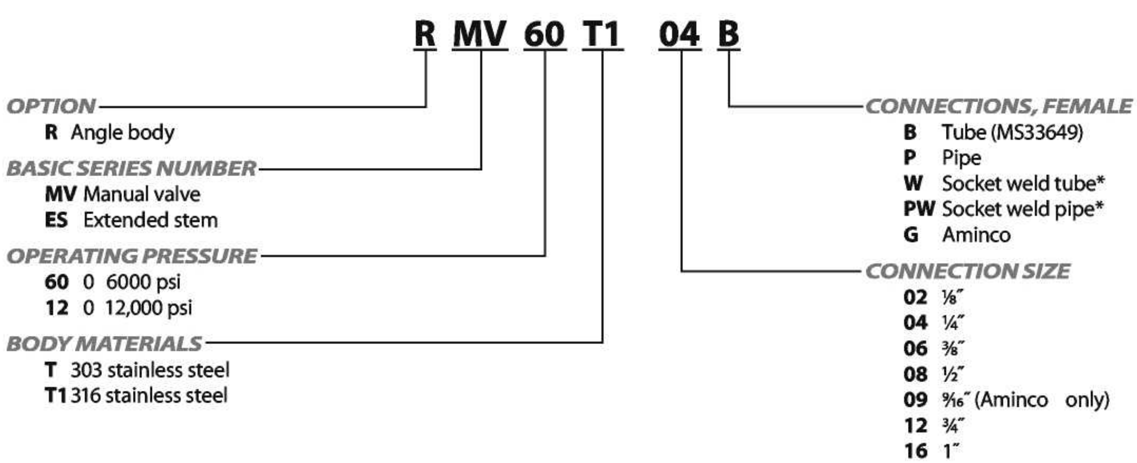


Figure A.45 LOX low pressure MGV nomenclature

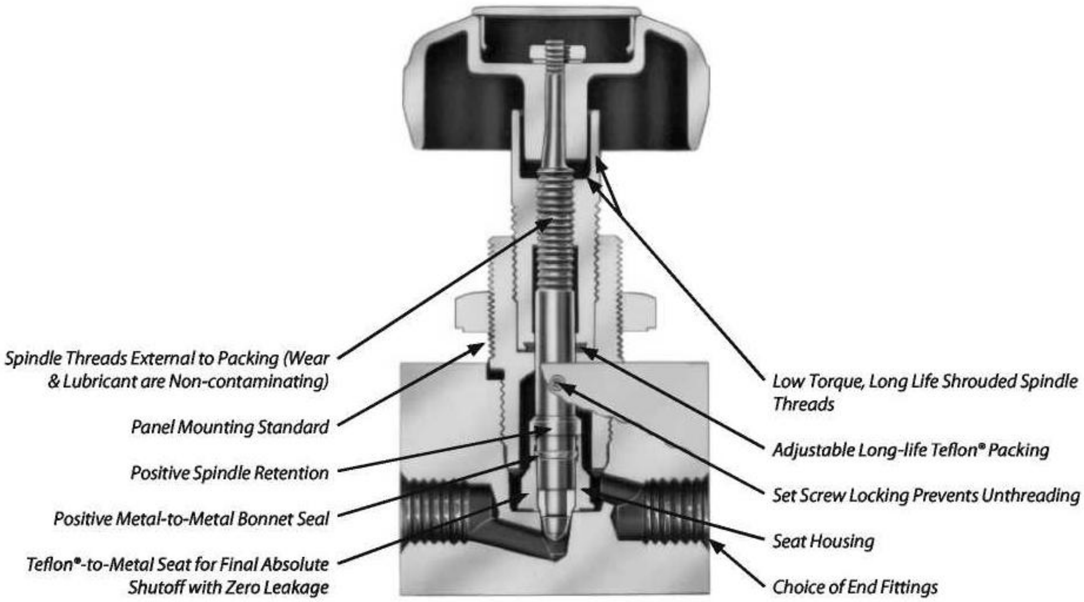


Figure A.46 LOX low pressure MGV cross section

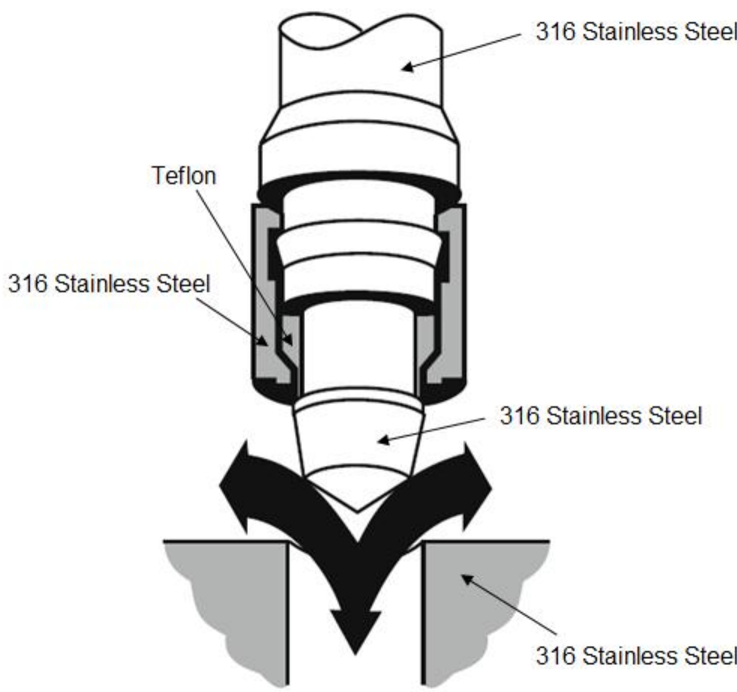


Figure A.47 LOX low pressure relief MGV oxygen wetted flow path

Table A.19 LOX low pressure MGV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX LPMGV	Manual Globe Valve, 1/2" Ports, With Fail Closed Actuator, Cv= 1.7	Circle Seal Controls, Inc	MV60T1-08B	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel			Yes[3]									
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon	Ambient[1]	2500[2]	Yes[4]	1[5]	0[6]	0[7]	0[8]	0[9]	1[10]	0[11]	Yes[12]	C[13]
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

1 Worst case operating sustained temperature from a single point failure.
2 Worst case operating pressure from max k-bottle pressure.
3 Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
4 Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
5 All characteristics of particle impact are present. However, the valve is operationally employed in low pressure situations.
6 Heat of Compression is not possible due to the lack of rapid pressurization.
7 Friction/Galling is not possible due to missing two or more rubbing surfaces.
8 Mechanical impact cannot occur due to the hand operated stem.
9 The component is not electrically powered.
10 Flow friction is remotely possible in this component. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
11 Chatter does not occur in this component.
12 A kindling chain exists if the Teflon ignites by flow friction and propagates to the stem and body. The probability of ignition by flow friction is low, but a kindling chain does exist.
13 The valve possesses flammable components, two remotely possible ignition mechanisms, as well as kindling chain; however the valve is hand operated increasing the effect on personnel. Ignition will lead to burn-out if ignition occurs while operated under pressures greater than the flammability limits of stainless steel. Though the probability of ignition is low, the reaction effect is critical

A.5.10 LOX Low Pressure Relief Valve

The LOX low pressure relief valve is connected to the run tank downstream of the LOX manual globe valve. The valve is set to a relief pressure of 150 psi (1.034 MPa) and allows the tank to vent before and between testing. The relief valve can be isolated from the tank using the LOX low pressure manual globe valve.

CIRCLE SEAL CONTROLS, INC.

500 Series

Adjustable Popoff & Inline Relief Valves
0.5 to 150 psig (10 bar)

Features

- Popoff or inline valves
- Adjustable crack pressure
- Zero leakage
- Optional factory preset
- Accurate set pressure
- Wide range of cracking pressure
- Tamper-proof adjustment
- 100% seat leakage tested
- PED certifications and CE marking available for most models

Applications

- System overpressure protection
- Storage tanks
- Freon® recovery systems
- Medical equipment
- Refrigeration & heating equipment
- Measuring & dispensing pumps
- Communications equipment
- Process control instruments
- R & D pilot plants
- Vacuum pump safety

Technical Data

Body Construction Materials	Aluminum, brass, 303 or 316 stainless steel
O-ring Materials	Buna N, ethylene propylene, neoprene, silicone, Teflon®, or Viton®
Spring Materials	302 stainless steel or 17-7 PH stainless steel
Operating Pressure	Vacuum to 200 psig (14 bar)
Inline Valve Proof Pressure	400 psig (28 bar)
Inline Valve Burst Pressure	Above 500 psig (34 bar)
Temperature Range	−320° F to +400° F (−196° C to +204° F) *Based on o-ring & body material, see "How to Order"*
Connection Sizes	⅛ inch to 1¼ inch

Figure A.48 LOX LPRV technical data

500 Series

How to Order

D 5 59 A – 2 M – 10

VARIATION††
- **D** Deflector cap
- **K** Cryogenic service, special cleaning & testing (stainless steel only)

SEAL MATERIAL & TEMPERATURE RANGE
- **20** Teflon®
  520 Series**: -100° F to +400° F (-73°C to +204°C)
  K520 Series**: -320° F to +165° F (-196°C to +74°C)
- **24** Silicone*, -70° F to +450° F (-57°C to +232°C)
- **32** Viton®, -20° F to +400° F (-29°C to +204°C)
- **33** Neoprene, -40° F to +300° F (-40°C to +149°C)
- **59** Buna N, -65° F to +275° F (-54°C to +135°C)
- **62** Ethylene propylene, -65° F to +300° F (-54°C to +149°C)
- **80** Teflon®, -320° F to +165° F (-196°C to +74°C)

CRACKING PRESSURE
Specify cracking pressure setting in psig (0.5 – 150 psig)

CONNECTION
See "Valve Size & Type Codes" table, below

VALVE SIZE
Pipe sizes in ⅛″ increments
(see "Valve Size & Type Codes" table, below)

BODY MATERIAL
- **A** Aluminum
- **B** Brass
- **T** 303 stainless steel†
- **T1** 316 stainless steel

'D' Variation: Prefixed part number is supplied with a cap which diverts high pressure blasts from personnel and instruments, and serves as a rain and dust shield.

* *Not available over 74.9 psi (5 bar)*

** *520 Series: Teflon® o-ring*
K520 Series: Polished Teflon® o-ring, cryogenic testing and serialization
580 Series: Polished Teflon® o-ring
† *Not available for PED applications*
†† *Blank if not required*

To specify PED certification, add PED prefix to the part number.

Valve Size & Codes

Size	Pipe Thread Male	Pipe Thread Male/Female	British Pipe Thread Male/Female	British Taper Pipe Male
⅛″	–1M	—	—	–1S
¼″	–2M	–2MP	–2SX	–2S
⅜″	–3M	–3MP	–3SX	–3S
½″	–4M	–4MP	–4SX	–4S
¾″	–6M	–6MP	–6SX	–6S
1″	–8M	–8MP	—	–8S
1¼″	—	–10MP	—	—

Figure A.49 LOX LPRV nomenclature

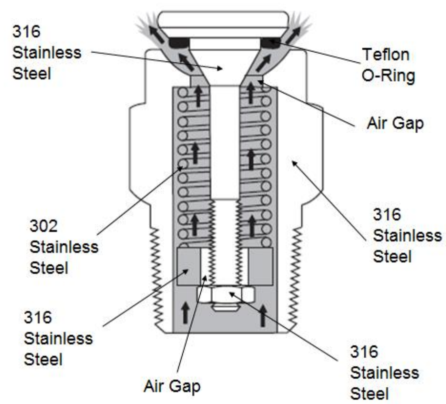


Figure A.50 LOX LPRV cross section

Table A.20 LOX LPRV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX LPRV	150 psig, ½" port, Cv=3.5	Circle Seal Controls, Inc	MV60T1-08B	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel			Yes[3]									
Nut	316 Stainless Steel			Yes									
Lower Spring Retainer	316 Stainless Steel	Ambient[1]	Ambient[2]	Yes	1[5]	0[6]	0[7]	1[8]	0[9]	1[10]	0[11]	Yes[12]	A[13]
Spring	302 Stainless Steel			Yes									
Poppet	316 Stainless Steel			Yes									
O-Ring	Teflon			Yes[4]									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] All characteristics of particle impact are present. Particulate may be present. However, with cracking pressure set to 150 psig, stainless steel considered burn-resistant, thus particle impingement on SS under this application is acceptable.
[6] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces
[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is remotely possible.
[9] The component is not electrically powered.
[10] Flow friction is remotely possible in this component. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[12] A kindling chain exists if the stainless steel ignites by particle impact or the Teflon ignites by flow friction and propagates to the body.
[13] The valve possesses flammable components, three remotely possible ignition mechanisms, as well as kindling chain; however the valve is autonomously operated. Due to the proximity to personnel, if ignition occurs and trim (i.e. thin) pieces of the stainless steel valve burn, the reaction effect is critical.

A.5.11 LOX Fill Filter

The LOX fill filter is located immediately downstream of the LOX fill Dewar source and directly upstream of the LOX fill pneumatic globe valve. The primary function is to filter out particulate entering the LOX run tank. The filter element is sintered bronze with a 220 micron (0.0087 in) rating. This serves as filtration point at the entrance to the LOX system. The LOX fill filter cross sectional diagram, and oxygen wetted flow path is the same as the LOX main filter. This information is found in section A.5.2 of this document

Table A.21 LOX fill filter OCA

Nomenclature		**Description**			**Manufacturer**				**Part Number**			**Facility Label**	
LOX Fill Filter		**Tee Filter assembly, 220μ filter element**			**Chase Filter & Components.**				**50B-8S8S-2P2**			**TBD**	
Component	**Material**	**Worse-Case Operating Condition**		**Material Flammable?** Yes/No	**Ignition Mechanism Ratings** (0-4)							**Kindling Chain? Yes/No**	**Reaction Effect (A-D)**
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter		
Head	Brass	Ambient[1]	2500[2]	No[3]	0[6]	0[7]	0[8]	0[9]	0[10]	2[11]	0[12]	No[13]	A[14]
Bowl	Brass			No									
Element	Sintered Bronze			No[4]									
O - Ring	Teflon			Yes[5]									
O - Ring	Teflon Encap. Viton A			Yes									
Back – Up Ring	Teflon			Yes									
Port Seal	Teflon			Yes									

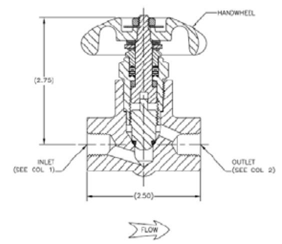
[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[4] Bronze is not considered flammable at the worst case operating conditions stated above Bronze does not burn until experiencing pressures > 10,000 psi. (Manual 36, Table 3.1, pg 18)
[5] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[6] Particle Impact is not probable in this valve due to missing the characteristic element of a flammable target
[7] Heat of Compression is not possible in Liquid Oxygen.
[8] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[9] Mechancal impact cannot occur in this component.
[10] The component is not electrically powered.
[11] Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[12] Chatter does not occur in this component.
[13] A kindling chain does not exist. If the Teflon ignites by flow friction and propagates to the burn resistant brass body will extinguish the combustion. The probability of ignition by flow friction is low and no kindling chain exists.
[14] The valve possesses flammable components, one possible remotely possible ignition mechanism, as well as no kindling chain. Personnel are present at the time of operation of this component; however, this component presents low risk of ignition. The reaction effect is negligible.

A.5.12 LOX Fill Line Vent Valve

The LOX fill line vent valve is located in the LOX fill line between the LOX fill filter and the LOX fill valve. This component is used to vent the pressure in the LOX transfer hose after filling the LOX run tank.

Short Stem Cryogenic Valves

T9450 Series
T9460 Series



Application

The T9450 and T9460 series valves are designed for use on portable cryogenic cylinders and other in-line shut-off valve applications. Approved for TPED in accordance with EN1626.

Features

- Spring loaded stem seal automatically adjusts for any gasket wear, eliminating the need to constantly retighten the packing nut.
- Non-rising stem and low profile allow the valve to fit into tight areas and still provide easy access.
- Unique pressure-sealed moisture barrier helps prevent freeze up at cryogenic temperatures.
- Conical swivel seal design helps prevent seat galling from over torquing.
- Cleaned for liquid oxygen service per CGA G-4.1.
- Maximum working pressure is 600 PSIG.
- Working temperature range is -320°F to +165°F.

Materials

Body....................Brass
Bonnet....................Brass
Seat Disc....................CTFE
Stem Seal Gasket....................PTFE
Handwheel....................Aluminum
Spring....................Stainless Steel
Upper Stem....................Brass
Lower Stem....................Manganese Bronze

Ordering Information

Part Number	Inlet	Outlet	Orifice A	Length B	Height (Approx.) C	Tube D	Cv Factor
T9452	¼" F.NPT	¼" F.NPT	.250	2½"	2¾"	None	.72
T9453	⅜" F.NPT	⅜" F.NPT	.406				1.08
T9454	½" F.NPT	½" F.NPT					1.10
T9464CA	.675 Tube	⅜" F.NPT	.406	2½"	2¾"	1⅛"	1.08
T9464DA						2⅛"	
T9464ADA						3⅜"	

Figure A.51 LOX fill line vent technical data

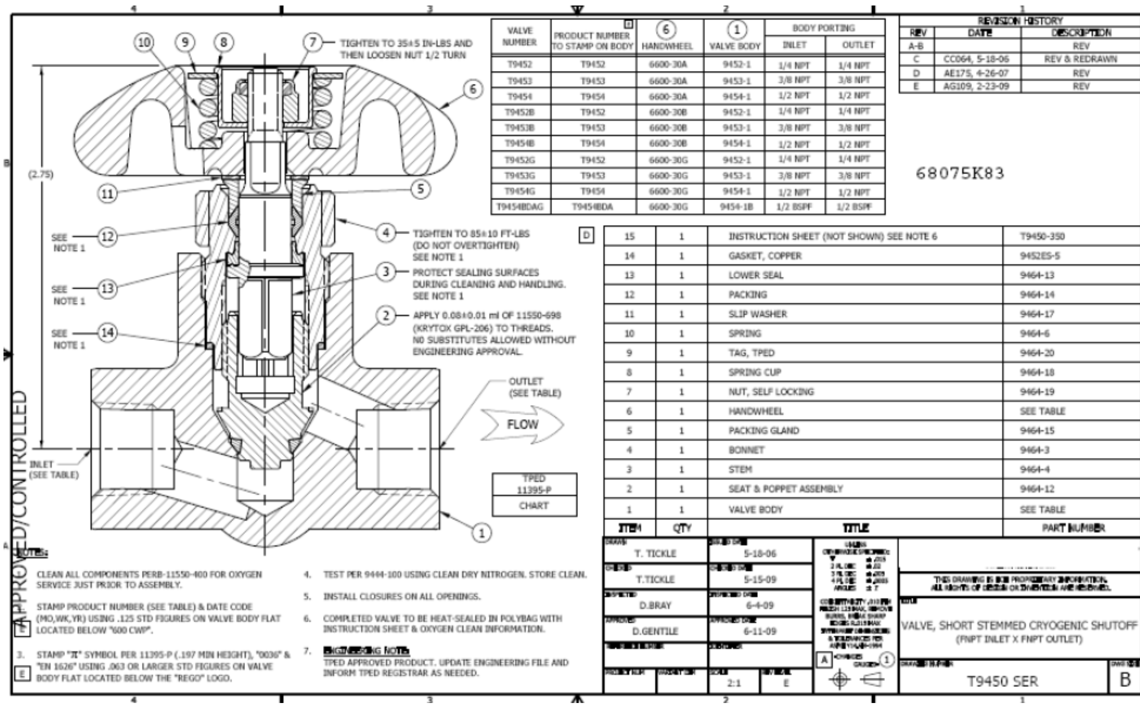


Figure A.52 LOX fill vent valve manufacturer part drawing

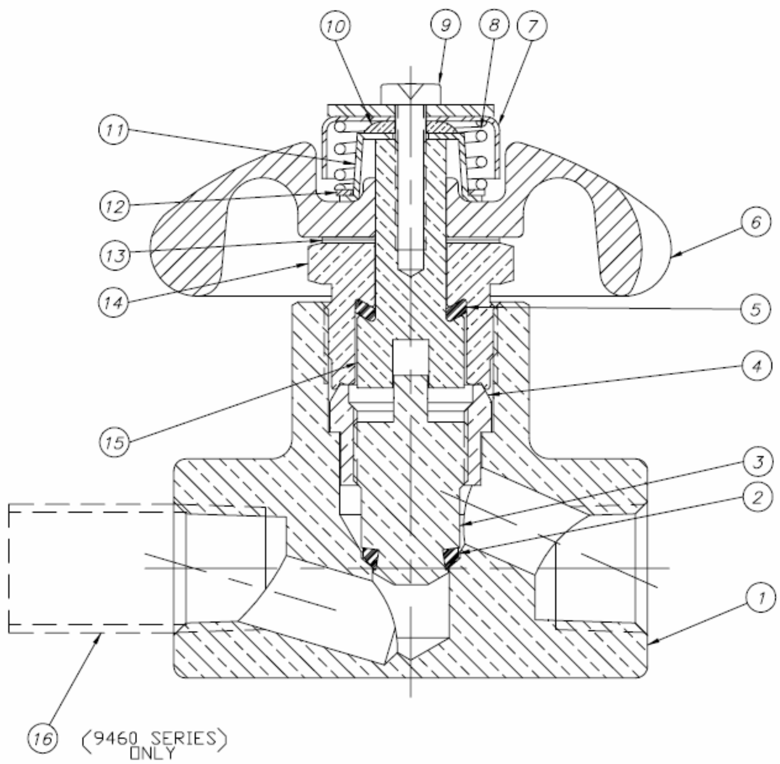


Figure A.53 LOX fill line vent valve cross section

Table A.22 LOX fill line vent valve component materials

Item Number	Description	Material
1	Body	Brass
2	Seat Disc	PCTFE
3	Nipple	Manganese Bronze
4	Bushing	Brass
5	Gasket	PTFE
6	Hand wheel	Aluminum
7	Spring Retainer	302 SS
8	Spring	302 SS
9	Screw and Washer	302 SS
10	Washer	Brass
11	Seal	LDPE
12	Washer	Nylon
13	Washer	PTFE
14	Bonnet	Brass
15	Stem	Brass
16	Tube	304 SS

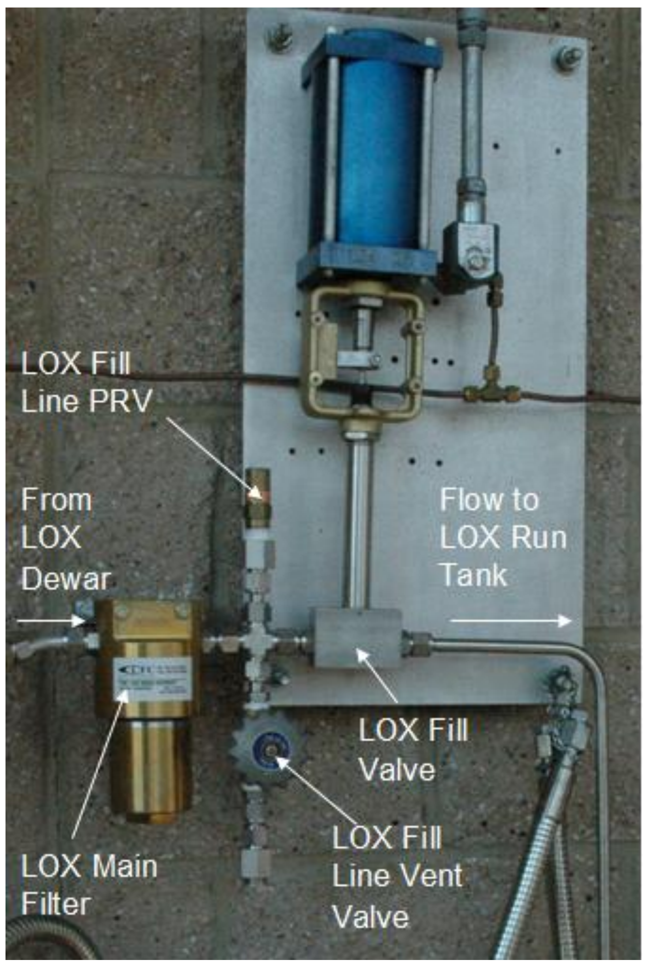


Figure A.54 LOX fill valve on facility

Table A.23 LOX fill line vent valve OCA

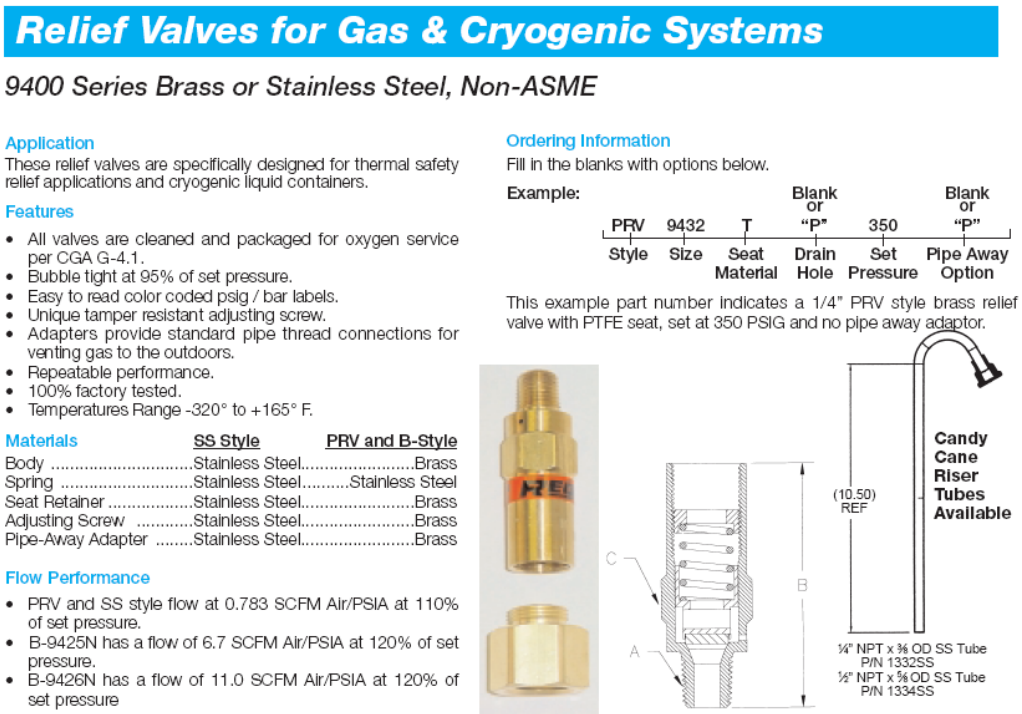
Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Fill Line Vent Valve	Short Stem Cryogenic Shutoff Valve	Rego Cyro-Flow Products	T9454	TBD

Component	Material	Worse-Case Operating Condition		Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter		
Body	Brass	Ambient[1]	2500[2]	No[3]	0[10]	0[11]	0[12]	0[13]	0[14]	1[15]	0[16]	No[17]	A[18]
Seat Disc	PCTFE			Yes[4]									
Nipple	Manganese Bronze			No[5]									
Bushing	Brass			No									
Gasket	PTFE			Yes									
Hand Wheel	Aluminum			Yes[6]									
Spring Retainer	302 Stainless Steel			Yes[7]									
Spring	302 Stainless Steel			Yes									
Screw & Washer	302 Stainless Steel			Yes									
Seal	LDPE			Yes[8]									
Washer	Nylon			Yes[9]									
Washer	PTFE			Yes									
Bonnet	Brass			Yes									
Stem	Brass			No									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Bronze is not considered flammable at the worst case operating conditions stated above. Bronze does not burn until experiencing pressures > 7000 psi. (Manual 36, Table 3.1, pg 18)
[6] Aluminum (commercially pure) is flammable at any pressure in 100% Oxygen (Manual 36, pp 19, Table 3.1)
[7] 300 Series Stainless Steel must be considered flammable above 111 psi in 100% Oxygen. (Manual 36, pp 19, Table 3.1)
[8] PE is flammable in 17.5 % Oxygen at ambient pressure. (Manual 36, pg 31, Table 3.12)
[9] Nylon is flammable in 21 % Oxygen at ambient pressure. (Manual 36, pg 31, Table 3.12)
[10] Particle Impact is not probable in this valve due to missing the characteristic element of a flammable target
[11] Heat of Compression is not possible due to no volume to compress.
[12] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[13] Mechanical impact cannot occur in this valve because of the multi-turn, hand operated stem.
[14] The component is not electrically powered.
[15] All characteristic elements of flow friction are present; however this is only remotely possible due to the Teflon material choice for the seal and sealing tape.
[16] Chatter does not occur in this component.
[17] A kindling chain does not exist in this valve. If the Teflon seat disc ignites by flow friction the only possible ignition source, the combustion will not propagate to the stem and body because of non-flammable materials.
[18] The valve possesses flammable and non-flammable components, one possible/no probable ignition mechanism, and no kindling chain; the reaction effect is negligible.

A.5.13 LOX Fill Line Pressure Relief Valve

This component is used to relieve the pressure build up from the LOX transfer hose after filling. This is a passive relief device that supplies pressure relief if there is any cryogenic fluid remaining in the transfer hose that is not sufficiently vented with the LOX fill line vent valve.



Relief Valves for Gas & Cryogenic Systems

9400 Series Brass or Stainless Steel, Non-ASME

Application

These relief valves are specifically designed for thermal safety relief applications and cryogenic liquid containers.

Features

- All valves are cleaned and packaged for oxygen service per CGA G-4.1.
- Bubble tight at 95% of set pressure.
- Easy to read color coded psig / bar labels.
- Unique tamper resistant adjusting screw.
- Adapters provide standard pipe thread connections for venting gas to the outdoors.
- Repeatable performance.
- 100% factory tested.
- Temperatures Range -320° to +165° F.

Materials	SS Style	PRV and B-Style
Body	Stainless Steel	Brass
Spring	Stainless Steel	Stainless Steel
Seat Retainer	Stainless Steel	Brass
Adjusting Screw	Stainless Steel	Brass
Pipe-Away Adapter	Stainless Steel	Brass

Flow Performance

- PRV and SS style flow at 0.783 SCFM Air/PSIA at 110% of set pressure.
- B-9425N has a flow of 6.7 SCFM Air/PSIA at 120% of set pressure.
- B-9426N has a flow of 11.0 SCFM Air/PSIA at 120% of set pressure

Ordering Information

Fill in the blanks with options below.

Example:

PRV	9432	T	Blank or "P"	350	Blank or "P"
Style	Size	Seat Material	Drain Hole	Set Pressure	Pipe Away Option

This example part number indicates a 1/4" PRV style brass relief valve with PTFE seat, set at 350 PSIG and no pipe away adaptor.

Figure A.55 LOX fill line pressure relief valve technical data

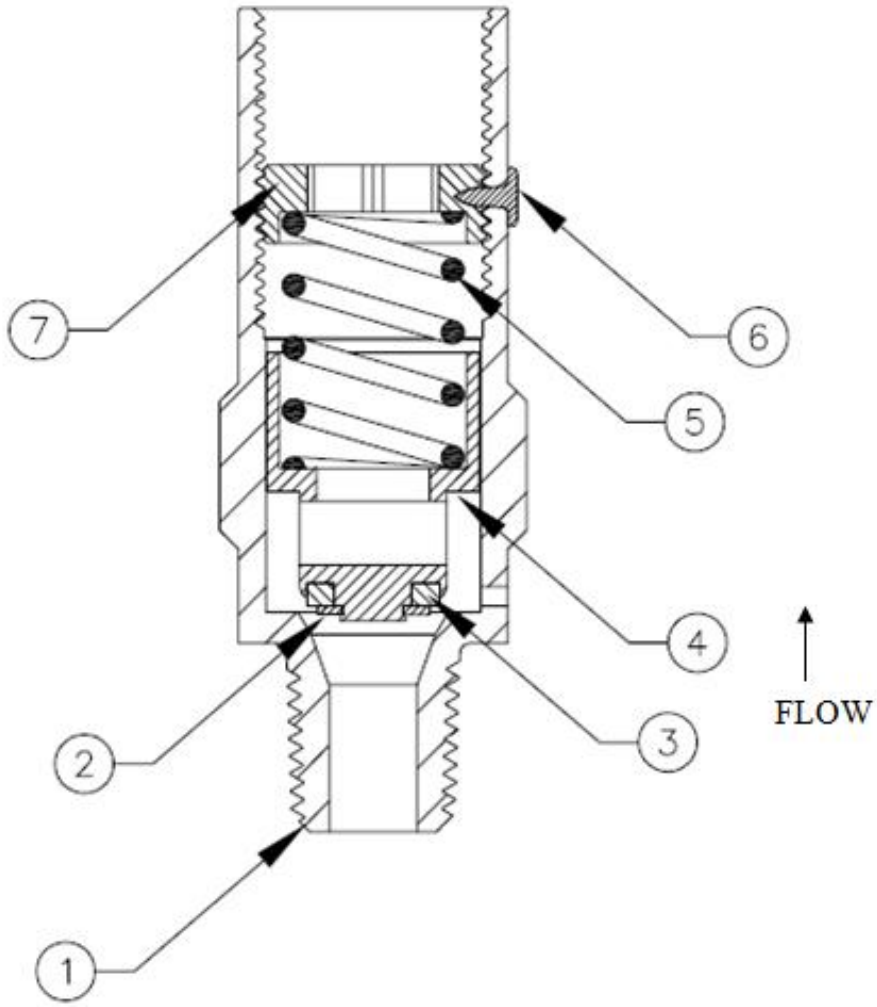


Figure A.56 LOX fill line pressure relief valve cross section

Table A.24 LOX fill line pressure relief component materials

Item Number	Description	Material
1	Body	Brass
2	Washer	Brass
3	Seat Disc	PTFE
4	Poppet	Brass
5	Spring	302 Stainless Steel
7	Adjusting Screw	Brass

Table A.25 LOX fill line pressure relief valve OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Fill Line PRV	Low Pressure Relief Valve, 1/2" Ports, 350 psi,	Rego Cyro-Flow Products	PRV9434F	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	Brass	Ambient[1]	2500[2]	No[3]	0[6]	0[7]	0[8]	0[9]	0[10]	0[11]	0[12]	No[13]	A[14]
Washer	Brass			No									
Seat Disc	PTFE			Yes[4]									
Poppet	Brass			No									
Spring	302 Stainless Steel			Yes[5]									
Adjusting Screw	Brass			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Brass is not considered flammable at the worst case operating conditions stated above. Brass does not burn until experiencing pressures > 7000 psi, and will melt before it burns. (Manual 36, Table 3.1, pg 18)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] 300 Series Stainless Steel must be considered flammable above 111 psi in 100% Oxygen. (Manual 36, pp 19, Table 3.1)
[6] Particle Impact is not probable since the GOX vent flow is to atmosphere. This removes the characteristic element of flammable target. The valve material is constructed of a non-flammable Brass.
[7] Heat of Compression is not possible. There is not an exposed non-metal to ignite when venting to atmosphere. This removes one characteristic element.
[8] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[9] Mechanical impact is possible in this relief valve configuration since there is no nonmetal or reactive metal at the point of impact.
[10] The component is not electrically powered.
[11] The flow friction characteristic element of exposed nonmetal in flow path is missing from configuration.
[12] Chatter does not occur in this component.
[13] A kindling chain does not exist. If there was a source of ignition the combustion would extinguish due to valves materials non-flammability.
[14] The valve possesses flammable and non-flammable components, no credible ignition mechanisms, and no kindling chain; the reaction effect is negligible.

A.5.14 LOX Fill Valve

This component isolates the LOX Dewar and the LOX run tank. The LOX fill valve technical data, nomenclature, cross-sectional diagram, and oxygen wetted flow path is the same as the LOX Main valve. This information can be found in Section A.5.3.

Table A.26 LOX fill PGV OCA

Nomenclature		Description			Manufacturer				Part Number				Facility Label	
LOX Fill Valve		**Pneumatic Globe Valve, 1/2" Ports, With Fail Closed Actuator, Cv= 1.7**			**Circle Seal Controls, Inc**				**CES60T1-08B-NC**				**TBD**	
Component	**Material**	**Worse-Case Operating Condition**		**Material Flammable? Yes/No**	**Ignition Mechanism Ratings (0-4)**							**Kindling Chain? Yes/No**	**Reaction Effect (A-D)**	
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/ Spark	Flow Friction	Other/ Chatter			
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[5]	0[6]	0[7]	0[8]	0[9]	2[10]	0[11]	Yes[12]	B[13]	
Stem	316 Stainless Steel			Yes										
Stem Seal	Teflon			Yes[4]										
Poppet	316 Stainless Steel			Yes										
Seat	316 Stainless Steel			Yes										
Port Seal	Teflon			Yes										

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Viton A is flammable in 31.5 -57.5 % Oxygen at ambient pressure. (Manual 36, pg 33, Table 3.12)
[6] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. The initial flow from the fire valve to the flow control orifice is not jacketed with cryogenic nitrogen however it is insulated. GOX could be present in the initial flow from the LOX fire valve to the LOX flow control orifice providing all the characteristic elements of particle impact ignition mechanism. This ignition source is controlled by filtration.
[7] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end.
[8] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[9] In mechanical impact test data Teflon experienced 0/40 reactions/tests at 500 psi (Manual 36, Table 3.16, pg 42).
[10] The component is not electrically powered.
[11]Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or Teflon port seal. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[12] Chatter does not occur in this component.
[13] A kindling chain exists if the valve body ignites by particle impact or the Teflon ignites by flow friction and propagates to the stem and body. The probability of ignition by flow friction is low but a kindling chain does exist.
[14] The valve possesses flammable components, two possible ignition mechanism, as well as kindling chain; the valve is remotely operated decreasing the risk on personnel. The reaction effect is marginal.

A.5.15 LOX Non Return Check Valve

This component is used to prevent the back flow of LOX from the tank into the LOX fill line.

CIRCLE SEAL CONTROLS, INC.

200 Series *0 to 3000 psig Check Valves*
H200 Series *0 to 6000 psig Check Valves*

Features & Benefits

Quick opening/positive closing
- Provides a wide range of adaptability

Large flow capacity
- The patented sealing principle effects complete leakproof closing under all pressure conditions

Zero leakage
- Compact, easy installation. Efficient inline piston reduces size and weight

Floating o-ring
- The streamlined poppet and full ports offer minimum restriction to flow

Technical Data

Body Construction Materials	Aluminum, brass, steel, 303 or 316 stainless steel
O-ring Materials	Buna N, ethylene propylene, fluorosilicone, Kalrez®, neoprene, Teflon®, and Viton®
Operating Pressure	*200 Series:* to 3000 psig (207 bar) *H200 Series:* to 6000 psig (414 bar)
Proof Pressure	1.5 times operating pressure
Rated Burst Pressure	*200 Series:* 2.5 : 1 *H200 Series:* 4 : 1
Cracking Pressure	0.1 to 25 psig (0.007 to 1.72 bar)
Temperature Range	−320° F to +550° F (−196° C to +288° C) *Based on o-ring & body material, see "How to Order"*
Connection Sizes	⅛″ to 2″

Note: Proper filtration is recommended to prevent damage to sealing surfaces.

Figure A.57 LOX fill NRCV

200 Series / H200 Series

How to Order

H 2 49 T1 – 4TT (L) – 1

VARIATION
- **H** Modified construction for 6000 psig service (¼″ to 1½″ tube, ⅛″ to 1¼″ pipe and larger)
- **K** Cryogenic service, special cleaning and testing (stainless steel valves only)

O-RING MATERIAL, TEMPERATURE & CRACKING PRESSURE RANGE
- **49** Buna N, −65° F to +250° F, 2–4 psig
- **59** Buna N, −65° F to +275° F, 0.5–1 psig
- **69** Buna N (fuels), −65° F to +180° F, 0.5–1 psig
- **62** Ethylene propylene, −65° F to +300° F, 2–4 psig
- **64** Fluorosilicone, −80° F to +350° F, 0.5–1 psig
- **65** Kalrez®, −40° F to +550° F, 0.5–1 psig
- **33** Neoprene, −40° F to +300° F, 2–4 psig
- **53** Neoprene, −40° F to +250° F, 0.5–1 psig
- **24** Silicone, −70° F to +450° F, 0.5–1 psig
- **32** Viton®, −20° F to +400° F, 0.5–1 psig
- **20*** Teflon®, −100° F to +400° F, 8 psig maximum
- **20*** Teflon® (K220T), −320° F to +165° F, 8 psig maximum
- **80*** Teflon® (no cyrogenic testing), −320° F to +165° F, 8 psig

MATERIAL
- **A** 2024–T4/T351 aluminum††
- **B** Brass††
- **A1** 6061–T6/T651 aluminum††
- **S** Steel†
- **T** 303 stainless steel†
- **T1** 316 stainless steel

CRACKING PRESSURE
Call out dash number if not standard
- **1** 1 psig

SPECIAL CHARACTERISTICS
- **030** Hole in poppet head, thousandth of an inch
- **L** Lock wire

SIZE & END CONNECTIONS (INLET/OUTLET)
Pipe sizes in ⅛″ increments
Tube sizes in 1⁄16″ increments
- **P** Female pipe, NPT
- **T** Male tube, AS4395 (MS33656)
- **B** Female tube, AND10050
- **C** Gyrolok® tube fittings
- **D** Male straight thread, AS4395 (MS33656) w/ cone point removed
- **E** Flareless male tube, MS33514 (SAE)
- **F** Male tube, SAE flare 45°
- **H** Hose, MS33658
- **J** Female tube, MS33649
- **K** British parallel pipe (male)
- **L** British parallel pipe (female)
- **R** Female tube, SAE straight thread, MS16142
- **S** British taper pipe (male)
- **X** British taper pipe (female)
- **U** Bulkhead tube, AS4396 (MS33657)

* *For Teflon®, specify stainless steel body material. The stainless steel valve design provides a Teflon® static seal for use in systems with low or high temperatures or with liquids or gases which would cause excessive swell or shrinkage of elastomeric compounds.*
† *Not available for PED applications.*
†† *For PED applications, brass bodies are limited to a maximum temperature of +100° F (+38° C), aluminum bodies are limited to a maximum temperature of +200° F (+93° C)*

Figure A.58 LOX fill NRCV nomenclature

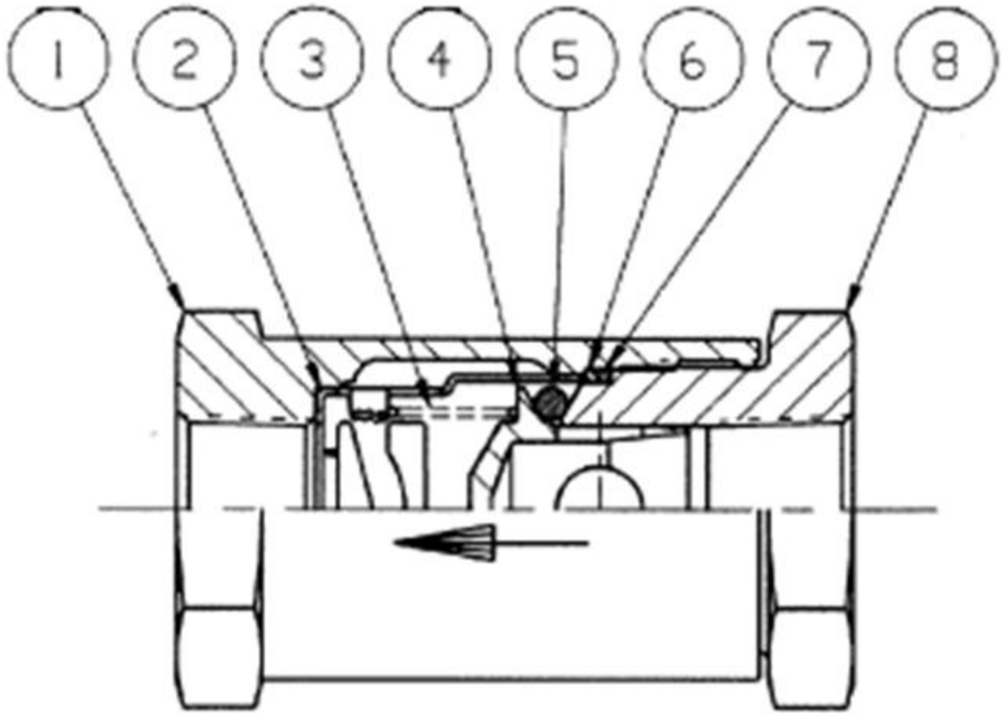


Figure A.59 LOX fill NRCV cross section

Table A.27 LOX main relief NRCV component materials

Component Number	Component	Material
1	Housing	316 Stainless Steel
2	Spring Guide	316 Stainless Steel
3	Spring	302 Stainless Steel
4	Poppet	316 Stainless Steel
5	O-Ring	Teflon
6	Back up Ring	316 Stainless Steel
7	Gasket	Teflon
8	End	316 Stainless Steel

Table A.28 LOX fill NRCV OCA

<table>
<tr><th colspan="2">Nomenclature</th><th colspan="3">Description</th><th colspan="4">Manufacturer</th><th colspan="4">Part Number</th><th>Facility Label</th></tr>
<tr><td colspan="2">Non Return Check Valve (NRCV)</td><td colspan="3">3000 psig, 1/2" Port, Cv= 3.5</td><td colspan="4">Circle Seal Controls, Inc</td><td colspan="4">K220T1-4PP</td><td>TBD</td></tr>
<tr><th rowspan="2">Component</th><th rowspan="2">Material</th><th colspan="2">Worse-Case Operating Condition</th><th rowspan="2">Material Flammable?
Yes/No</th><th colspan="7">Ignition Mechanism Ratings (0-4)</th><th rowspan="2">Kindling Chain? Yes/No</th><th rowspan="2">Reaction Effect (A-D)</th></tr>
<tr><th>Temp (°F)</th><th>Press (psi)</th><th>Particle Impact</th><th>Comp. Heating</th><th>Friction/Galling</th><th>Mechanical Impact</th><th>Elec. Arc/ Spark</th><th>Flow Friction</th><th>Other/ Chatter</th></tr>
<tr><td>Body</td><td>316 Stainless Steel</td><td rowspan="8">Ambient[1]</td><td rowspan="8">350[2]</td><td>Yes[3]</td><td rowspan="8">2[5]</td><td rowspan="8">0[6]</td><td rowspan="8">0[7]</td><td rowspan="8">0[8]</td><td rowspan="8">0[9]</td><td rowspan="8">1[10]</td><td rowspan="8">0[11]</td><td rowspan="8">Yes[12]</td><td rowspan="8">B[13]</td></tr>
<tr><td>Spring Guide</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Spring</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Poppet</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>O-Ring</td><td>Teflon</td><td>Yes[4]</td></tr>
<tr><td>Back up Ring</td><td>316 Stainless Steel</td><td>Yes</td></tr>
<tr><td>Gasket</td><td>Teflon</td><td>Yes</td></tr>
<tr><td>End Body</td><td>316 Stainless Steel</td><td>Yes</td></tr>
</table>

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max Dewar pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] Particle impact in LOX is generally limited by flow velocities except during boil-off/cavitation conditions during filling. Under these conditions, ignition potential is limited due to filtration and low pressures. During chill down when filling LOX in the tank, GOX flow will be present in the lines. The initial flow from the fire valve to the flow control orifice is not jacketed with cryogenic nitrogen however it is insulated. GOX could be present in the initial flow from the LOX fire valve to the LOX flow control orifice providing all the characteristic elements of particle impact ignition mechanism. This ignition source is controlled by filtration.
[6] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] In mechanical impact test data Teflon experienced 0/40 reactions/tests at 500 psi (Manual 36, Table 3.16, pg 42).
[9] The component is not electrically powered.
[10] Flow friction is not a credible ignition source for in Liquid Oxygen; however, during chill down GOX flow could leak past the Teflon sealing surface or the Teflon tape port connection seal presenting all the characteristic elements of flow friction ignition. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[11] In operation this valve will experience chatter (repeated impacts) on the check valve seat. In mechanical impact test data Teflon experienced 0/40 reactions/tests at 500 psi (Manual 36, pg 41, Table 3.16). This is not a significant ignition source.
[12] A kindling chain exists if the Teflon stem seal or seat seal ignites by flow friction or compression heating and propagates to the stem and body. The probability of ignition by both ignition mechanisms is low, but a kindling chain does exist.
[13] The valve possesses flammable components, credible ignition mechanisms, as well as kindling chain; and the valve is not remotely operated increasing the risk on personnel. These reasons give the valve a marginal rating.

A.5.16 LOX Line Vent Valve

The LOX line vent valve is the active source of pressure relief for the LOX feed lines. The LOX line vent valve technical data, nomenclature, cross-sectional diagram, and oxygen wetted flow path is the same as the LOX main valve. This information is found in Section A.5.3.

Table A.29 LOX line vent PGV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
LOX Line Vent Valve	Pneumatic Globe Valve, 1/2" Ports, With Fail Open Actuator, Cv= 1.7	Circle Seal Controls, Inc	CES60T1-08B-NO	TBD

Component	Material	Worse-Case Operating Condition: Temp (°F)	Worse-Case Operating Condition: Press (psi)	Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4): Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/Chatter	Kindling Chain? Yes/No	Reaction Effect (A-D)
Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[5]	0[6]	0[7]	1[8]	0[9]	2[10]	0[11]	Yes[12]	B[13]
Stem	316 Stainless Steel			Yes									
Stem Seal	Teflon			Yes[4]									
Poppet	316 Stainless Steel			Yes									
Seat	316 Stainless Steel			Yes									
Port Seal	Teflon			Yes									

[1] Worst case operating sustained temperature from a single point failure.
[2] Worst case operating pressure from max k-bottle pressure.
[3] Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
[4] Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
[5] All characteristics of particle impact are present due to LOX to GOX flash vaporization potential, high-pressure, high-velocity venting with flammable stainless steel impingement sites. This is potentially one of the most severe service operations on the system. Thus remote operation is critical.
The LOX flow is filtered directly in front of this component to mitigate this ignition hazard.
[6] Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
[7] Friction/Galling is not possible due to missing two or more rubbing surfaces.
[8] In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, Table 3.16, pg 42). This ignition mechanism is possible but not probable.
[9] The component is not electrically powered.
[10] All characteristic elements of flow friction are present; flow could leak past the Teflon sealing surface or the Teflon port connection seal presenting a flow friction ignition hazard. Leaks must be monitored and corrected to address flow friction ignition mechanism in this component.
[11] Chatter does not occur in this component.
[12] A kindling chain exists if the Teflon stem seal or seat seal ignites by particle impact, or flow friction and propagates to the stem and body. The probability of ignition by compressive heating is low due to the lower initial temperature of the oxygen gas, however particle impact and flow friction present more critical ignition sources.
[13] The valve possesses flammable components, one remotely possible and two possible credible ignition mechanisms, as well as kindling chain. The valve is remotely operated minimizing the effect on personnel. The reaction effect is marginal.

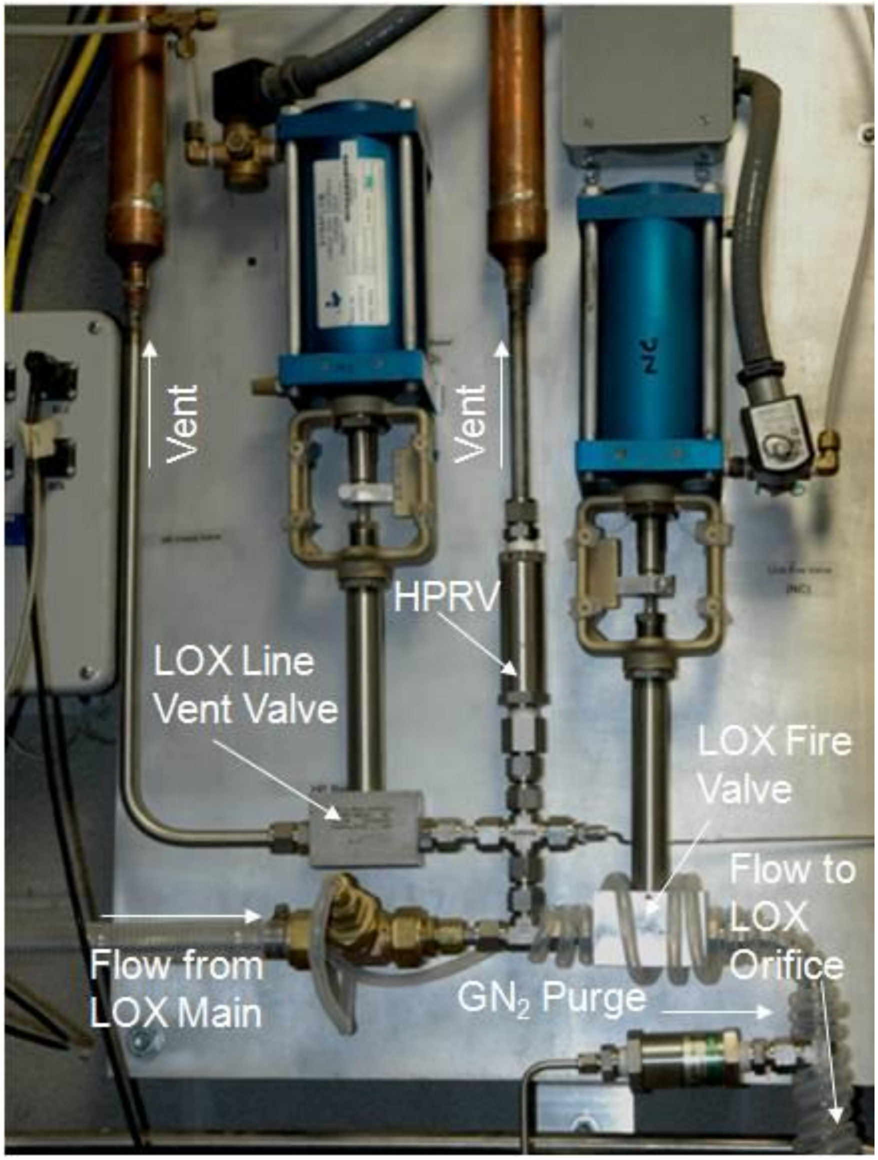


Figure A.60 LOX line vent valve on facility

A.5.17 LOX Line Vent High Pressure Relief Valve

This component is utilized in the facility as the passive source of pressure relief for the LOX feed lines. This is redundancy measure to maintain pressures less than the maximum operational pressure of the flow lines. The LOX line vent HPRV technical data, nomenclature, and cross-sectional diagram, is the same as the LOX main relief HPRV. This information is found in Section A.5.8 of this document.

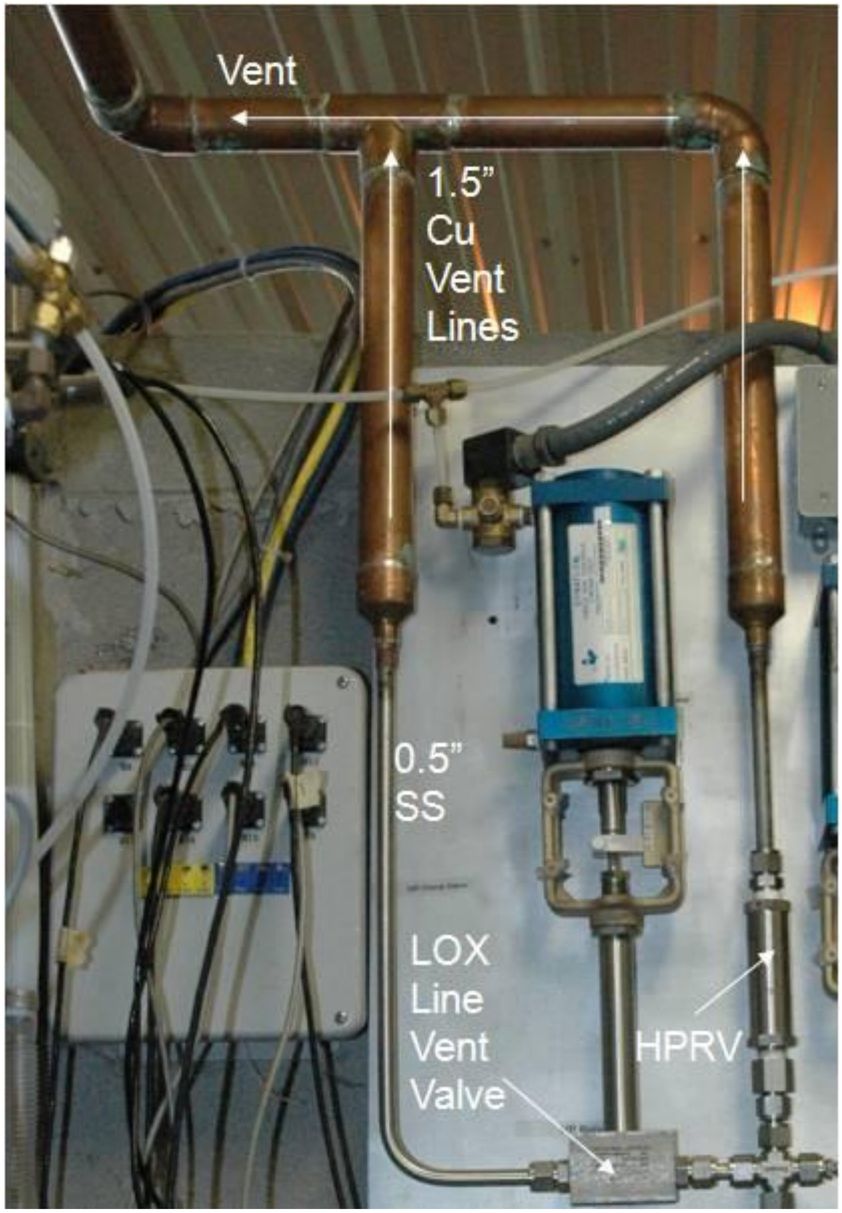


Figure A.61 LOX line vent on facility

Table A.30 LOX line vent HPRV OCA

Nomenclature	Description	Manufacturer	Part Number	Facility Label
High Pressure Relief Valve (HPRV)	2400 psig, 1/2" Port	Generant	HPRV-500SS-T-2400	TBD

Component	Material	Worse-Case Operating Condition		Material Flammable? Yes/No	Ignition Mechanism Ratings (0-4)							Kindling Chain? Yes/No	Reaction Effect (A-D)
		Temp (°F)	Press (psi)		Particle Impact	Comp. Heating	Friction/Galling	Mechanical Impact	Elec. Arc/Spark	Flow Friction	Other/ Chatter		
Upper Body	316 Stainless Steel	Ambient[1]	2500[2]	Yes[3]	2[6]	0[7]	0[8]	1[9]	0[10]	1[11]	1[12]	Yes[13]	B[14]
Lower Body	316 Stainless Steel			Yes									
Spring Chamber	316 Stainless Steel			Yes									
Spring Retainer	316 Stainless Steel			Yes									
Spring	302 Stainless Steel			Yes									
Poppet	316 Stainless Steel			Yes									
Poppet O-ring Seal Outlet Seal	PTFE			Yes[4]									
Body Seal	Viton			Yes[5]									
Locking Screw	18-8 Stainless Steel			Yes									

1 Worst case operating sustained temperature from a single point failure.
2 Worst case operating pressure from max k-bottle pressure.
3 Stainless steel must be considered flammable above 111 psi in 100% oxygen. (Manual 36, Table 3.1, pg 19)
4 Teflon is flammable in 95 -100 % Oxygen at ambient pressure. (Manual 36, pg 29, Table 3.12)
5 Viton is flammable in 31.5 -57.5 % Oxygen at ambient pressure. (Manual 36, pg 33, Table 3.12)
6 All characteristics of particle impact are present due to LOX to GOX flash vaporization potential, high-pressure, high-velocity venting with flammable stainless steel impingement sites. This is potentially one of the most severe service operations on the system. Thus remote operation is critical.
7 Compression heating is not possible due to missing the characteristic element of an exposed nonmetal close to dead end
8 Friction/Galling is not possible due to missing two or more rubbing surfaces.
9 In operation this valve will experience chatter (repeated impacts) on the check valve seat. In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, pg 41, Table 3.16). This ignition mechanism is possible but not probable.
10 The component is not electrically powered.
11 All characteristic elements of flow friction are present; flow could leak past the Teflon sealing surface however the configuration is unlikely to produce a vibrating or chafed Teflon sliver in the flow path.
12 In operation this valve will experience chatter (repeated impacts) on the check valve seat. In mechanical impact test data Teflon experienced 3/40 reactions/tests at 2500 psi (Manual 36, pg 41, Table 3.16). This is not a significant ignition source.
13 A kindling chain exists if the stainless steel body ignites by particle impact or Teflon sealing tape ignites by flow friction and propagates to body.
14 The valve possesses flammable components, three remotely probable and one possible ignition mechanisms, as well as kindling chain. The component is autonomously operated (passive relief device). The reaction effect is marginal.

A.6 OCA System Cleanliness

Oxygen system cleanliness analysis – 1

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

August 6, 2010

Reply to Attn of: EM10 (010-869)

TO: Henry W. Mulkey
Graduate Research Assistant
Propulsion Research Center
University of Alabama Huntsville
Huntsville, AL

FROM: EM10/Gail H. Gordon

SUBJECT: Oxygen Line Samples UAH-PRC (10-093)

The subject samples have been analyzed as requested for NVR and particulates. Results of the analyses which included FTIR analysis of particles are attached.

If you have any questions, please contact Robert Graves at 544-3072 or Richard Boothe at 544-0477.

Gail H. Gordon
Branch Chief
Materials Test Branch

Enclosures

Cc:
EM10/Mr. Perkins/Mr. Boothe
EM10- METTS/Mr. Rohe
EM10-METTS/Mr. Graves
EM10/File

Log # 10-093

Sample Medium	Location	Requestor	Org.	Date Sampled	Particulate < 100u Max= no silting	Particulate 100-250u Max= 93	Particulate 250-300u Max= 3	Particulate >300u Max= 0	NVR mg. / 100ml. Max= 1mg.
#1 Fire Section	JRC	Mulkey	UAH	7/21/2010	not silted	36	1	11	1.2
#2 GOX	JRC	Mulkey	UAH	7/20/2010	not silted	18	1	6	0.1
#3 Igniter	JRC	Mulkey	UAH	7/20/2010	not silted	9	0	0	<=0.1
#4 LOX Main Tank	JRC	Mulkey	UAH	7/20/2010	not silted	TNC	TNC	TNC	0.6

The above samples were analyzed per SN-C-0005 / Level 300A.
TNC= Too numerous to count

Particulate Observations:

#1- The largest synthetic particle/fiber measured 3,750u. The largest metallic particle measured 220u. Also observed were grit, pollen, possible Teflon tape shreds, and possible oxygen compatible lubricant.

#2- The largest synthetic particle/fiber measured 850u. The largest metallic particle measured 75u. Also observed were pollen, possible flash rust, particles with a carbon appearance, and possible oxygen compatible lubricant.

#3- The largest synthetic particle/fiber measured 190u. The largest metallic particle measured 125u. Also, grit,and smaller metallic and synthetic particles/fibers were observed.

#4- A synthetic particle measuring 3500u and a metallic particle measuring 1350u were observed. The sample contained everything listed in the forementioned samples. In addition, possible copper, brass, and stainless steel particles were observed. The sample also contained numerous dark green particles.

FTIR analysis was performed on the NVRs from samples 1 and 4 and two types of particles from sample 4. Analysis showed that both NVRs contained a polyfluoride material (as found in Krytox and other oxygen compatible lubricants) and silicone. White particles from the filter pad were found to be Teflon and the dark green particles were found to be polyamide-polyimide (commonly used in the semi-conductor industry).

Robert Graves/ERC in support of EM 10 at MSFC.

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

September 1, 2010

Reply to Attn of: EM10 (010-931)

TO: Henry W. Mulkey
Graduate Research Assistant
Propulsion Research Center
University of Alabama Huntsville
Huntsville, AL

FROM: EM10/Gail H. Gordon

SUBJECT: Oxygen Line Samples UAH-PRC (10-110)

The subject samples have been analyzed as requested for NVR and particulates. Results of the analyses which included FTIR analysis of particles are attached.

If you have any questions, please contact Robert Graves at 544-3072 or Richard Boothe at 544-0477.

Gail H. Gordon
Gail H. Gordon
Branch Chief
Materials Test Branch

Enclosures

Cc:
EM10/Mr. Perkins/Mr. Boothe
EM10-METTS/Mr. Graves
EM10/File

Log # 10-110

Sample Medium	Location	Requestor	Org.	Date Sampled	Particulate < 100u Max= no silting	Particulate 100-250u Max= 93	Particulate 250-300u Max= 3	Particulate >300u Max= 0	NVR mg. / 100ml. Max= 1mg.
#1 LOX Main Tank	JRC	Mulkey	UAH	8/23/2010	not silted	21	2	8	0.1
#2 LOX Fire	JRC	Mulkey	UAH	8/23/2010	not silted	44	5	7	0.2

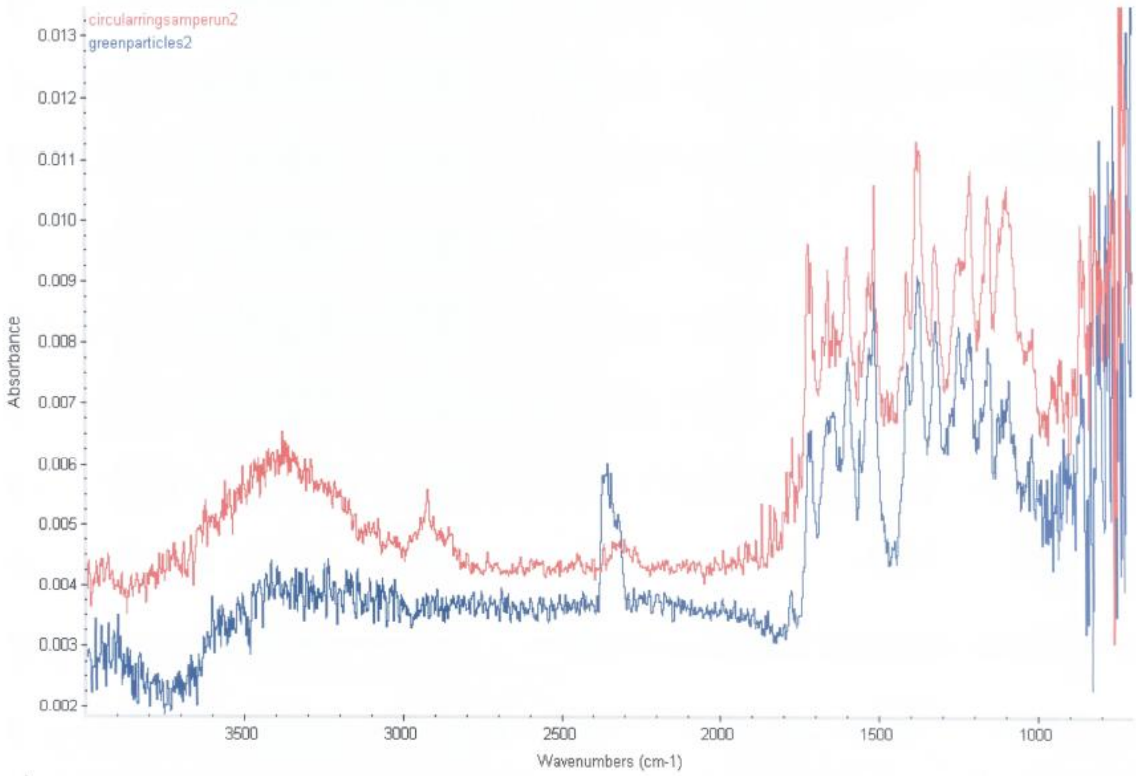
The above samples were analyzed per SN-C-0005 / Level 300A.

Particulate Observations:

#1- The largest synthetic particle/fiber measured 730u. The largest metallic particle/fiber measured 500u. Also observed were grit, pollen, and flora.

#2- The largest synthetic particle/fiber measured 1,020u. The largest metallic particle measured 190u. Also observed were pollen, flora, possible corrosion,and particles with a carbon appearance.

FTIR analysis on the coating from Grayloc ring , PN51239N, was found to be polyamide-polyimide.



circularringsamperun2
greenparticles2
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
Absorbance
3500
3000
2500
2000
1500
1000
Wavenumbers (cm-1)

APPENDIX B

GCH_4 Fuel Annulus Sizing

GCH_4 fuel annulus sizing to match liquid methane injection velocity for the designed LCH_4 mass flow rate of 0.027 kg/s

$m_{GCH4} := 0.027 \cdot \frac{kg}{s}$ — Mass flow of GCH_4

$\rho_{GCH4} := 12.688 \cdot \frac{kg}{m^3}$ — Density of GCH_4 at injection conditions @ 298 K and 1.9 MPa taken from NIST

$t := 0.051 \cdot cm$ — Nozzle thickness of interior LOX swirl post

$d_{O2} := 0.475 \cdot cm$ — LOX nozzle diameter

$$A_{O2} := \frac{\pi}{4} \cdot d_{O2}^2$$

$A_{O2} = 0.177 \cdot cm^2$ — LOX nozzle area

$V_{LCH4} := 38.953 \cdot \frac{m}{s}$ — Liquid methane design velocity

$$A_{GCH4} := \frac{m_{GCH4}}{\rho_{GCH4} \cdot V_{LCH4}}$$

$A_{GCH4} = 0.546\, cm^2$ — GCH_4 required fuel annulus area to match injection velocity

Mathcad Solve Block

$d_{CH4} := 0.676 \cdot cm$ — GCH_4 fuel annulus diameter initial guess

Given

$$A_{GCH4} = \frac{\pi}{4} \cdot \left[d_{CH4}^2 - \left(d_{O2} + 2t \right)^2 \right]$$

$$D_{CH4} := \mathrm{Find}(d_{CH4})$$

$D_{CH4} = 1.0141 \cdot cm$ $\quad$ $D_{CH4} = 0.399\, in$ — GCH_4 required fuel annulus diameter to match injection velocity

APPENDIX C

LOX – GCH_4 Nozzle Sizing

LOX-GCH4 Nozzle Throat Diameter for MISER injector conditions

Conditions

$p_C := 1.896 \cdot MPa$ Designed Chamber Pressure

$C_{star} := 1797.2 \cdot \frac{m}{s}$ Theoretical Characteristic Velocity from Cequel

$m_{LOX} := 0.081 \cdot \frac{kg}{s}$ Liquid Oxygen Mass Flow Rate

$m_{GCH4} := 0.027 \cdot \frac{kg}{s}$ Liquid Methane Mass Flow Rate

$OF := \frac{m_{LOX}}{m_{GCH4}} = 3$ Oxygen to Fuel mass ratio

Find nozzle throat diameter

$A_t := \frac{C_{star} \cdot (m_{GCH4} + m_{LOX})}{p_C}$ $d_t := \sqrt{\frac{4}{\pi} \cdot A_t}$ $d_t = 1.14168 \cdot cm$ $d_t = 0.44948 \cdot in$

Exisitng nozzle

$D_t := 1.135 \cdot cm$ Throat diameter of existing nozzle

$$P_C := \frac{C_{star} \cdot (m_{GCH4} + m_{LOX})}{\left[\frac{\pi (D_t)^2}{4}\right]}$$

$P_C = 1.918 \cdot MPa$ $P_C = 278.24\, psi$ Chamber pressure using exiting nozzle

APPENDIX D

GCH_4 Discharge Coefficient

GCH4 Orifice Discharge Coefficient

$P_{atm} := 14.7 \cdot psi$ Atmospheric Pressure

$\gamma_{Air} := 1.4$ Specific heat ratio of air

$D_F := 0.063 \cdot in$ GCH_4 Orifice Diameter

$R_{Air} := 1716 \cdot \frac{ft \cdot lbf}{slug \cdot R}$ Air Gas constant

$$A_F := \frac{\pi \cdot D_F^{\,2}}{4} = 3.1172 \times 10^{-3} \cdot in^2$$ GCH_4 Orifice area

$T_{Air} := 536.4 \cdot R$ Air Temperature

Air flow driving Pressure gage

$$P_D := \begin{pmatrix} 70 \\ 80 \\ 90 \\ 100 \end{pmatrix} \cdot psi$$

Experimental Air Flow in SCFH

$$Q_{Exp} := \begin{pmatrix} 267 \\ 298 \\ 331 \\ 362 \end{pmatrix} \cdot \frac{ft^3}{hr}$$

Air flow driving Pressure absolute

$$P_{Abs} := P_D + P_{atm}$$

$$P_{Abs} = \begin{pmatrix} 84.7 \\ 94.7 \\ 104.7 \\ 114.7 \end{pmatrix} \cdot psi$$

Air flow from choked propellant mass flow equation

$$m_{dot} := \frac{P_{Abs} \cdot \frac{\pi \cdot D_F^{\,2}}{4} \cdot \gamma_{Air} \cdot \sqrt{\left(\frac{2}{\gamma_{Air} + 1}\right)^{\frac{\gamma_{Air}+1}{\gamma_{Air}-1}}}}{\sqrt{\gamma_{Air} \cdot R_{Air} \cdot T_{Air}}} = \begin{pmatrix} 0.00606 \\ 0.00678 \\ 0.00749 \\ 0.00821 \end{pmatrix} \cdot \frac{lbm}{s}$$

Density of Air at flow conditions

$$\rho_1 := \frac{P_{Abs}}{R_{Air} \cdot T_{Air}} = \begin{pmatrix} 0.4263 \\ 0.4767 \\ 0.527 \\ 0.5773 \end{pmatrix} \cdot \frac{lbm}{ft^3}$$

$i := 0, 1 .. 3$ indices to perform iteration

Air flow from choked propellant equation in SCFH

$$Q_{g_i} := \frac{m_{dot_i}}{\rho 1_i} \qquad Q_{GSC_i} := \frac{Q_{g_i} \cdot P_{Abs_i}}{P_{atm}} \qquad Q_{GSC} = \begin{pmatrix} 4.916 \\ 5.497 \\ 6.077 \\ 6.658 \end{pmatrix} \cdot \frac{ft^3}{min}$$

GCH4 Orifice discharge coefficient

$$C_G := \frac{Q_{Exp}}{Q_{GSC}} = \begin{pmatrix} 0.905 \\ 0.904 \\ 0.908 \\ 0.906 \end{pmatrix} \qquad C_G := mean(C_G) = 0.906$$

APPENDIX E

LOX Orifice Calibration

LOX Orifice Characteristics		
Orifice Diameter m (ft)	1.19390E-03	3.9170E-03
Orifice Area m^2 (ft^2)	1.11969E-06	1.20482E-05

Table E.1 LOX orifice discharge coefficient – 3.45 MPa test set

	Measured Values		NIST Data		Calculated Values			
3.45 MPa Test - 1	**Pressure (MPa)**	**Temp (K)**	**Viscosity (kg/m-s)**	**Density (kg/m^3)**	**Mass Flow (kg/s)**	**Velocity (m/s)**	**C_D**	**Re_D**
1	3.661	279.7	1.444E-03	1001.65	0.0626	55.83	0.6531	46235.71
2	3.647	280.0	1.429E-03	1001.63	0.0625	55.77	0.6537	46654.96
3	3.641	280.2	1.422E-03	1001.62	0.0622	55.47	0.6508	46644.55
4	3.638	280.2	1.422E-03	1001.62	0.0618	55.13	0.6470	46350.44
5	3.636	280.3	1.415E-03	1001.60	0.0623	55.52	0.6518	46914.15
6	3.685	279.2	1.464E-03	1001.57	0.0631	56.27	0.6562	45963.67
7	3.671	279.6	1.446E-03	1001.65	0.0635	56.58	0.6610	46781.89
8	3.649	279.7	1.444E-03	1001.65	0.0625	55.76	0.6534	46182.21
9	3.643	279.8	1.437E-03	1001.63	0.0629	56.05	0.6574	46654.58
10	3.642	280.0	1.429E-03	1001.62	0.0616	54.90	0.6440	45927.83
					Mean		0.6529	
					Std Dev		0.0049	
					2*Stdev		0.0098	

Table E.2 LOX orifice discharge coefficient – 5.17 MPa test set

	Measured Values		NIST Data		Calculated Values			
5.17 MPa Test - 2	**Pressure (MPa)**	**Temp (K)**	**Viscosity (kg/m-s)**	**Density (kg/m^3)**	**Mass Flow (kg/s)**	**Velocity (m/s)**	**C_D**	**Re_D**
1	5.286	282.8	1.313E-03	1002.195	0.0768	68.48	0.6669	62403.32
2	5.283	282.6	1.323E-03	1002.227	0.0758	67.56	0.6582	61105.38
3	5.297	282.4	1.328E-03	1002.243	0.0751	66.90	0.6509	60292.93
4	5.294	282.7	1.317E-03	1002.211	0.0748	66.65	0.6486	60549.60
5	5.312	282.9	1.311E-03	1002.211	0.0745	66.42	0.6453	60628.17
6	5.319	283.0	1.307E-03	1002.195	0.0752	67.01	0.6506	61357.50
7	5.363	283.1	1.305E-03	1002.211	0.0757	67.49	0.6525	61899.18
8	5.354	283.1	1.305E-03	1002.211	0.0753	67.14	0.6498	61582.28
9	5.349	280.7	1.397E-03	1002.403	0.0751	66.90	0.6478	57333.96
10	5.340	280.7	1.397E-03	1002.403	0.0747	66.55	0.6449	57031.08
					Mean		0.6516	
					Std Dev		0.0066	
					2*Stdev		0.0132	

Table E.3 LOX orifice discharge coefficient – 6.21 MPa test set

6.21 MPa Test - 3	Measured Values		NIST Data		Calculated Values			
	Pressure (MPa)	**Temp (K)**	**Viscosity (kg/m-s)**	**Density (kg/m^3)**	**Mass Flow (kg/s)**	**Velocity (m/s)**	C_D	Re_D
1	6.305	280.9	1.386E-03	1002.836	0.0808	71.96	0.6419	62160.02
2	6.315	281.6	1.359E-03	1002.804	0.0793	70.60	0.6293	62190.90
3	6.318	281.9	1.348E-03	1002.772	0.0807	71.88	0.6405	63828.40
4	6.314	282.2	1.337E-03	1002.756	0.0807	71.88	0.6407	64345.77
5	6.320	282.2	1.337E-03	1002.756	0.0813	72.37	0.6448	64788.42
6	6.335	282.2	1.335E-03	1002.756	0.0813	72.37	0.6440	64888.69
7	6.339	282.3	1.331E-03	1002.740	0.0823	73.31	0.6522	65944.21
8	6.360	282.7	1.318E-03	1002.724	0.0818	72.87	0.6472	66180.61
9	6.349	282.9	1.308E-03	1002.692	0.0817	72.78	0.6469	66630.66
10	6.336	282.9	1.308E-03	1002.676	0.0812	72.33	0.6436	66217.45
					Mean		0.6431	
					Std Dev		0.0060	
					2*Stdev		0.0120	

Table E.4 LOX orifice discharge coefficient – 7.24 MPa test set

7.24 MPa Test - 4	Measured Values		NIST Data		Calculated Values			
	Pressure (MPa)	**Temp (K)**	**Viscosity (kg/m-s)**	**Density (kg/m^3)**	**Mass Flow (kg/s)**	**Velocity (m/s)**	C_D	Re_D
1	7.314	280.6	1.401E-03	1003.348	0.0863	76.83	0.6365	65697.49
2	7.328	280.7	1.394E-03	1003.348	0.0878	78.13	0.6466	67138.20
3	7.336	280.8	1.389E-03	1003.348	0.0878	78.16	0.6465	67384.14
4	7.346	280.9	1.387E-03	1003.348	0.0896	79.75	0.6593	68872.26
5	7.308	280.2	1.415E-03	1003.381	0.0878	78.19	0.6480	66193.73
6	7.313	280.4	1.406E-03	1003.365	0.0871	77.55	0.6424	66087.82
7	7.311	280.4	1.403E-03	1003.365	0.0875	77.85	0.6450	66454.16
8	7.313	280.5	1.403E-03	1003.348	0.0883	78.64	0.6515	67126.08
9	7.318	280.6	1.401E-03	1003.348	0.0884	78.68	0.6516	67272.93
					Mean		0.6475	
					Std Dev		0.0064	
					2*Stdev		0.0127	

Table E.5 LOX orifice discharge coefficient – 9.31 MPa test set

9.31 MPa Test - 5	Measured Values		NIST Data		Calculated Values			
	Pressure (MPa)	**Temp (K)**	**Viscosity (kg/m-s)**	**Density (kg/m^3)**	**Mass Flow (kg/s)**	**Velocity (m/s)**	C_D	Re_D
1	9.532	291.5	1.040E-03	1002.836	0.0997	88.76	0.6440	102226.50
2	9.524	292.1	1.024E-03	1002.708	0.0994	88.54	0.6426	103505.62
3	9.525	292.5	1.014E-03	1002.628	0.0994	88.58	0.6428	104538.42
4	9.519	292.8	1.007E-03	1002.564	0.0993	88.42	0.6419	105049.55
5	9.522	293.0	1.002E-03	1002.516	0.1003	89.35	0.6485	106730.26
6	9.529	293.2	9.967E-04	1002.467	0.0999	89.01	0.6458	106891.48
7	9.533	293.4	9.914E-04	1002.419	0.1001	89.18	0.6469	107659.92
8	9.534	293.6	9.887E-04	1002.403	0.1004	89.43	0.6486	108244.22
9	9.495	282.7	1.313E-03	1004.197	0.0998	88.80	0.6459	81093.70
10	9.50097928	282.88889	1.307E-03	1004.181	0.1005	89.35	0.6497	82063.33
					Mean		0.6457	
					Std Dev		0.0028	
					2*Stdev		0.0056	

Table E.6 LOX orifice discharge coefficient – 10.34 MPa test set

10.34 MPa Test - 6	Measured Values Pressure (MPa)	Measured Values Temp (K)	NIST Data Viscosity (kg/m-s)	NIST Data Density (kg/m^3)	Calculated Values Mass Flow (kg/s)	Calculated Values Velocity (m/s)	C_D	Re_D
1	10.188	282.8	1.308E-03	1004.502	0.1029	91.48	0.6425	83881.57
2	10.170	282.9	1.304E-03	1004.486	0.1057	93.95	0.6604	86415.08
3	10.165	283.0	1.302E-03	1004.470	0.1037	92.23	0.6485	84963.88
4	10.249	279.2	1.454E-03	1004.838	0.1036	92.04	0.6446	75922.15
5	10.252	279.4	1.445E-03	1004.822	0.1080	96.01	0.6723	79732.74
6	10.244	279.6	1.440E-03	1004.822	0.1067	94.86	0.6645	79041.38
7	10.232	279.6	1.437E-03	1004.806	0.1080	96.02	0.6730	80133.33
8	10.228	279.7	1.433E-03	1004.806	0.1059	94.08	0.6595	78785.48
9	10.228	279.8	1.430E-03	1004.790	0.1061	94.34	0.6614	79133.72
10	10.2304449	279.94444	1.423E-03	1004.790	0.1050	93.32	0.6541	78665.91
					Mean		0.6581	
					Std Dev		0.0106	
					2*Stdev		0.0213	

Table E.7 LOX orifice discharge coefficient test summary - averages

Test Series	Set Pressure (MPa)	Pressure (MPa)	Temp (K)	Viscosity (kg/m-s)	Density (kg/m^3)	Mass Flow (kg/s)	Velocity (m/s)	C_D	Re_D
1	3.45	3.651	279.87	1.4353E-03	1001.62	0.0625	55.727	0.6529	46431.00
2	5.17	5.320	282.40	1.3300E-03	1002.25	0.0753	67.110	0.6516	60418.34
3	6.21	6.329	282.19	1.3368E-03	1002.75	0.0811	72.235	0.6431	64717.51
4	7.24	7.321	280.57	1.4000E-03	1003.36	0.0878	78.196	0.6475	66914.09
5	9.53	9.521	290.77	1.0683E-03	1002.89	0.0999	88.942	0.6457	100800.30
6	10.34	10.219	280.61	1.3976E-03	1004.71	0.1056	93.834	0.6581	80667.53

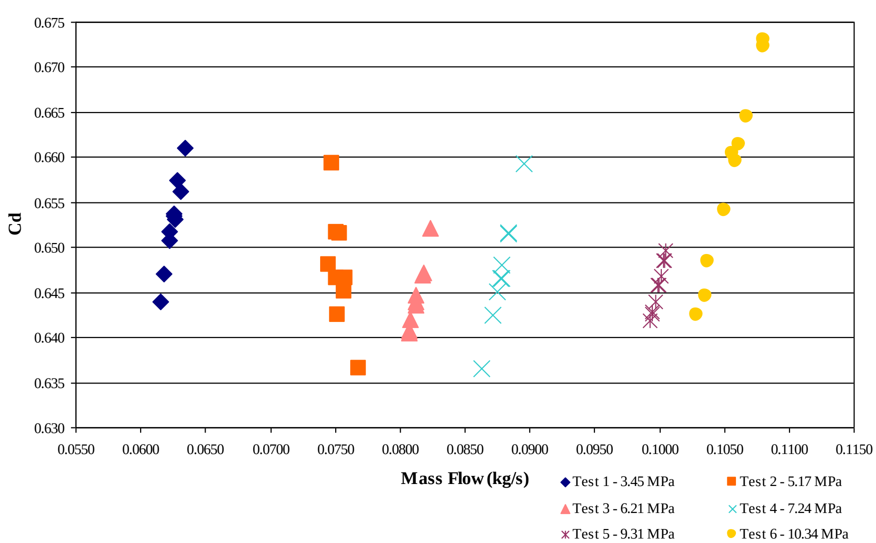


Figure E.1 LOX orifice discharge coefficient versus water mass flow

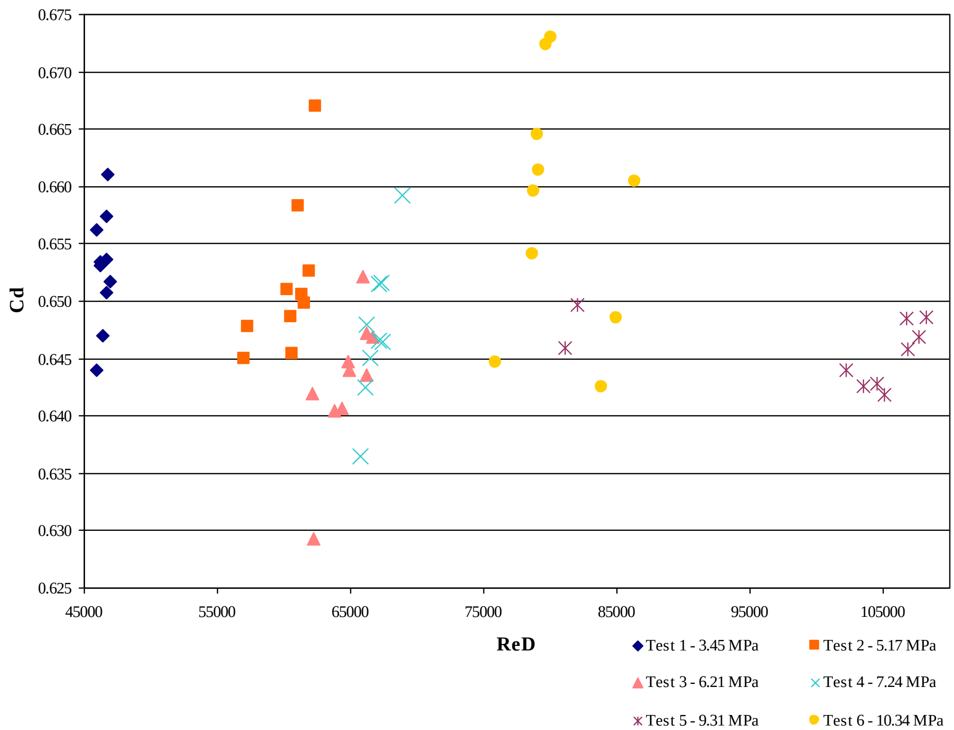


Figure E.2 LOX orifice discharge coefficient versus Reynolds number

APPENDIX F

General Uncertainty Analysis

Taylor Series General Uncertainty Analysis

General Uncertainty Analysis - Measurement of C*
$LOX\text{-}GCH_4$ Rocket Engine

Chamber Pressure

$P_C := 1.896 \cdot MPa \quad P_C = 275\,psi$

Uncertainty associated Chamber Pressure

$U_{PC} := 0.021 \cdot MPa \quad U_{PC} = 3\,psi$

Nozzle Diameter

$D_T := 1.135 \cdot cm \quad D_T = 0.447\,in$

Uncertainty associated Nozzle Diameter

$U_{DT} := 0.0254 \cdot mm \quad U_{DT} = 0.001\,in$

GCH_4 Orifice Discharge Coeff

$C_G := 0.91$

Uncertainty associated GCH_4 Discharge Coeff

$U_{CG} := 0.015$

Fuel Orifice Pressure

$P_F := 8.687 \cdot MPa \quad P_F = 1260\,psi$

Uncertainty associated Fuel Orifice Pressure

$U_{PF} := 0.021 \cdot MPa \quad U_{PF} = 3\,psi$

Fuel Orifice Diameter

$D_F := 0.16 \cdot cm \quad D_F = 0.063\,in$

Uncertainty associated Fuel Orifice Diameter

$U_{DF} := 0.0254 \cdot mm \quad U_{DF} = 0.001\,in$

Fuel Orifice Temperature

$T_F := 298 \cdot K \quad T_F = 536.4\,R$

Uncertainty associated Fuel Orifice Temperature

$U_{TF} := 3 \cdot K \quad U_{TF} = 5.4\,R$

LOX Orifice Discharge Coeff

$C_D := 0.65$

Uncertainty associated LOX Discharge Coeff

$U_{CD} := 0.015$

LOX Orifice Diameter

$D_{LOX} := 0.119 \cdot cm \quad D_{LOX} = 0.047\,in$

Uncertainty associated LOX Orifice Diameter

$U_{DLOX} := 0.0254 \cdot mm \quad U_{DLOX} = 0.001\,in$

LOX Orifice Pressure

$P_{LOX} := 6.136 \cdot MPa \quad P_{LOX} = 889.952\,psi$

Uncertainty associated LOX Orifice Pressure

$U_{PLOX} := 0.021 \cdot MPa \quad U_{PLOX} = 3\,psi$

LOX Orifice Temperature

$T_{LOX} := 103 \cdot K \quad T_{LOX} = 185\,R$

Uncertainty associated LOX Orifice Temperature

$U_{TLOX} := 3 \cdot K \quad U_{TLOX} = 5.4\,R$

LOX Vapor Pressure and Density from Temperature Measurement from NIST @
103 K and 2.241 MPa

LOX Vapor Pressure

$P_V := 0.324 \cdot MPa \quad P_V = 46.992\,psi$

Uncertainty associated Vapor Pressure

$U_{Pv} := 10\% \cdot P_V \quad U_{Pv} = 0.032\,MPa \quad U_{Pv} = 4.699\,psi$

LOX Density

$\rho_{LOX} := 1081.8 \cdot \frac{kg}{m^3} \quad \rho_{LOX} = 67.535\,\frac{lbm}{ft^3}$

Uncertainty associated LOX Density Measurement

$U_\rho := 5\% \cdot \rho_{LOX} \quad U_\rho = 54.09 \cdot \frac{kg}{m^3} \quad U_\rho = 3.377\,\frac{lbm}{ft^3}$

Propellant mass flow rates

Constants for Methane Gas

$$\gamma_F := 1.305$$

$$R_F := 518 \cdot \frac{J}{kg \cdot K}$$

$$R_F = 96.277 \cdot \frac{lbf \cdot ft}{lbm \cdot R}$$

GCH4 Mass Flow

$$m_{GCH4} := \left[\frac{C_G \cdot P_F \cdot \frac{\pi \cdot D_F^{\ 2}}{4} \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{\gamma_F \cdot R_F \cdot T_F}} \right] = 0.027 \cdot \frac{kg}{s}$$

LOX Mass Flow

$$m_{LOX} := C_D \cdot \frac{\pi \cdot D_{LOX}^{\ 2}}{4} \cdot \sqrt{2 \cdot ((\rho_{LOX})) \cdot (P_{LOX} - P_V)} \qquad m_{LOX} = 0.081 \cdot \frac{kg}{s} \qquad m_{LOX} = 0.179 \cdot \frac{lb}{s}$$

Nominal Measured C* Calculation

$$C_{Star} := \frac{P_C \cdot \frac{\pi \cdot D_T^{\ 2}}{4}}{\left[\frac{C_G \cdot P_F \cdot \frac{\pi \cdot D_F^{\ 2}}{4} \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{\gamma_F \cdot R_F \cdot T_F}} \right] + C_D \cdot \frac{\pi \cdot D_{LOX}^{\ 2}}{4} \cdot \sqrt{2 \cdot ((\rho_{LOX})) \cdot [P_{LOX} - (P_V)]}}$$

$$C_{Star} = 1774.605 \cdot \frac{m}{s} \qquad C_{Star} = 5822.2 \cdot \frac{ft}{s}$$

Derivatives for the UMF's

1) Chamber Pressure

$$\theta_{PC} := \frac{\pi \cdot D_T^{\ 2}}{\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^{\ 2} \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^{\ 2} \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}}$$

2) Nozzle Throat Diameter

$$\theta_{DT} := \frac{2 \cdot \pi \cdot D_T \cdot P_C}{\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^{\ 2} \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^{\ 2} \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}}$$

3) Fuel Orifice Discharge

$$\theta_{CG} := -\frac{\pi^2 \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

4) Pressure at Fuel Orifice

$$\theta_{PF} := -\frac{\pi^2 \cdot C_G \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

5) Fuel Orifice Diameter

$$\theta_{DF} := -\frac{2 \cdot \pi^2 \cdot C_G \cdot D_F \cdot D_T^2 \cdot P_C \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

6) Temperature at Fuel Orifice

$$\theta_{TF} := \frac{\pi^2 \cdot C_G \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot P_F \cdot R_F \cdot \gamma_F^2 \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{2 \cdot \left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot (R_F \cdot T_F \cdot \gamma_F)^{\frac{3}{2}}}$$

7) LOX Orifice Discharge Coeff

$$\theta_{CD} := -\frac{\sqrt{2}\cdot\pi^2\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}{\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2}$$

8) LOX Orifice Diameter

$$\theta_{DLOX} := -\frac{2\cdot\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}\cdot P_C\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}{\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2}$$

9) Pressure at LOX Orifice

$$\theta_{PLOX} := -\frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot\rho_{LOX}}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}$$

10) LOX Density

$$\theta_{\rho LOX} := \frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot(P_V - P_{LOX})}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}$$

11) LOX Vapor Pressure

$$\theta_{PVLOX} := \frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot\rho_{LOX}}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}$$

Uncertainty Magnification Factors (UMF's):

1) Chamber Pressure

$$UMF_{PC} := \left[\frac{P_C}{C_{Star}}\cdot(\theta_{PC})\right] = 1$$

$UMF_{PC} = 1$

$$U_{TPC} := \left(\frac{U_{PC}}{P_C}\right)$$ $U_{TPC} = 0.011076$

2) Nozzle Throat Diameter

$$UMF_{DT} := \left[\frac{D_T}{C_{Star}}\cdot(\theta_{DT})\right] = 2$$

$UMF_{DT} = 2$

$$U_{TDT} := \left(\frac{U_{DT}}{D_T}\right)$$ $U_{TDT} = 0.002238$

3) Fuel Orifice Discharge Coeff

$$UMF_{CG} := \left[\frac{C_G}{C_{Star}}\cdot(\theta_{CG})\right] = -0.251$$

$UMF_{CG} = -0.250807$

$$U_{TCG} := \left(\frac{U_{CG}}{C_G}\right)$$ $U_{TCG} = 0.016484$

4) Pressure at Fuel Orifice

$$UMF_{PF} := \left[\frac{P_F}{C_{Star}}\cdot(\theta_{PF})\right] = -0.251$$

$UMF_{PF} = -0.250807$

$$U_{TPF} := \left(\frac{U_{PF}}{P_F}\right)$$ $U_{TPF} = 0.002417$

5) Fuel Orifice Diameter

$$UMF_{DF} := \left[\frac{D_F}{C_{Star}}\cdot(\theta_{DF})\right] = -0.502$$

$UMF_{DF} = -0.501614$

$$U_{TDF} := \left(\frac{U_{DF}}{D_F}\right)$$ $U_{TDF} = 0.015875$

6) Fuel Temperature at Orifice

$$UMF_{TF} := \left[\frac{T_F}{C_{Star}}\cdot(\theta_{TF})\right] = 0.125$$

$UMF_{TF} = 0.125404$

$$U_{TTF} := \left(\frac{U_{TF}}{T_F}\right)$$ $U_{TTF} = 0.010067$

7) LOX Orifice Discharge Coeff

$$UMF_{CD} := \left[\frac{C_D}{C_{Star}}\cdot(\theta_{CD})\right] = -0.749$$

$UMF_{CD} = -0.749193$

$$U_{TCD} := \left(\frac{U_{CD}}{C_D}\right)$$ $U_{TCD} = 0.023077$

8) LOX Orifice Diameter

$$UMF_{DLOX} := \left[\frac{D_{LOX}}{C_{Star}}\cdot(\theta_{DLOX})\right] = -1.498$$

$UMF_{DLOX} = -1.498386$

$$U_{TDLOX} := \left(\frac{U_{DLOX}}{D_{LOX}}\right)$$ $U_{TDLOX} = 0.021345$

9) Pressure at LOX Orifice

$$UMF_{PLOX} := \left[\frac{P_{LOX}}{C_{Star}}\cdot\left(\theta_{PLOX}\right)\right] = -0.396$$

$$UMF_{PLOX} = -0.395877$$

$$U_{TPLOX} := \left(\frac{U_{PLOX}}{P_{LOX}}\right) \qquad U_{TPLOX} = 0.003422$$

10) LOX Density

$$UMF_{\rho LOX} := \left[\frac{\rho_{LOX}}{C_{Star}}\cdot\left(\theta_{\rho LOX}\right)\right]$$

$$UMF_{\rho LOX} = -0.374973$$

$$U_{T\rho LOX} := \left(\frac{U_{\rho}}{\rho_{LOX}}\right) \qquad U_{T\rho LOX} = 0.05$$

11) LOX Vapor Pressure

$$UMF_{PV} := \left[\frac{P_V}{C_{Star}}\cdot\left(\theta_{PVLOX}\right)\right]$$

$$UMF_{PV} = 0.020904$$

$$U_{TPVLOX} := \left(\frac{U_{Pv}}{P_V}\right) \qquad U_{TPVLOX} = 0.1$$

Overall Uncertainty C*:

$$UU_T := \left[\left(UMF_{PC}^2\cdot U_{TPC}^2\right) + \left(UMF_{DT}^2\cdot U_{TDT}^2\right) + \left(UMF_{CG}^2\cdot U_{TCG}^2\right) + \left(UMF_{PF}^2\cdot U_{TPF}^2\right) \ldots + \left(UMF_{DF}^2\cdot U_{TDF}^2\right) + \left(UMF_{TF}^2\cdot U_{TTF}^2\right) + \left(UMF_{CD}^2\cdot U_{TCD}^2\right) \ldots + \left(UMF_{DLOX}^2\cdot U_{TDLOX}^2\right) + \left(UMF_{PLOX}^2\cdot U_{TPLOX}^2\right) + \left(UMF_{\rho LOX}^2\cdot U_{T\rho LOX}^2\right) \ldots + \left(UMF_{PV}^2\cdot U_{TPVLOX}^2\right)\right]^{\frac{1}{2}}$$

$$UU_T = 0.0437 \qquad Uncertainty := 100\cdot UU_T \qquad Uncertainty = 4.37$$

Percentage !!!

$$UncertaintyC_{Star} := UU_T\cdot C_{Star} \qquad UncertaintyC_{Star} = 77.492\cdot\frac{m}{s} \qquad UncertaintyC_{Star} = 254.24\cdot\frac{ft}{s}$$

Uncertainty Percentage Contributions (UPC's):

1) Chamber Pressure

$$UPC_{PC} := \frac{\left(UMF_{PC}^2\right)\cdot U_{TPC}^2}{UU_T^2}\cdot 100$$

$$UPC_{PC} = 6.43351$$

2) Nozzle Throat Diameter

$$UPC_{DT} := \frac{\left(UMF_{DT}^2\right)\cdot U_{TDT}^2}{UU_T^2}\cdot 100$$

$$UPC_{DT} = 1.05056$$

3) Fuel Orifice Discharge Coeff

$$UPC_{CG} := \frac{\left(UMF_{CG}{}^{2}\right)\cdot U_{TCG}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{CG} = 0.89768$

4) Pressure at Fuel Orifice

$$UPC_{PF} := \frac{\left(UMF_{PF}{}^{2}\right)\cdot U_{TPF}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{PF} = 0.01931$

5) Fuel Orifice Diameter

$$UPC_{DF} := \frac{\left(UMF_{DF}{}^{2}\right)\cdot U_{TDF}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{DF} = 3.33051$

6) Fuel Temperature at Orifice

$$UPC_{TF} := \frac{\left(UMF_{TF}{}^{2}\right)\cdot U_{TTF}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{TF} = 0.08371$

7) LOX Orifice Discharge Coeff

$$UPC_{CD} := \frac{\left(UMF_{CD}{}^{2}\right)\cdot U_{TCD}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{CD} = 15.69952$

8) LOX Orifice Diameter

$$UPC_{DLOX} := \frac{\left(UMF_{DLOX}{}^{2}\right)\cdot U_{TDLOX}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{DLOX} = 53.72347$

9) Pressure at LOX Orifice

$$UPC_{PLOX} := \frac{\left(UMF_{PLOX}{}^{2}\right)\cdot U_{TPLOX}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{PLOX} = 0.096218$

10) LOX Density

$$UPC_{\rho LOX} := \frac{\left(UMF_{\rho LOX}{}^{2}\right)\cdot U_{T\rho LOX}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{\rho LOX} = 18.425132$

11) LOX Vapor Pressure

$$UPC_{PVLOX} := \frac{\left(UMF_{PV}{}^{2}\right)\cdot U_{TPVLOX}{}^{2}}{UU_{T}{}^{2}}\cdot 100$$

$UPC_{PVLOX} = 0.229039$

$$Total := UPC_{PC} + UPC_{DT} + UPC_{CG} + UPC_{PF} + UPC_{DF} + UPC_{TF} + UPC_{CD} + UPC_{DLOX} \cdots + UPC_{PLOX} + UPC_{\rho LOX} + UPC_{PVLOX}$$

$Total = 100$

Monte Carlo Simulation General Uncertainty Analysis

Table F.1 Monte Carlo general uncertainty analysis – sample set 1

Variables	**Symbol**	**Nominal Values**	**Units**	**Iteration n**	**Pc Errors**	**Error Influenced Pc**	**Dt Errors**	**Error Influenced Dt**
Chamber Pressure	**Pc**	1.896E+06	*Pa*	1	-18958.4	1877041.565	-4.7E-06	0.011345258
Nozzle Diameter	**Dt**	0.01135	*m*	2	-1984.9	1894015.096	-8.1E-06	0.011341934
Fuel Orifice Discharge	**Cg**	0.91	-	3	-11837.3	1884162.724	-3E-06	0.011347036
Fuel Orifice Pressure	**Pf**	8.687E+06	*Pa*	4	-8927.08	1887072.922	2.36E-05	0.011373569
Fuel Orifice Diameter	**Df**	0.0016	*m*	5	1077.826	1897077.826	2.75E-05	0.011377474
Fuel Orifice Temperature	**Tf**	298.00	*K*	6	-13995.6	1882004.445	-7.2E-06	0.011342823
LOX Orifice Discharge Coeff	**Cd**	0.650	-	7	1023.727	1897023.727	-1.4E-07	0.011349862
LOX Orifice Diameter	**DLOX**	0.00119	*m*	8	12438.93	1908438.931	9.49E-07	0.011350949
LOX Orifice Pressure	**PLOX**	6.136E+06	*Pa*	9	-4053.18	1891946.823	1.85E-05	0.011368548
LOX Orifice Temperature	**TLOX**	103.0	*K*	10	-5738.05	1890261.947	-8.1E-06	0.011341936
LOX Vapor Pressure	**PVLOX**	3.24E+05	*Pa*	11	-2281.76	1893718.244	-1.8E-05	0.011331992
LOX Density	**ρLOX**	1081.8	*kg/m^3*	12	6665.878	1902665.878	-1.6E-06	0.011348379
				13	2478.719	1898478.719	1.72E-06	0.01135172
				14	-3284.62	1892715.383	-1.8E-05	0.011331981
				15	21660.14	1917660.139	-2.7E-05	0.011322802
				16	7838.747	1903838.747	-1.7E-05	0.011333377
Constants				17	5300.892	1901300.892	-3.2E-06	0.011346825
Specific Heat Ratio GCH4	**k**	1.305		18	-7488.58	1888511.416	5.96E-06	0.011355955
Gas Constant GCH4	**Rf**	518	*J/kg*K*	19	2436.628	1898436.628	-7.8E-06	0.011342169
Characteristic Velocity	**C***	1774.6	*m/s*	20	-4420.03	1891579.972	5.77E-06	0.01135577
				21	11733.23	1907733.232	-1.7E-05	0.01133339
Mean C*				22	14316.42	1910316.424	2.15E-05	0.011371473
1775.5				23	1127.891	1897127.891	-3.2E-06	0.01134684
Stdev C*				24	9173.986	1905173.986	-5.4E-06	0.011344555
38.7				25	5442.801	1901442.801	-1.2E-05	0.011338079
2*Stdev C*				26	-20553.2	1875446.766	1.42E-05	0.011364203
77.4				27	-2884.56	1893115.443	-7.8E-06	0.011342201
Percentage				28	7150.608	1903150.608	7.92E-06	0.011357916
4.36%				29	-6288.9	1889711.097	-7.4E-07	0.011349263

Table F.2 Monte Carlo general uncertainty analysis – sample set 2

Cg Errors	**Error Influenced Cg**	**Pf Errors**	**Error Influenced Pf**	**Df Errors**	**Error Influenced Df**	**Tf Errors**	**Error Influenced Tf**	**Cd Errors**	**Error Influenced Cd**
0.007702	0.917701982	11076.88	8698076.881	9.016E-06	0.001609016	2.51202	300.51202	-0.003652	0.64634795
0.004808	0.914808459	1271.804	8688271.804	-1.59E-05	0.001584138	-0.3883	297.61170	-0.004114	0.64588606
-0.00746	0.902539949	1562.819	8688562.819	-2.65E-06	0.001597347	-0.63658	297.36342	-0.000765	0.64923475
-0.017394	0.892606323	13556.79	8700556.794	-1.39E-05	0.001586121	1.295675	299.29568	-0.003187	0.64681272
-0.001347	0.908652828	-5915.14	8681084.86	-1.86E-06	0.001598139	0.964795	298.96480	-0.020616	0.62938412
0.007679	0.917678688	8062.377	8695062.377	-4.79E-06	0.001595205	1.330006	299.33001	-0.00364	0.64636022
-0.003383	0.906616953	-8517.64	8678482.365	2.995E-05	0.001629947	0.98663	298.98663	-0.003113	0.64688666
0.010613	0.920613019	-10496.9	8676503.095	1.851E-05	0.001618508	0.727441	298.72744	-0.0064	0.64360043
0.007345	0.917345199	-8345.76	8678654.236	-1.2E-05	0.001588049	0.324673	298.32467	0.0098021	0.65980215
-0.009928	0.900072496	18512.56	8705512.56	2.054E-05	0.001620542	-0.38806	297.61194	-0.00646	0.64353994
9.73E-05	0.910097253	2768.779	8689768.779	1.727E-06	0.001601727	1.75815	299.75815	0.0068331	0.65683308
0.003241	0.91324074	4196.351	8691196.351	-1.96E-05	0.001580377	1.420862	299.42086	0.0052966	0.65529658
0.002882	0.912882149	-11046.1	8675953.892	7.304E-06	0.001607304	1.60705	299.60705	-0.009644	0.64035605
0.006325	0.916324763	-478.487	8686521.513	-9.32E-06	0.001590677	-0.10686	297.89314	-0.004405	0.64559481
-0.012862	0.897138403	-4960.56	8682039.435	6.504E-06	0.001606504	-2.87837	295.12163	0.0017929	0.65179294
0.005292	0.915292168	20318.31	8707318.312	-2.58E-06	0.001597424	-1.53187	296.46813	-0.005031	0.64496885
-0.006772	0.90322838	15917.96	8702917.956	2.919E-05	0.001629188	2.361032	300.36103	-0.000556	0.64944440
0.014072	0.924072498	106.4313	8687106.431	-7.3E-06	0.0015927	2.219738	300.21974	0.0046865	0.65468649
0.002079	0.912079463	-7818.6	8679181.403	-9.92E-06	0.001590077	1.478334	299.47833	-0.006047	0.64395259
0.003643	0.913643004	12667.07	8699667.073	-3.52E-05	0.001564828	-1.29218	296.70782	-0.002099	0.64790145
0.018164	0.928163792	1401.37	8688401.37	-7.61E-06	0.001592388	-0.76732	297.23268	-0.00386	0.64614047
-0.00214	0.907859649	6540.586	8693540.586	1.537E-05	0.001615374	0.733771	298.73377	0.0085655	0.65856551
0.016615	0.926615377	10463.84	8697463.839	-5.54E-06	0.001594458	-1.63005	296.36995	0.0044496	0.65444958
-0.007402	0.902598066	68.67424	8687068.674	2.236E-05	0.001622364	-0.93995	297.06005	0.0003447	0.65034465
-0.005365	0.904635459	-6002.89	8680997.11	-8.17E-06	0.001591829	-1.89365	296.10635	0.0004234	0.65042336
-0.007563	0.902436676	22261.1	8709261.102	-1.86E-05	0.001581444	-0.14821	297.85179	0.0012866	0.65128658
0.002204	0.912204368	-8054.81	8678945.191	-1.12E-05	0.001588805	0.764971	298.76497	-0.010315	0.63968459
-0.0086	0.901400261	2778.758	8689778.758	4.389E-06	0.001604389	1.348642	299.34864	0.0017623	0.65176226
0.006819	0.916819181	-4337.66	8682662.338	-2.29E-05	0.001577054	-0.97725	297.02275	-0.003019	0.64698147

Table F.3 Monte Carlo general uncertainty analysis – sample set 3

DLOX Errors	Error Influenced DLOX	PLOX Errors	Error Influenced PLOX	PVLOX Errors	Error Influenced PVLOX	ρLOX Errors	Error Influenced ρLOX	Error Influenced Cstar
4.945E-06	0.0011949454	-2066.7449	6133933.255145	35389.3847	359389.3847205	-46.2623262	1035.5376738	1777.449
2.71E-06	0.0011927101	-5569.9905	6130430.009451	-2279.9941	321720.0059220	29.79259959	1111.5925996	1761.012
-9.22E-06	0.0011807838	4950.69287	6140950.692869	3571.00362	327571.0036173	-5.45204954	1076.3479505	1792.680
1.174E-05	0.0012017394	6474.40629	6142474.406291	-4072.2625	319927.7374728	-0.2658659	1081.5341341	1769.076
-6.67E-06	0.0011833288	8072.07016	6144072.070159	-6163.0817	317836.9182928	-28.4732013	1053.3267987	1862.584
-1.77E-05	0.0011722969	-10947.435	6125052.564615	-878.64464	323121.3553585	17.97169824	1099.7716982	1796.268
9.417E-06	0.0011994171	5104.74138	6141104.741376	-10374.06	313625.9396337	-19.3899776	1062.4100224	1757.515
-1.91E-05	0.0011709047	-14963.894	6121036.106409	4687.31741	328687.3174142	3.922897872	1085.7228979	1828.164
-1.13E-05	0.0011786657	1520.59783	6137520.597834	-4935.755	319064.2450131	16.26526165	1098.0652616	1775.216
-2.55E-05	0.0011644662	4430.56877	6140430.568765	-8221.0863	315778.9136816	24.3718501	1106.1718501	1813.619
1.001E-05	0.0012000146	5309.10484	6141309.104836	-11970.66	312029.3398746	-14.9866333	1066.8133667	1738.369
3.651E-06	0.0011936506	-13991.639	6122008.360793	15079.3494	339079.3493958	3.129973669	1084.9299737	1772.786
-2.46E-07	0.0011897537	-4274.7536	6131725.246436	-31807.431	292192.5692130	1.595010895	1083.3950109	1790.089
-1.46E-05	0.0011754209	-19196.987	6116803.013386	5132.53326	329132.5332606	1.458249994	1083.2582500	1811.957
1.189E-05	0.0012018877	8720.13629	6144720.136293	-13105.528	310894.4723858	16.4441454	1098.2441454	1744.476
-1.1E-05	0.0011789507	22470.6218	6158470.621843	21880.8054	345880.8054342	-50.9390078	1030.8609922	1841.256
-3.3E-06	0.0011866963	501.000841	6136501.000841	-20207.081	303792.9194756	-15.417916	1066.3820840	1782.268
-8.52E-06	0.0011814769	1334.14005	6137334.140052	-19360.596	304639.4043844	19.88819564	1101.6881956	1763.452
3.979E-06	0.0011939789	-6479.2528	6129520.747239	-8051.1381	315948.8618616	34.41504423	1116.2150442	1762.897
-1.14E-05	0.0011785946	-27511.524	6108488.476487	7905.61899	331905.6189861	-15.9983196	1065.8016804	1833.483
1.268E-06	0.0011912675	3878.91873	6139878.918733	-11280.554	312719.4462644	21.66983843	1103.4698384	1765.357
4.515E-06	0.0011945153	-11710.766	6124289.233670	-12205.128	311794.8721405	49.21670597	1131.0167060	1730.702
-2.12E-07	0.0011897877	-13485.028	6122514.972079	7973.4491	331973.4491010	26.78244545	1108.5824454	1745.790
-2.28E-05	0.0011672165	-1570.9486	6134429.051402	3052.04594	327052.0459404	33.06360794	1114.8636079	1803.208
1.643E-05	0.0012064286	1966.92667	6137966.926675	26376.2922	350376.2922259	5.070422674	1086.8704227	1744.320
1.482E-05	0.0012048183	1317.1416	6137317.141596	2049.0188	326049.0188035	50.7815852	1132.5815852	1706.816
1.777E-06	0.0011917774	-1298.5197	6134701.480308	5691.14491	329691.1449065	-43.0693527	1038.7306473	1821.290
-9.45E-06	0.0011805509	12848.5408	6148848.540791	-35277.044	288722.9560651	7.410423814	1089.2104238	1794.094
-2.45E-05	0.0011655434	7967.77556	6143967.775559	1947.8648	325947.8648028	-29.0045026	1052.7954974	1857.987

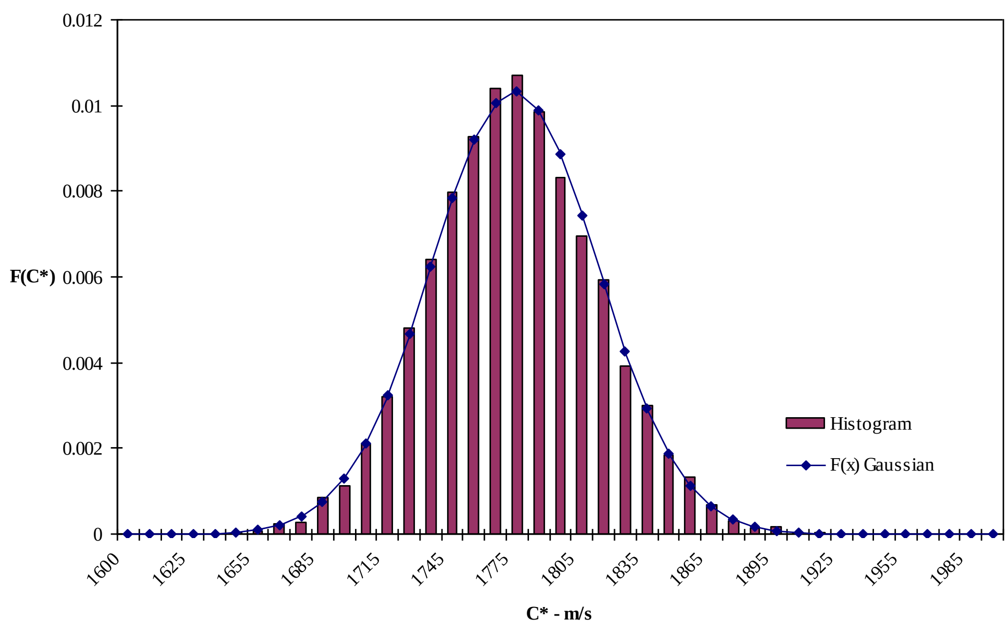


Figure F.1: Monte Carlo Simulation (Gaussian Error Distribution) [Normalized Histogram of 10,000 generated random influenced $\overline{C}^*$ compared to Gaussian distribution with $\overline{C}^* = 1773.7$ m/s and $S_{C^*} \approx 38.6$ m/s which is calculated from the 10,000 measurements]

Table F.4 Taylor series method – general uncertainty results

Variable	Stated Estimate	Uncertainty Estimate	Units	UMFs	UPCs
P_C	1.896 (275)	0.021 (3.0)	*MPa (psi)*	1	6.44 %
D_T	1.135 (0.447)	0.0254 (0.001)	*cm (in)*	2	1.05%
C_G	0.91	0.015	-	-0.2508	0.897%
P_F	8.687 (1260)	0.021 (3.0)	*MPa (psi)*	-0.2508	0.019 %
D_F	0.16 (0.063)	0.0254 (0.001)	*cm (in)*	0.0158	3.33 %
T_F	298 (536.4)	3 (5.4)	*K (R)*	0.0100	0.084%
C_D	0.65	0.015	-	0.0230	15.7 %
D_{LOX}	0.119 (0.047)	0.0254 (0.001)	*cm (in)*	0.0213	53.72 %
P_{LOX}	6.136 (890)	0.021 (3.0)	*MPa (psi)*	-0.3954	0.096 %
P_V	0.324 (46.9)	0.032 (4.7)	*MPa (psi)*	-0.3745	18.43 %
ρ_{LOX}	1081.8 (67.54)	54.1 (3.37)	kg/m^3 (lb/ft^3)	-0.0208	0.023 %
C^*	1774.8 (5808.7)	77.4 (253.8)	*m/s (ft/s)*	**Percentage Uncertainty Estimate**	4.37 %

Table F.5 Monte Carlo simulation – general uncertainty results

	Mean ($\overline{C}^*$)	**Standard Deviation** (S_{C^*})	**Uncertainty Estimated** ($\approx 2S_{C^*}$)	**Percentage Uncertainty Estimate**
Gaussian Error Distribution	1775.5 m/s	38.7 m/s	77.4 *m/s*	4.36 %

APPENDIX G

LOX/GCH_4 Test Procedure

Date: ________________

Red Team Members:

Dr. Lineberry ______________________

Dr. Han ______________________

Tony Hall ______________________

Henry Mulkey ______________________

Matthew Hitt ______________________

> Other operators or Red Team Members not shown on this document must be certified by the Test Engineer or Dr. Lineberry

Red Team Members Required Training:

1) AED/CPR
2) Attended or reviewed Chip Sauer's presentation from Orbital Technologies Corporation Cryogenic Safety and Hazards for Propulsion Systems
3) At least one Red Team Member must have participated in ASTM Certification in Fire Safety in Oxygen Systems

Procedure Approval:

Mr. Henry Mulkey: ______________________

Mr. Matthew Hitt: ______________________

Mr. Tony Hall: ______________________ **(Test Engineer)**

Dr. Han: ______________________

Dr. Lineberry: ______________________

Dr. Frederick: ______________________

Waiver for Pending Safety-Enhancing Modifications

The following safety-enhancing measures criteria are not yet implemented for this test procedure:

Table G.1 Facility safety waivers

Safety Enhancing Item	Safety Issues	Temporary Measures to Compensate	Actions Underway to Provide Item	Person Responsible for Fix
Non-Functional Automatic over/under pressure abort controller	Flowing un-ignited gases into test cell after failed ignition. Lag in stopping propellant gases in response to a pressure spike.	Use of test stand video and manual stop button Put over/under pressure audio alarm on LabVIEW code	Current automatic abort systems is being checkout by Waiver Expires: 1 December 2010.	David Lineberry
High Pressure flex line restraints	Rupturing a high pressure flex line while personnel in area. After Rupture flex line dancing around while relieving pressure	Flex lines restrained to concrete wall with chain with a factor of safety for thrust versus proof load of chain. Stress analysis is contained in Appendix 9 (pg 30)	Hose Restraints are currently being researched for procurement and implementation to the existing facility Waiver Expires: 1 December 2010.	Tony Hall

The undersigned acknowledge they have read this waiver and understand the safety issues involved:

Mr. Henry Mulkey ________________________________

Date: _____________

Mr. Matthew Hitt _________________________________

Date: _____________

Mr. Tony Hall ____________________________________

Date: _____________

Dr. Han ____

Date: _____________

Dr. David Lineberry ________________________________

Date: _____________

Dr. Robert Frederick ________________________________

Date: ___________

Table G.2 Emergency contact phone numbers

Police **Fire Department** **Hazardous Materials Incident** **Utility Failure**	**911 or** **256-824-6911** **(6911 from campus phone)**
PRC Contacts	
Tony Hall	**Office : 256-824-2887**
David Lineberry	**Office : 256-824-2888** **Cell : 256-348-8978**
Han	**Office : 256-824-2890**
Robert Frederick	**Office : 256-824-7200** **Cell : 256-503-4909**
PRC Main Office	**256-824-7200**
JRC Test Stand	**256-824-1756 or 256-824-1759**
Bobby Dempsey	**256-824-2352**
John Horack	**256-824-6100**
Other Emergency Numbers of Interest	
Huntsville Police Department	**256-722-7100**
Madison County Sheriff's Office	**256-722-7181**
Alabama State Troopers	**256-533-4202**
Crestwood Medical Center	**256-882-3100**
Huntsville Hospital Main	**256-265-1000**

Pre-Test Certifications:

Injector: ______________________________

Table G.3 Experimental mass flow settings and ranges

Test No.	Main Oxygen Regulator Pressure [psi]	Main Fuel Regulator Pressure [psi]	Chamber Pressure [psi]	Mixture Ratio O/F	L* [in]

Filenames:

LabVIEW Operating Program: D:\Mulkey\LOX_GCH4 rev4.vi_______

LabVIEW Test Record: D:\Mulkey\Tests*date**date*_test.lvm__________

CXOne PLC Program: D:\Mulkey\LOX_GCH4_Jan_14.cxt___________

PLC Timing Sheet: D:\Mulkey\PLCtimes.xls ______________________

Sensor Locations Sheet: D:\Mulkey\Sensor Info and Locations.xls______

Pre-Test Procedures:
This test procedure assumes the following:

1.) **Test engine has been installed on the test stand.**
2.) **All lines have been connected.**
3.) **The facility is clean**
4.) **The system has been leak checked in accordance with Appendix 1 (pg 12) and all leaks corrected.**
5.) **All instrumentation has been calibrated as required.**
6.) **All Red Team members have reviewed and understand Cryogenic and Oxygen safety hazards in Appendix 2 (pg 14) and additionally completed the required safety trainings stated on page 1 of this document.**
7.) **Test Engine Chamber pressure checked at 500 psi**

Pre-Test Certifications: The undersigned certify that the pre-test procedures have been completed.

Tony Hall ______________________________ (Test Engineer)

Dr. Lineberry ___________________________

Henry Mulkey __________________________

Test Stand Preparation:

- ☐ Open all gates on Test Stand
- ☐ Attach pressurization air to actuated fire valve air manifold on the back of the test stand (plastic tubing)
- ☐ Attach the pressurization air to the compressor in the instrumentation room and make sure that the compressor is on auto compress
- ☐ Ensure air compressor tank pressure is at least 80 psi
- ☐ Attach the water line from the instrumentation room to the quick disconnect fitting on the nozzle.
- ☐ Attach water drainage line
- ☐ Put up all blockades around the test facility
  - ➢ See JRC Test stand footprint for blockade location in Appendix 3 (pg 19)
- ☐ Close and Lock Security Fence

Igniter Setup

- ☐ Attach blue igniter ground to actuator grounding post
- ☐ Attach oxygen line to the igniter
- ☐ Attach hydrogen line to the igniter
- ☐ Clamp grounding clamp to the copper plate behind the thrust stand

Instrumentation

- ☐ Check the *Sensor Locations Sheet* located in Appendix 4 (pg 20) for proper set-up channels with correct pressure sensors and/or thermocouples
- ☐ Set up video camera to view the nozzle and plume. Hook up RCA cables, BNC cable, and power cord. (ensure camera is in focus, also take camera off Demo mode)
- ☐ Turn on LabView and open the *LabVIEW Operating Program*
- ☐ Press RUN and ensure program is running properly
- ☐ Type in the appropriate *LabVIEW Data Record* filename ____________________
- ☐ Press RECORD and press STOP after 5 seconds. This will record a zeros file
- ☐ Ensure LabVIEW recorded properly

Control Room Settings

- ☐ Ensure PLC times are correct in *CXOne PLC Program*, referencing the *PLC Timing Sheet* located in Appendix 5 (pg 21)
- ☐ Upload PLC timing values to PLC within *CXOne PLC Program* under the *Memory* tab
- ☐ Announce over intercom clear the test area
- ☐ Give key to inspector

- ☐ Walk test stand area to make sure test facility is clear
- ☐ Check with Range Safety Officer to make sure test facility area is clear
- ☐ Insert key and toggle all valves
- ☐ Insert enable plug
- ☐ Press Reset on the control board
- ☐ Press FIRE on the control board
- ☐ Ensure the actuators are functioning properly

ONLY Red Team allowed in test cell area from this point forward

<u>Water Leak Check</u> (Only needs to be performed when installed at beginning of testing and when equipment is changed)

Nozzle Cooling Lines

- ☐ Place the drainage line of the water hose in the drain
- ☐ Open water main line in the instrumentation room
- ☐ Remove Nozzle Plug or tape over nozzle
- ☐ Ensure that there is no leakage from the H_2O system
- ☐ Verify strong H_2O flow to provide proper cooling
- ☐ Turn off water

<u>LOX Run Tank Fill Procedure</u>[1] – Only needed at beginning of testing series

- ☐ Reference Appendix 6 (Pg 23) for LOX Run Tank fill procedure

<u>Propellant Line Fill</u>

- ☐ With all Red Team members in the control room place key in control board
- ☐ Use control board to switch on the
  - **GOX main**
  - **GOX secondary dome**
  - **Fuel main**
  - **Fuel primary dome**
  - **Fuel secondary dome**
- ☐ Remove the key from the control board
- ☐ Give test engineer control key
- ☐ Open the nitrogen ball valves on the nitrogen manifold
- ☐ Crack open tanks to slowly bleed in pressure
- ☐ Completely open nitrogen tanks
- ☐ Ensure that there is sufficient pressure in the manifold (at least 1.5 times operating pressure)
- ☐ Adjust the pressure settings to the appropriate pressures, according to the Pressure Board Settings Table 4 below
- ☐ Remove plug from nozzle
- ☐ Return to control room

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[1] Familiarize yourself with Cryogenic and Oxygen safety hazards in Section G.2 Cryogenic safety table mode and solutions before fill procedure

Table G.4 Pressure regulator settings

Oxygen Ignition	**Fuel Ignition**	**Oxygen Main**	**Fuel Main**
220 psi	200 psi	_890_ psi	__1260_ psi
Oxygen Ignition Purge	**Fuel Ignition Purge**	**Oxygen Main Purge**	**Fuel Main Purge**
30 psi	30 psi	100 psi	100 psi

Commence Purge Check Sequence

- ☐ Replace key and turn on board
- ☐ Switch on fuel primary purge
- ☐ Confirm fuel injector purge flow
- ☐ Switch off fuel primary purge
- ☐ Switch on fuel secondary purge
- ☐ Confirm fuel igniter purge flow
- ☐ Switch off fuel secondary purge
- ☐ Switch on LOX primary purge
- ☐ Confirm LOX injector purge flow from video
- ☐ Switch off LOX primary purge
- ☐ Switch on GOX secondary purge
- ☐ Confirm GOX igniter purge flow from video
- ☐ Switch off GOX secondary purge

NEVER go out to the test stand without the control board key when propellants are present in the lines

At any point, if a Red Team Member sees a questionable situation he can, and should, call for a solution discussion or experimental shut-down

- ☐ Remove key and give to Test engineer
- ☐ Close vent to igniter fuel manifold
- ☐ Open the ball valve to the igniter fuel manifold
- ☐ Crack open the igniter fuel tank to slowly bleed in pressure
- ☐ Completely open igniter fuel tank
- ☐ Ensure that there is sufficient pressure in the manifold (at least 1.5 times operating pressure)
- ☐ Verify that system pressure is ambient by inspecting GOX Igniter system pressure analogue gage
- ☐ Open the GOX Igniter ball valve on the GOX Igniter manifold
- ☐ Verify that GOX pneumatic main valve is open
- ☐ Close the GOX k-bottle pressurization regulator
- ☐ Open the GOX pressurization k-bottle valve to pressurize the high pressure side of the pressurization regulator
- ☐ Crack the k-bottle pressurization regulator to let the GOX system slowly pressurize between all k-bottles to be used and the pneumatic GOX fire valve
- ☐ When pressure equalizes fully open GOX pressurization regulator

- ☐ Fully open GOX k-bottle cylinder valve and back off ¼ turn
- ☐ Ensure that there is sufficient pressure in the manifold (at least 1.5 times operating pressure)
- ☐ Make sure that the pressure settings are correct on the pressure regulator board and record

  Fuel Igniter _____ Ox Igniter _____
- ☐ Turn on Water
- ☐ Call UAH Mail Room @ 6116
- ☐ With control key walk test stand area to make sure test facility is clear
- ☐ Check with Range Safety Officer to make sure test facility area is clear
- ☐ Announce Clear the test area
- ☐ Check to make sure all Red Team members are in the control room

Firing Sequence[2]

1st Firing – Igniter test, no spark

- ☐ Run *LabVIEW Operating Program*
- ☐ Check to make sure all Red Team members are in the control room
- ☐ Make sure that the following are switched on
  - **GOX main**
  - **GOX secondary dome**
  - **Fuel main**
  - **Fuel primary dome**
  - **Fuel secondary dome**
- ☐ Ensure that all test stand pressures are correct in Labview
- ☐ Hit record on the DVD recorder
- ☐ Announce the Test Number and what test it is
- ☐ Insert key into control panel and turn on
- ☐ Press Reset
- ☐ Insert enable plug
- ☐ Press FIRE on the control board
- ☐ After sequence is complete press Reset
- ☐ Remove the Enable Key and Control Key
- ☐ Stop the LabVIEW program
- ☐ Ensure LabVIEW recorded to the appropriate file name _____________________
- ☐ Record igniter and chamber pressures Chamber: _____ Igniter: _____
- ☐ Stop DVD Recorder

2nd Firing – Igniter test with spark

- ☐ Give test engineer control key
- ☐ Attach red spark plug connection to the spark plug tip on the igniter
- ☐ Walk test stand area to make sure test facility is clear
- ☐ Check with Range Safety Officer to make sure test facility area is clear

[2] Familiarize yourself with failure mode solutions in Section G.2 before firing sequence

- ☐ Check to make sure all Red Team members are in the control room
- ☐ Announce clear the test area
- ☐ Ensure that all test stand pressures are correct in LabVIEW
- ☐ Hit record on the DVD recorder
- ☐ Announce the Test Number and what test it is
- ☐ Press Reset
- ☐ Insert key into control panel and turn on
- ☐ Insert enable plug
- ☐ Press FIRE on the control board
- ☐ After sequence is complete press Reset
- ☐ Remove the Enable Key and Control Key
- ☐ Stop the LabVIEW program
- ☐ Ensure LabVIEW recorded to the appropriate file name ___________________
- ☐ Record igniter and chamber pressures and ensure higher values than igniter test, no spark

  Chamber: _____ Igniter: _____
- ☐ Stop DVD Recorder

3rd Firing – Main propellants included

- ☐ Give test engineer control key
- ☐ Close vent to Fuel Main manifold
- ☐ Open the Fuel Main ball valves on Fuel Main manifold
- ☐ Crack open the Fuel Main tanks to slowly bleed in pressure
- ☐ Completely open tanks
- ☐ Ensure that there is sufficient pressure in the manifold (at least 1.5 times operating pressure)
- ☐ Turn on LOX Main Purge
- ☐ Crack LN_2 Tank Jacket Valve at bottom of tank
- ☐ Ensure strong flow through LN_2 jacketed lines
- ☐ Adjust LN_2 Tank Jacket Valve to accommodate the requisite LN_2 flow
- ☐ Close LOX low pressure manual globe valve
- ☐ Open LOX Main Relief valve
- ☐ Walk test stand area to make sure test facility is clear
- ☐ Check with Range Safety Officer to make sure test facility area is clear
- ☐ Go back to control room
- ☐ Monitor LN_2 jacket thermocouple
- ☐ When LN_2 jacket thermocouple reads near -180 °C (≈ 15 minutes) go forward to LOX tank pressurization
- ☐ Check to make sure all Red Team members are in control room
- ☐ Close LOX Main Relief valve
- ☐ Open LOX Main valve
- ☐ Open LOX Dome Loader and LOX Tank Pressure Shutoff to pressurize LOX Run Tank

- ☐ Ensure that there is sufficient pressure in the LOX Run Tank (operating pressure) and pressure reading steady,
    - o If LOX Tank Pressure is not steady
        - ▪ Close LOX Tank Pressure Shutoff
        - ▪ Announce Venting LOX Tank on Facility intercom
        - ▪ Open LOX Main Relief Valve to vent LOX Main tank
        - ▪ Call for a solution discussion and fix problem, or
        - ▪ Proceed to experimental shut-down sequence
    - o Otherwise, continue
- ☐ Make sure test facility area is clear
- ☐ Check to make sure all Red Team members are in control room
- ☐ Ensure that all test stand pressures are correct in Labview
- ☐ If dome pressures are not holding constant, perform following 3 procedures; otherwise, skip ahead
    - o If needed, Open Primary Fuel Fire Valve to bring Fuel to Fuel Fire Valve
    - o If needed, purge the Primary Oxidizer
    - o If needed, purge the Primary Fuel

*************Repeat tests can begin from here**************

- ☐ Hit record on the DVD recorder
- ☐ Announce the Test Number and what test it is
- ☐ Press Reset
- ☐ Insert key into control panel and turn on

<u>LOX Line Chill-Down Sequence</u> – The LOX line is chilled by flowing liquid Oxygen through the injector and engine to ensure LOX flow to the injector. This takes around 30 - 60 seconds to establish liquid flow through the LOX propellant line. Read over this sequence before going forward, this firing sequence must be done in a time controlled fashion.

- ☐ Open LOX Fire valve
- ☐ Monitoring temperature measurements T LOX Inj and T LOX Orifice and P LOX Inj pressure measurement to establish liquid phase in LOX line (30-60 seconds)
- ☐ Close LOX Fire valve
- ☐ Briefly open LOX Main purge and GOX Secondary purge (10 – 45 seconds)
- ☐ Close LOX Main purge and GOX Secondary purge
- ☐ Insert enable plug
- ☐ Press FIRE on the control board
- ☐ After sequence is complete/purged press Reset and remove the Enable Key and Control Key
- ☐ Stop the LabVIEW program
- ☐ Ensure LabVIEW recorded to the appropriate file name
- ☐ Stop DVD Recorder

<u>To Adjust Methane Flow Rate</u>

- ☐ Close Fuel main valve
- ☐ Open Fuel vent valve
- ☐ Verify Fuel line pressure is at ambient
- ☐ Close Fuel vent valve

- ☐ With control key, go out to nitrogen pressurant area
- ☐ Adjust Fuel main pressure on regulator board in accordance to table 3 for the next test (After 2nd test just need to adjust the regulator
- ☐ Return to control room
- ☐ Open Fuel main valve
- ☐ Verify Fuel line pressure to see if transducer is reading at correct pressure
- ☐ Press Reset on control board
- ☐ Insert key into control panel and turn on
- ☐ Announce the Test Number and what test it is
- ☐ Go to LOX Chill-Down Sequence above

Shut-Down Sequence

- ☐ Ensure all Red Team members are in the control room
- ☐ Close LOX Main valve
- ☐ Vent LOX Line Vent
- ☐ Purge LOX Line
- ☐ Close LOX Dome Loader
- ☐ Announce Venting LOX Main Tank on Facility
- ☐ Vent LOX Main Relief
- ☐ Close LOX Tank Pressure Shutoff
- ☐ Open LOX Line Vent
- ☐ Open LOX Main Relief
- ☐ Close Main Fuel tanks
- ☐ Vent Main Fuel manifold
- ☐ Close Main Fuel Manifold Ball valves
- ☐ Close Igniter Fuel tank
- ☐ Vent Igniter Fuel manifold
- ☐ Close Igniter Fuel manifold ball valves
- ☐ Close Igniter GOX tank
- ☐ Vent Igniter GOX manifold and open regulator
- ☐ Close Igniter GOX manifold ball valves
- ☐ Open LOX Low Pressure Manual Globe Valve
- ☐ Purge all lines with Nitrogen
- ☐ Close all Domes and Mains
- ☐ Turn off all switches
- ☐ Close Nitrogen tanks
- ☐ Vent Nitrogen manifold
- ☐ Close Nitrogen manifold ball valves
- ☐ Ensure all pressures are back to ambient with LabVIEW
- ☐ Open vents and cycle control board switches to relieve any remaining pressure if necessary
- ☐ Turn off water
- ☐ Detach water line
- ☐ Detach actuator air line from the compressor
- ☐ Detach instrumentation and store camera in instrumentation room

G.1 Propellant Line Leak Check

Table G.5 Experimental pressure settings

Oxygen Ignition	Fuel Ignition	Oxygen Main	Fuel Main
220 psi	200 psi	1500 psi	1500 psi
Oxygen Ignition Purge	**Fuel Ignition Purge**	**Oxygen Main Purge**	**Fuel Main Purge**
30 psi	30 psi	150 psi	150 psi

- ☐ Install nozzle vent on chamber
- ☐ Tighten all fittings and components from the test stand connection to the injector for each line

<u>Fuel Main Line</u>

- ☐ Turn on the control board
- ☐ Turn on the
    - **Fuel main**
    - **LOX main**
    - **LOX primary dome**
    - **Fuel primary dome**
    - **GOX secondary dome**
    - **Fuel secondary dome**
- ☐ Go outside to the fuel and nitrogen storage area
- ☐ Open manifold ball valves to nitrogen manifold
- ☐ Crack open nitrogen bottles to the nitrogen manifold to bleed in pressure
- ☐ Completely open nitrogen bottles
- ☐ Check to make sure there is sufficient pressure in the manifold using the analog gauges
- ☐ Set the Experimental Pressure Settings on the pressure regulator board
- ☐ Open the fuel main manifold valve
- ☐ Crack open nitrogen bottle connected to fuel main manifold to bleed in pressure
- ☐ Completely open the nitrogen bottle on the fuel main manifold
- ☐ Check to make sure there is sufficient pressure in the manifold using the analog gauges
- ☐ One red team member must return to the control room, the others go to the test cell

Table G.6 Fuel main leak check procedure

Step	Control Room	Test Cell
1	Replace key and turn on board	
2	Communication check with the intercom	
3		When ready, tell the control room to actuate the fuel primary fire valve
4	Switch on the fuel main fire valve	
5		Find leaks with bubble solution
6		Tighten the appropriate fittings
7	Iterate Steps 5 & 6 until no leaks are present	

- ☐ Close nitrogen tanks on fuel main manifold
- ☐ Close Fuel Main fire valve
- ☐ Open fuel main manifold vent to relieve pressure between tanks and fire valve
- ☐ Note: There is still pressure in the chamber and igniter
- ☐ Confirm chamber pressure with control room
- ☐ Vent chamber pressure

<u>LOX Main Line</u>

- ☐ Move the nitrogen tank to the oxygen main manifold
- ☐ Open the LOX main
- ☐ Crack open nitrogen bottle on oxygen main manifold to bleed in pressure
- ☐ Completely open the nitrogen bottle to the oxidizer main manifold
- ☐ Check to make sure there is sufficient pressure in the manifold using the analog gauges

Table G.7 LOX main leak check procedure

Step	Control Room	Test Cell
1	Replace key and turn on board	
2	Communication check with the intercom	
3		When ready, tell the control room to actuate the LOX fire valve
4	Switch on the LOX main fire valve	
5		Find leaks with bubble solution
6		Tighten the appropriate fittings
7	Iterate Steps 5 & 6 until no leaks are present	

- ☐ Close nitrogen tanks on oxygen main manifold
- ☐ Close LOX Main fire valve
- ☐ Open oxygen main manifold vent to relieve pressure between tanks and fire valve
- ☐ Note: There is still pressure in the chamber and igniter
- ☐ Confirm chamber pressure with control room

<u>Igniter Fuel Line</u> (skip this leak check if the igniter has not been disassembled since the previous experimental session)

- ☐ Move the nitrogen tank to the fuel secondary manifold
- ☐ Open the fuel secondary manifold ball valve
- ☐ Crack open nitrogen bottle on fuel secondary manifold to bleed in pressure
- ☐ Completely open the nitrogen bottle to the fuel secondary manifold
- ☐ Check to make sure there is sufficient pressure in the manifold using the analog gauges

Table G.8 Fuel igniter leak check procedure

Step	Control Room	Test Cell
1	Replace key and turn on board	
2	Communication check with the intercom	
3		When ready, tell the control room to actuate the fuel secondary fire valve
4	Switch on the Fuel igniter fire valve	
5		Find leaks with bubble solution
6		Tighten the appropriate fittings
7	Iterate Steps 5 & 6 until no leaks are present	

- ☐ Close nitrogen tanks on fuel secondary manifold
- ☐ Close fuel secondary fire valve
- ☐ Open fuel secondary manifold vent to relieve pressure between tanks and fire valve
- ☐ Note: There is still pressure in the chamber and igniter
- ☐ Confirm chamber pressure with control room

<u>Igniter GOX Line</u> (skip this leak check if the igniter has not been disassembled since the previous experimental session)

- ☐ Move the nitrogen tank to the oxygen secondary manifold
- ☐ Open the oxygen secondary manifold ball valve
- ☐ Crack open nitrogen bottle on oxygen secondary manifold to bleed in pressure
- ☐ Completely open the nitrogen bottle to the oxygen secondary manifold
- ☐ Check to make sure there is sufficient pressure in the manifold using the analog gauges

Table G.9 GOX igniter leak check procedure

Step	Control Room	Test Cell
1	Replace key and turn on board	
2	Communication check with the intercom	
3		When ready, tell the control room to actuate the GOX secondary fire valve
4	Switch on the GOX main fire valve	
5		Find leaks with bubble solution
6		Tighten the appropriate fittings
7	Iterate Steps 5 & 6 until no leaks are present	

- ☐ Close nitrogen tanks on oxygen secondary manifold
- ☐ Close GOX secondary fire valve
- ☐ Open GOX secondary manifold vent to relieve pressure between tanks and fire valve
- ☐ Note: There is still pressure in the chamber and igniter
- ☐ Confirm chamber pressure with control room
- ☐ Open nozzle vent on chamber
- ☐ Confirm there is no pressure in any of the lines
- ☐ Open vents and cycle control board switches to relieve any remaining pressure

G.2 Oxygen Safety and Failure Modes

Oxygen Safety

Oxygen safety is important because fires and physical injury can occur. Oxygen is a strong oxidizer that supports combustion but is not flammable by itself. Oxygen hazards are subtle and erratic; ignition is often unpredictable and not repeatable. Fires can occur in high or low pressure, in gaseous or liquid oxygen systems, and in less than 100% oxygen environments.

Manage the risks in oxygen systems by minimizing hazards, maximizing best materials, and utilizing good practices. Tables 10 and 11 present the normal Oxygen atmosphere and the associated health concerns with reduced Oxygen atmosphere.

TREAT OXYGEN SYSTEMS WITH RESPECT!

Table G.10 Normal oxygen atmosphere

Gas	% Volume
Nitrogen	78 %
Oxygen	21 %
Argon	1 %

Table G.11 Health effects of reduced oxygen atmosphere

Percentage of Oxygen in the air (%)	Symptoms (effects noted below are time dependent)
21 – 19	None
> 19 - 15	Reduced Reaction Times
> 15 - 12	Heavy breathing, rapid pulse, lack of coordination
> 12 - 10	Dizziness, unclear thinking, lips slightly blush
> 10 - 8	Nausea, vomiting, loss of consciousness
> 8 - 6	Death within 8 minutes, brain damage within 4-8 minutes
4	Coma within 40 seconds, respiratory failure, death

Table G.12: Cryogenic physiological hazards

HAZARD	DEFINTION	MITIGATION	EFFECT
Contact Burn	Direct contact with cryogenic fluids, boiled off cryogenic vapor or surfaces cooled by cryogenic fluids	- Protective clothing as stated in Appendix 2 - Stay out of the path of all boil off vapor - Ensure that all pressure relief valves and rupture disk vent paths are directed away from personnel - Perform routine inspections of cryogenic system - Buddy System	- Similar to heat burns; can locally freeze and tear or remove skin - Due to decrease in feeling can lead to frostbite
Frostbite	Freezing of skin and body parts due to the exposure to low temperatures	- Protective clothing as stated in Appendix 2 - Stay out of the path of all boil off vapor - Ensure that all pressure relief valves and rupture disk vent paths are directed away from personnel - Perform routine inspections of cryogenic system - Buddy System	- Can lead to permanent damage and discoloration up to loss of limb - Prolonged exposure of cold vapor or gas can damage lungs and the eyes - Exposure is on the order of seconds, not minutes
Hypothermia	Body not capable of maintaining normal temperature	- Protective clothing as stated in Appendix 2 - Stay out of the path of all boil off vapor - Ensure that all pressure relief valves and rupture disk vent paths are directed away from personal - Perform routine inspections of cryogenic system - Buddy System - Avoid long term exposure	- Fatigue - Confusion - Loss of coordination - Unconsciousness - Death
Oxygen Deficiency/ Asphyxiation	Extreme volume expansion from a liquid to a gas when warmed can reduce the amount of oxygen in the air	- Oxygen monitoring in the test area or on personnel - Buddy System	See Table for Symptoms of rarefied oxygen atmosphere

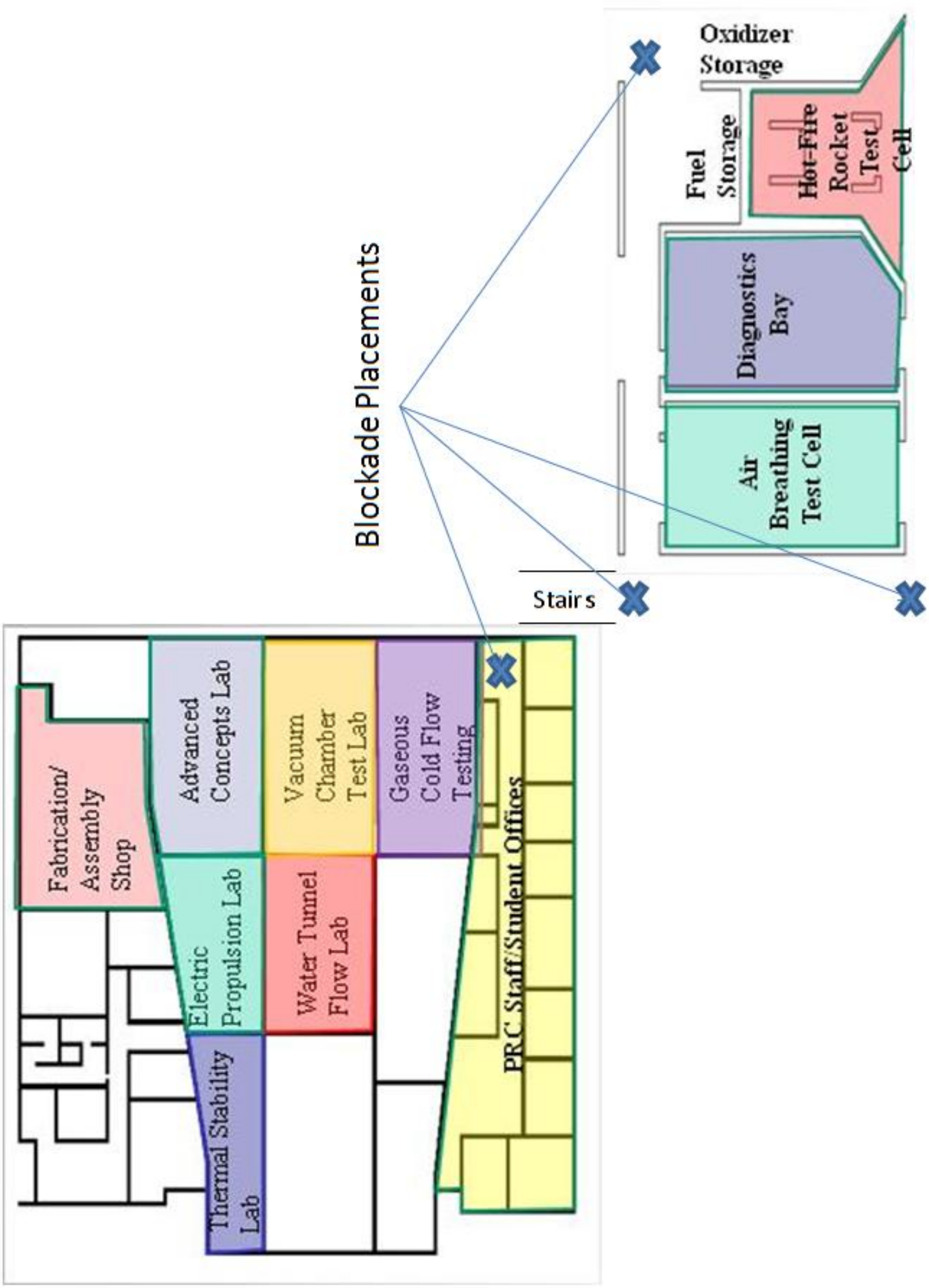
Table G.13: Failure modes and mitigations

FAILURE MODE	MITIGATION	SOLUTION	EFFECT
Leaks in supply lines	Leak check before test	Leak Check	Possible oxygen enrichment of test area
Power failure	Shut-down sequence when power returns	Fuel vent valve releases fuel to drainage. Close Tanks and vent	No Power
Missed Ignition	Try sequence once more or adjust PLC timing/ injector ignition operating conditions	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Unburned propellants in test stand
LOX Pooling in Engine	Purge GN_2 through engine to remove all LOX and GOX vapor	Monitor Main flow line Pressure and Temperature to recognize when there is not liquid As second measure, visually watch the cryogenic cloud dissipate out of the engine	Start up Over Pressurization Experiment damage
Oxygen Enrichment	Ensure that area is well ventilated. Vent oxygen vapor away from test area Monitor air condensation	Carefully remove any oxygen enriched material from any ignition sources. Do not use any oxygen enriched tools or materials near an ignition source for 30 minutes after enrichment.	Increased possibility of fire. Causes materials to become flammable
Particle Impact	Use filters to remove particles from flow. Limit assembly contaminant. Minimize impact points. Clean lines.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Damaged components. Inadvertent burning of experiment.
Rapid Pressurization	Cryogenic valves timed to open slowly to prevent rapid pressurization. Open valves slowly. Vents used wherever cryogenic fluids could be trapped.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Damaged components. Inadvertent burning of experiment.
Flow Friction	Leak check. Tighten or replace parts as needed.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Damaged components. Inadvertent burning of experiment.
Mechanical Impact	Remove chattering valves. Do not step on pressurized flex hoses. Do not step in LOX. Use caution if boots are exposed to LOX.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Damaged components. Inadvertent burning of experiment.
Pressure Buildup due to Vaporization	Ensure that all areas where cryogenic fluids could be trapped are equipped with relief valves.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW. Check for damaged parts.	Damage to parts. Oxygen enrichment of test area.

Table G.14 Failure modes and mitigations (Cont)

FAILURE MODE	MITIGATION	SOLUTION	EFFECT
Inadvertent Burning of Experiment	Ensure fuel-rich mixture. Ensure propellant flows are correct with LabVIEW.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW.	Damaged components
Over Pressurization	All parts rated for higher pressures than supply pressure. Combustion pressure is also lower than rated parts. Vents used wherever cryogenic fluids could be trapped.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW. Check for damaged parts.	Shut-down sequence and assess failure location and possible damage. Nozzle proven to be first part to fail. Nozzle is calculated to eject towards retaining wall. Reference Appx. 3
No Cooling Water	Check water flow prior to firing.	Connect water hose. Assess any damage to nozzle.	Nozzle could erode.
Accidental Ignition or start of gas flow	Key ignitions, follow ignition procedure	Press BRB on the test stand control box and reset control switches. Close all valves. Open vents.	Combustible mixtures may be present in test stand.
Experiment will not stop	Check PLC Timing and valve operation. Purge sequence is initiated after firing.	Press BRB on the test stand control box and reset control switches. Stop LabVIEW. Turn key off. Close switches. Remove Enable plug.	Damage to parts
Combustible gas meter alarm	Leak check	Close valves, vent, and wait for alarm to stop	Combustible mixtures may be present in test stand.
Thermal Stresses	Ensure that material is capable of withstanding thermal stresses.	Press BRB on the test stand control box and reset control switches. Close all valves. Open vents.	Damage to parts. Oxygen enrichment of test area.

G.3 JRC Test Stand Footprint



G.4 Sensor Locations Sheet

Table G.15 Sensor location sheet

Sensor	Measurement	Nomenclature	Range	Voltage Range	Test Stand	CH #
						BNC-2095 SC1Mod2
HW 1196153	Chamber	Pch Center	0-3000 psig	0.03-5.03 V	A11	5
HW 1195775	Chamber	Pch Inj	0-3000 psig	0.03-5.03 V	A4	29
HW 1144300	Igniter	P_Ign	0-3000 psig	0.03-5.03 V	A5	28
HW 1196156	LOX Injecter	P LOX Inj	0-3000 psig	0.03-5.03 V	A8	4
Senso 768094	Fuel Injecter	P Fuel Inj	0-3000 psig	0.03-5.03 V	A7	14
HW 1144528	LOX Orifice	P LOX Orifice	0-3000 psig	0.03-5.03 V	A6	6
HW 1196151	Fuel Orifice	P Fuel Orifice	0-3000 psig	0.03-5.03 V	A3	1
Setra 1838940	GOX Ign Tank	P GOX Ign Tank	0-3000 psig	0.03-5.03 V	B16	16
Senso 740303	GOX Ign Dome	P GOX Ign Dome	0-1500 psig	4-20 mA	B9	17
Senso 800732	GOX Ign Line	P GOX Ign	0-2500 psig	4-20 mA	B5	18
Setra 961950	GOX Ign Purge	P GOX Ign Purge	0-3000 psig	0.03-5.03 V	B10	19
Setra 1838938	Fuel Ign Tank	P Fuel Ign Tank	0-3000 psig	0.03-5.03 V	A18	20
Senso 642290	Fuel Ign Dome	P Fuel Ign Dome	0-750 psig	4-20 mA	A13	21
Omega PX303A	Fuel Ign Line	P Fuel Ign Line	0-300 psia	0.5-5.5 V	B8	22
Setra 1838937	Fuel Ign Purge	P Fuel Ign Purge	0-3000 psig	0.03-5.03 V	A14	23
HW 1144534	LOX Main	P LOX Main	0-3000 psig	9-28 VDC	B18	8
Setra1838939	LOX Main Dome	P LOX Dome	0-3000 psig	4-20 mA	B11	9
HW 1144301	LOX Fire	P LOX Fire	0-3000 psig	9-28 VDC	B1	0
Senso 739772	LOX Main Purge	P LOX Purge	0-3000 psig	0-5 V	B12	26
HW 1144308	LOX Tank	P LOX Tank	0-3000 psig	9-28 VDC	B21	31
Senso 800524	Fuel Main Tank	P Fuel Main Tank	0-2500 psig	4-20 mA	A17	27
Setra 2373105	Fuel Main Dome	P Fuel Main Dome	0-3000 psig	0.03-5.05 V	A19	25
Senso 768092	Fuel Main Purge	P Fuel Main Purge	0-3000 psig	0.03-5.05 V	B7	11
						TC-2095
Type K	Chamber	T Ch	-200 – 1250 °C		1	1
Type K	Igniter	T Ign	-200 – 1250 °C		2	2
Type T	LOX Orifice	T LOX Orifice	-200 – 350 °C		6	27
Type T	LOX Injector	T LOX Inj	-200 – 350 °C		18	22
Type T	LOX Main	T LOX Main	-200 – 350 °C		14	31
Type T	LN2 Jacket	LN2 Jacket	-200 – 350 °C		12	24
Type T	LOX Pressure 1	T LOX Inj Press	-200 – 350 °C		7	21
Type T	LOX Pressure 2	T LOX Main Press	-200 – 350 °C		15	23
Type T	LOX Tank	T LOX Tank	-200 – 350 °C		16	30
Type K	Fuel Orifice	T Fuel	-200 – 1250 °C		3	3

G.5 PLC Timing Sheet

Table G.16 PLC timing values: times are in tenths of seconds

Address	Valve	Zone	Function	Address	Default				
DM001	Zone 1 Time	Pre-test time		**DM001**	10				
DM002	Zone 2 Time	Test time		**DM002**	300				
DM003	Zone 3 Time	Post-test time		**DM003**	20				
DM004	Zone 4 Time	Abort time		**DM004**	100				
DM005	Ox Main Purge	1	Delay	**DM005**	9999				
DM006	Ox Main Purge	1	Duration	**DM006**	1				
DM007	Ox Main Purge	2	Delay	**DM007**	20				
DM008	Ox Main Purge	2	Duration	**DM008**	100				
DM009	Ox Main Purge	3	Delay	**DM009**	9999				
DM010	Ox Main Purge	3	Duration	**DM010**	1				
DM011	Ox Main Purge	4	Delay	**DM011**	1				
DM012	Ox Main Purge	4	Duration	**DM012**	9999				
DM013	Fuel Main Purge	1	Delay	**DM013**	9999				
DM014	Fuel Main Purge	1	Duration	**DM014**	1				
DM015	Fuel Main Purge	2	Delay	**DM015**	20				
DM016	Fuel Main Purge	2	Duration	**DM016**	100				
DM017	Fuel Main Purge	3	Delay	**DM017**	9999				
DM018	Fuel Main Purge	3	Duration	**DM018**	1				
DM019	Fuel Main Purge	4	Delay	**DM019**	1				
DM020	Fuel Main Purge	4	Duration	**DM020**	9999				
DM021	Ox Sec Purge	1	Delay	**DM021**	9999				
DM022	Ox Sec Purge	1	Duration	**DM022**	1				
DM023	Ox Sec Purge	2	Delay	**DM023**	9				
DM024	Ox Sec Purge	2	Duration	**DM024**	100				
DM025	Ox Sec Purge	3	Delay	**DM025**	9999				
DM026	Ox Sec Purge	3	Duration	**DM026**	1				
DM027	Ox Sec Purge	4	Delay	**DM027**	1				
DM028	Ox Sec Purge	4	Duration	**DM028**	9999				
DM029	Fuel Sec Purge	1	Delay	**DM029**	9999				
DM030	Fuel Sec Purge	1	Duration	**DM030**	1				
DM031	Fuel Sec Purge	2	Delay	**DM031**	9				
DM032	Fuel Sec Purge	2	Duration	**DM032**	100				
DM033	Fuel Sec Purge	3	Delay	**DM033**	9999				
DM034	Fuel Sec Purge	3	Duration	**DM034**	1				
DM035	Fuel Sec Purge	4	Delay	**DM035**	1				
DM036	Fuel Sec Purge	4	Duration	**DM036**	9999				
DM037	Ox Main Fire	2	Delay	**DM037**	5	5	5		
DM038	Ox Main Fire	2	Duration	**DM038**	5	20	40		
DM039	Fuel Main Fire	2	Delay	**DM039**	6	6	6		
DM040	Fuel Main Fire	2	Duration	**DM040**	4	19	39		
DM041	Ox Sec Fire	2	Delay	**DM041**	2				
DM042	Ox Sec Fire	2	Duration	**DM042**	10				
DM043	Fuel Sec Fire	2	Delay	**DM043**	1				
DM044	Fuel Sec Fire	2	Duration	**DM044**	11				
DM045	Spark		Delay	**DM045**	1				
DM046	Spark		Duration	**DM046**	5				

Table G.17 PLC timing values (default)

DM047	Camera	1	Delay	**DM047**	9999			
DM048	Camera	1	Duration	**DM048**	1			
DM049	Camera	2	Delay	**DM049**	9999		10	
DM050	Camera	2	Duration	**DM050**	50		30	
DM051	Camera	3	Delay	**DM051**	9999			
DM052	Camera	3	Duration	**DM052**	1			
DM053	Camera	4	Delay	**DM053**	9999			
DM054	Camera	4	Duration	**DM054**	1			
DM055	Camera Pulse		Delay	**DM055**	5			
DM056	Camera Pulse		Duration	**DM056**	2			
DM057			Delay	**DM057**	9999			
DM058			Duration	**DM058**	0			
DM059			Delay	**DM059**	9999			
DM060			Duration	**DM060**	0			
DM061			Delay	**DM061**	0			
DM062			Duration	**DM062**	0			
DM063	Abort1	2	Delay	**DM063**	9999			
DM064	Abort1	2	Duration	**DM064**	0			
DM065	Abort2	2	Delay	**DM065**	9999			
DM066	Abort2	2	Duration	**DM066**	0			
DM067	Abort3	2	Delay	**DM067**	9999			
DM068	Abort3	2	Duration	**DM068**	0			
DM069	Abort4	2	Delay	**DM069**	9999			
DM070	Abort4	2	Duration	**DM070**	0			
DM071	Abort5	2	Delay	**DM071**	9999			
DM072	Abort5	2	Duration	**DM072**	0			
DM073	Abort6	2	Delay	**DM073**	9999			
DM074	Abort6	2	Duration	**DM074**	0			
DM075	Abort7	2	Delay	**DM075**	9999			
DM076	Abort7	2	Duration	**DM076**	0			
DM077	Abort8	2	Delay	**DM077**	9999			
DM078	Abort8	2	Duration	**DM078**	0			
DM079		2	Delay	**DM079**	9999			
DM080		2	Duration	**DM080**	0			
DM081	Air	2	Delay	**DM081**				
DM082	Air	2	Duration	**DM082**				

G.6 LOX Run Tank Fill Procedure

Pre-Test Procedures:
PRC Red Team members performing the cryogenic fill procedure must be properly clothed in protective clothing. All of the cryogenic protective clothing is located in the lockers in the instrumentation room. Protective clothing includes the following:

1) Closed toe shoes – non-absorbent, non cloth (sneakers or boots, not provided by PRC).
2) Pants – No cuff, No Shorts (not provided by PRC)
3) Lab Coat – Nomex Flame Resistant (No Pockets Preferred)
4) Cryogenic Apron
5) Cryogenic Gloves – worn above sleeve for actions above head, and worn tucked in sleeve for actions below head.
6) Safety Glasses
7) Mask with Face Shield

This test procedure assumes the following:

1) All lines have been connected.
2) The system has been leak checked in accordance with Appendix 1and all leaks corrected.
3) The system is clean
4) All instrumentation has been calibrated as required.
5) LN_2 Dewars has been delivered to the Facility
6) LOX Dewars has been delivered to the Facility
7) Transfer hose has been cleaned/ and capped till service
8) Fill area is secure and area clear
9) Requisite tools accessible

Facility Preparation

- ☐ Attach the pressurization air to the compressor in the instrumentation room and make sure that the compressor is on auto compress
- ☐ Ensure air compressor tank pressure is at least 80 psi
- ☐ Toggle all valves for functionality: LOX Fill, LOX Main, LOX Main Relief, LOX Fire, LOX Line Vent
- ☐ Turn on LOX Run Tank Level Sensor Monitor
- ☐ Put up all blockades around the test facility as illustrated in Appendix 3
- ☐ Close and Lock Security Fence
- ☐ Ensure strong flow through LN_2 jacketed lines (This can be done by connecting 50 psi regulated GN_2 gas to the LN_2 Tank Jacket Valve tee port at the bottom of the tank and flowing)

The liquid nitrogen (**LN_2**) fill takes approximately two hours to fill the liquid oxygen (**LOX**) run tank outer jacketed volume. The LOX fill takes approximately 30 minutes to fill the 23 gallon run tank volume completely. Monitor the LOX Run Tank Level Sensor to establish when the tank is full.

LN_2 Fill

- ☐ Turn TV monitor on so that fill area is completely visible from control room
- ☐ Go out to fill area
- ☐ Uncap LN_2 fill transfer hose
- ☐ Connect LN_2 fill transfer hose to 1st LN_2 Dewar
- ☐ Manually close LN_2 fill line vent valve
- ☐ Open LN_2 Vent Bypass valve to Atmosphere
- ☐ Open LN_2 fill valve
- ☐ Slowly open 1st LN_2 Dewar valve
- ☐ Completely open 1st LN_2 Dewar valve
- ☐ Empty 1st LN_2 Dewar (≈ 45-70 minutes)
- ☐ Close LN_2 fill valve
- ☐ Crack LN_2 fill line vent valve
- ☐ Close 1st LN_2 Dewar valve
- ☐ Open LN_2 fill line vent valve to vent excess pressure (keep feet away from the discharge area)
- ☐ Disconnect LN_2 transfer hose from 1st LN_2 Dewar
- ☐ Move 1st LN_2 Dewar out of fill area
- ☐ Reconnect LN_2 transfer hose to 2nd LN_2 Dewar
- ☐ Manually close LN_2 fill line vent valve
- ☐ Open LN_2 fill valve
- ☐ Slowly open 2nd LN_2 Dewar valve
- ☐ Completely open 2nd LN_2 Dewar valve
- ☐ Empty 2nd LN_2 Dewar (≈ 45-70 minutes)
- ☐ Close LN_2 fill valve
- ☐ Crack LN_2 fill line vent valve
- ☐ Close 2nd LN_2 Dewar valve
- ☐ Open LN_2 fill line vent valve to vent excess pressure (keep feet away from the discharge area)
- ☐ Disconnect LN_2 transfer hose from 2nd LN_2 Dewar
- ☐ Move 2nd LN_2 Dewar out of fill area
- ☐ Close LN_2 Vent Bypass valve to Atmosphere (LN_2 tank jacket volume should be full and there should be a thick frost encompassing the LOX Run Tank)
    - ➢ If the Outer Jacket is not full then repeat the process emptying 3rd LN_2 Dewar into outer jacket
    - ➢ If full then go forward
- ☐ Reconnect LN_2 transfer hose to3rd LN_2 Dewar (this Dewar is to be utilized to replenish the LN_2 in the outer jackets for chilling the LN2 jacketed lines and additionally to hold the LOX at cryogenic temperatures)

- ☐ As needed replenish LN_2 Outer Jacket
  - Shut LN_2 line vent
  - Open LN_2 fill valve
  - Slowly open LN_2 Dewar valve
  - Completely open LN_2 Dewar valve
  - Hold LN_2 Outer Jacket Tank with LN_2 from 3rd LN_2 Dewar

LOX Fill (Use LN_2 for first time checkouts)

- ☐ With all Red Team members in the control room, use the control board to close LOX Main, and LOX Fire valves
- ☐ Open LOX Main Relief valve
- ☐ Open LOX Fill valve
- ☐ Go out to fill area (at least two red team members)
- ☐ Wearing cleaning gloves: Uncap LOX fill transfer hose (place cap in clean baggy and seal)
- ☐ Connect the LOX fill transfer hose to LOX Dewar
- ☐ Manually close LOX Fill Line Vent valve
- ☐ Slowly open LOX Dewar valve
- ☐ Completely open LOX Dewar valve
- ☐ Fill LOX Main Tank (≈ 30 minutes)
  - Use the Dewar pressurization valve to adjust the LOX fill flow as needed
- ☐ Close LOX fill valve
- ☐ Crack LOX fill line vent valve
- ☐ Close LOX Dewar valve
- ☐ Open LOX fill line vent valve to relive any remaining pressure
- ☐ Close LOX Main Relief valve
- ☐ Open Low pressure manual globe valve
- ☐ Disconnect LOX fill transfer hose from LOX Dewar
- ☐ Take off baggy and cap LOX fill transfer hose
- ☐ Move LOX Dewar out of fill area

G.7 Facility Schematic

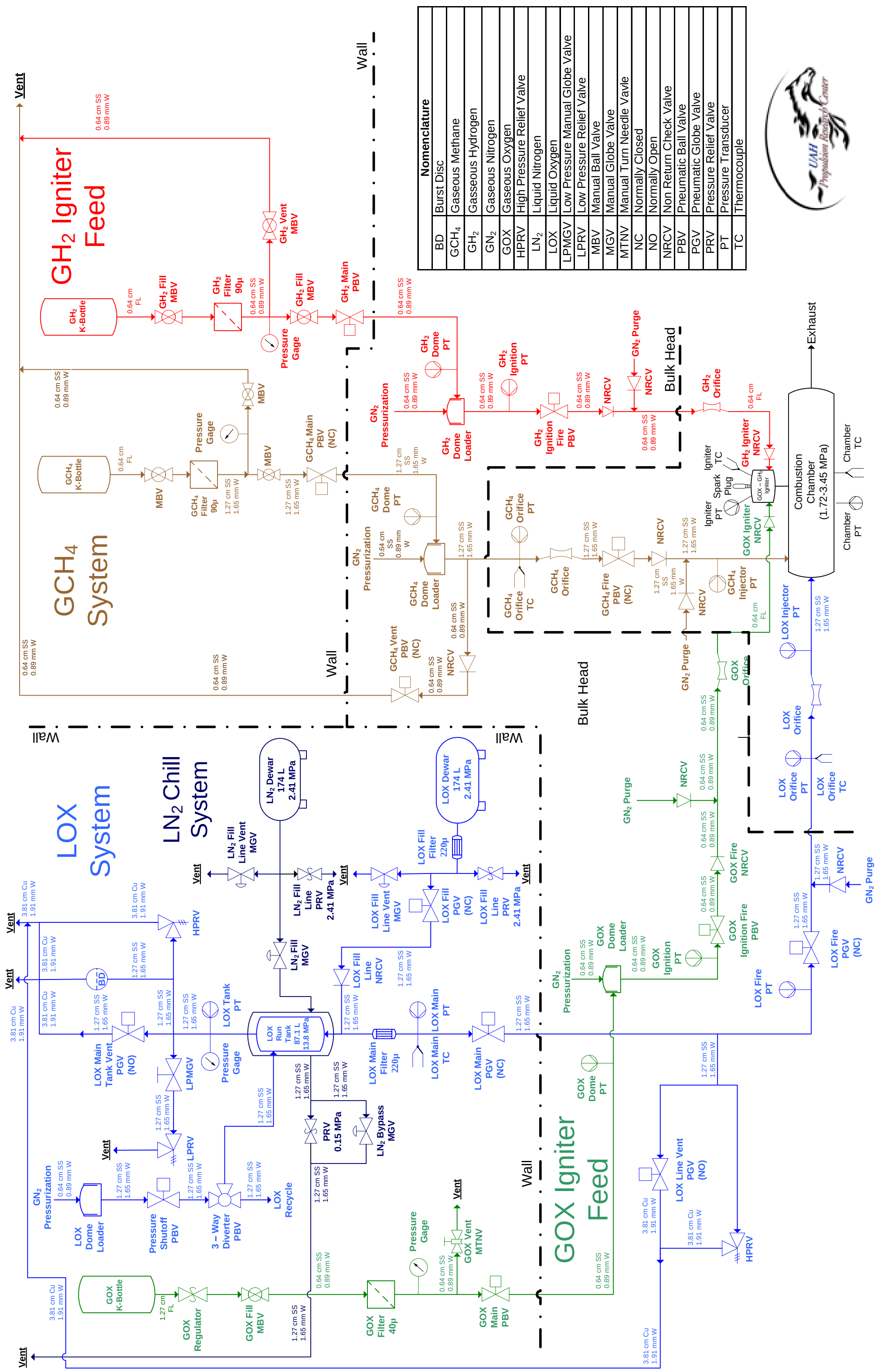


Figure G.1 LOX – GCH_4 facility

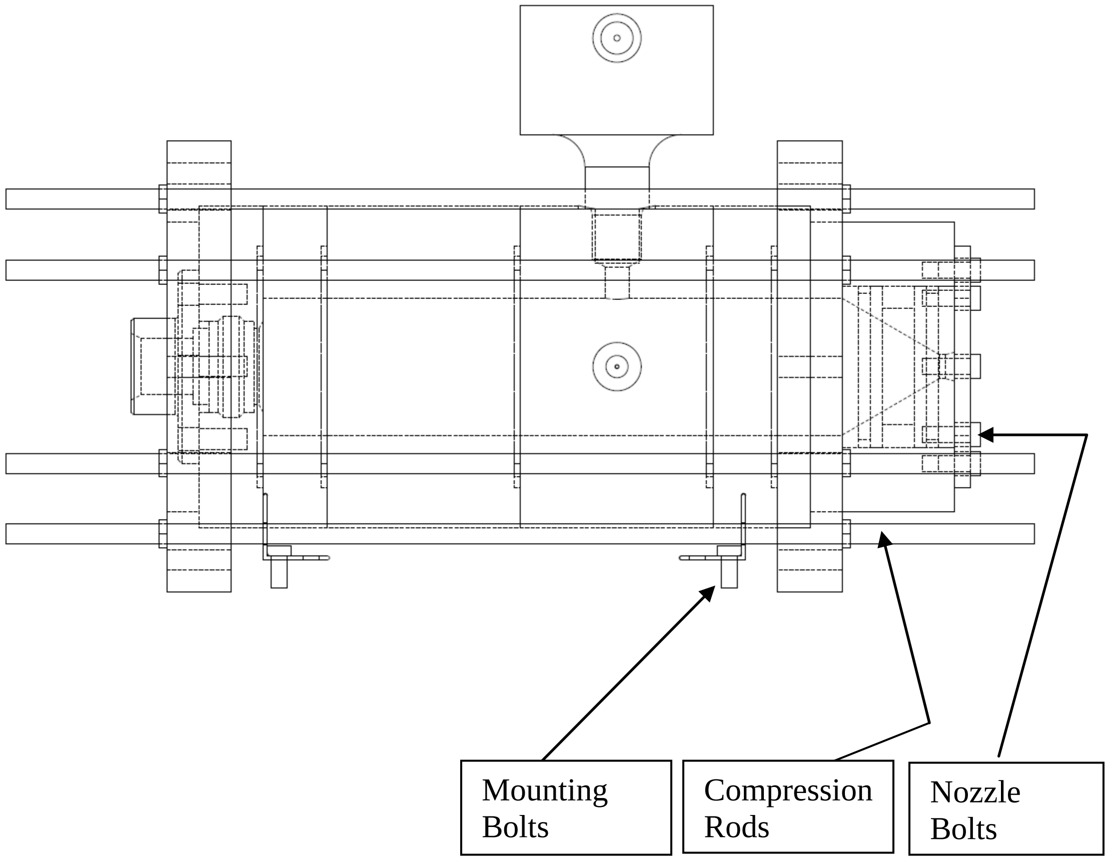


Figure G.2 Test chamber section view[32]

G.8 Over Pressurization Failure

Failure Analysis for Copper Chamber

$P_i := 1000 \cdot psi$ $\quad P_i = 6.895\,MPa$

$P_o := 14.7 \cdot psi$ $\quad P_o = 0.101\,MPa$

$r_i := 1.0625 \cdot in$ $\quad r_i = 2.699\,cm$

$r_o := 2.5 \cdot in$ $\quad r_o = 6.35\,cm$

$r_{bolt} := .125in$ $\quad r_{bolt} = 0.317\,cm$

$Length := 12 \cdot in$ $\quad Length = 30.48\,cm$

Material Properties

$Su_{cu} := 220MPa$ $\quad Sy_{cu} := 70MPa$

$Su_{shear316} := 140MPa$ $\quad Sy_{ss316} := 205MPa$ $\quad S_{y.grd8} := 130000psi$

Hoop Stress

$$\sigma_h := \left(\frac{P_i \cdot r_i^2 - P_o \cdot r_o^2}{r_o^2 - r_i^2}\right) - \left[\frac{r_i^2 \cdot r_o^2 \cdot (P_o - P_i)}{r_o^2 \cdot \left(r_o^2 - r_i^2\right)}\right] \qquad \sigma_h = 419.704\,psi$$

$$FS_{hoop} := \frac{Sy_{cu}}{\sigma_h} \qquad FS_{hoop} = 24.19$$

Nozzle Bolts Stress

$r_{nozzarea} := \left(\frac{2.5}{2}\right) in$ $\quad F_{nozz} := P_i \cdot \pi \cdot r_{nozzarea}^2$ $\quad n := \frac{20}{in}$

$F_{bolt} := \frac{F_{nozz}}{8}$ $\quad F_{bolt} = 613.592\,lbf$ $\quad P := \frac{1}{n}$

$dia := \left(\frac{4}{16}\right) in$ $\quad d_m := dia - 1.299038 \cdot P$

$d_p := dia - 0.649519 \cdot P$

$$A_s := \frac{\pi \cdot \left(\frac{d_m + d_p}{2}\right)^2}{4} \qquad A_s = 0.032\,in^2 \qquad \sigma_c := \frac{F_{bolt}}{A_s} \qquad \sigma_c = 1.928 \times 10^4\,psi$$

$$FS_{nozz} := \frac{Sy_{ss316}}{\sigma_c} \qquad FS_{nozz} = 1.542 \qquad A_{bolt} := \pi \cdot r_{bolt}^2 \qquad A_{bolt} = 0.049\,in^2$$

Mounting Bolts Stress

$$Thrust := 500lbf$$

$$Ax := 125 \cdot lbf$$

$$By := 125 \cdot lbf$$

$$\sigma_{sh} := \frac{Ax}{\pi \cdot r_{bolt}^{2}} \qquad \sigma_{sh} = 2.546 \times 10^{3} \cdot psi$$

$$\sigma_{t} := \frac{By}{\pi \cdot r_{bolt}^{2}} \qquad \sigma_{t} = 2.546 \times 10^{3} \cdot psi$$

$$Resultant := \sqrt{\sigma_{sh}^{2} + \sigma_{t}^{2}} \qquad Resultant = 3.601 \times 10^{3} \cdot psi$$

$$FS_{res} := \frac{Sy_{ss316}}{Resultant} \qquad \boxed{FS_{res} = 8.256}$$

$$FS_{sh} := \frac{Su_{shear316}}{\sigma_{sh}} \qquad \boxed{FS_{sh} = 7.974}$$

Stress on Compression Rods

$$r_{rodarea} := \left(\frac{3}{2}\right) in \qquad F_{rods} := P_{i} \cdot \pi \cdot r_{rodarea}^{2} \qquad F_{rods} = 7.069 \times 10^{3} \cdot lbf$$

$$dia_{rod} := \left(\frac{4}{16}\right) in \qquad n_{rod} := \frac{18}{in} \qquad P_{rod} := \frac{1}{n}$$

$$d_{m.rod} := dia - 1.299038 \cdot P \qquad d_{p.rod} := dia - 0.649519 \cdot P$$

$$A_{s.rod} := \frac{\pi \cdot \left(\frac{d_{m.rod} + d_{p.rod}}{2}\right)^{2}}{4} \qquad A_{s.rod} = 0.032 \cdot in^{2}$$

$$F_{rod} := \frac{F_{rods}}{8} \qquad \sigma_{c.rod} := \frac{F_{rod}}{A_{s.rod}} \qquad \sigma_{c.rod} = 2.777 \times 10^{4} \cdot psi$$

$$FS_{rod} := \frac{S_{y.grd8}}{\sigma_{c.rod}} \qquad \boxed{FS_{rod} = 4.682}$$

The first point of failure should occur at the nozzle section.

G.9 High Pressure Flex Line Failure

Thrust Calculations

Calculation Constants

Gas: Hydrogen

$Ru := 8314 \frac{J}{mol \cdot K}$ $\gamma := 1.4$ $MW_N := 2.02 \frac{gm}{mol}$

Calculation Variables

$P_{exit} := 2500 psi$ k-bottle assumed pressure

$P_a := 14.7 psi$ ambient pressure

$T_{exit} := 273 K$ assumed temperature at the exit of the flex hose

The thrust on the hose is calculated according to the rocket thrust equation which comes from the momentum equation. It is assumed the exit velocity is sonic, but the pressure and temperature are assumed to be stagnation conditions. No fanno effects are considered in the line. This is felt to be a conservative approach

$$\rho := \frac{P_{exit}}{\frac{Ru}{MW_N} \cdot T_{exit}}$$ the gas density at the exit is

$$\rho = 0.015 \frac{kg}{m^3}$$

$$v := \sqrt{\gamma \cdot \frac{Ru}{MW_N} \cdot T_{exit}}$$ the sonic velocity is the effective exhaust velocity

$$P_A := 14.7 psi$$

$$A_{exit} := \frac{(.19 in)^2 \pi}{4}$$ the exit area is the tube exit area

The thrust is calculated according to

$$F := \left[\rho \cdot v^2 + \left(P_{exit} - P_a\right)\right] \cdot A_{exit}$$

$$F = 169.7 lbf$$

Shear Stress Analysis for Hydrogen Flex Line $FS_m = 1.921$

#10 Bolt

Material: Steel

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Structural Steel

Bolt Diameter Source: http://www.gizmology.net/nutsbolts.htm accessed 9/21/2010

Yield Stress of Bolt $\tau_{yb} := 21ksi$

Root Diameter of Bolt $d_b := 0.1570in$

Cross Sectional Area of Bolt $A_b := \frac{\pi}{4} \cdot d_b^2$

Max Thrust $P := 170lbf$

Shear Stress in Bolt $\tau_b := \frac{P}{A_b}$ $\tau_b = 8.781 \cdot ksi$

Factor of Safety of Bolt $FS_b := \frac{\tau_{yb}}{\tau_b}$ $FS_b = 2.391$

Mounting Piece

Material: Brass

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Yellow Brass, Cold Rolled

Yield Stress of Mount $\tau_{ym} := 32ksi$

Mount Thickness $t_m := 0.0325in$

Bearing Stress of Mount $\sigma_{bm} := \frac{\frac{P}{2}}{t_m \cdot d_b}$ $\sigma_{bm} = 16.659 \cdot ksi$

Factor of Safety of Mount $FS_m := \frac{\tau_{ym}}{\sigma_{bm}}$

Thrust Calculations

Calculation Constants

Gas: Methane

$Ru := 8314 \frac{J}{mol \cdot K}$ $\gamma := 1.3$ $MW_N := 16.04 \frac{gm}{mol}$

Calculation Variables

$P_{exit} := 2500 psi$ k-bottle assumed pressure

$P_a := 14.7 psi$ ambient pressure

$T_{exit} := 273 K$ assumed temperature at the exit of the flex hose

the thrust on the hose is calculated according to the rocket thrust equation which comes from the momentum equation. It is assumed the exit velocity is sonic, but the pressure and temperature are assumed to be stagnation conditions. No fanno effects are considered in the line. This is felt to be a conservative approach

$$\rho := \frac{P_{exit}}{\frac{Ru}{MW_N} \cdot T_{exit}}$$

the gas density at the exit is

$$\rho = 0.122 \frac{kg}{m^3}$$

$$v := \sqrt{\gamma \cdot \frac{Ru}{MW_N} \cdot T_{exit}}$$

the sonic velocity is the effective exhaust velocity

$P_A := 14.7 psi$

$$A_{exit} := \frac{(.19 in)^2 \pi}{4}$$

the exit area is the tube exit area

The thrust is calculated according to

$$F := \left[\rho \cdot v^2 + \left(P_{exit} - P_a\right)\right] \cdot A_{exit}$$

$$F = 162.612 lbf$$

Shear Stress Analysis for Methane Flex Line

#10 Bolt

Material: Steel

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Structural Steel

Bolt Diameter Source: http://www.gizmology.net/nutsbolts.htm accessed 9/21/2010

Yield Stress of Bolt	$\tau_{yb} := 21 ksi$	
Root Diameter of Bolt	$d_b := 0.1570 in$	
Cross Sectional Area of Bolt	$A_b := \frac{\pi}{4} \cdot d_b^{\ 2}$	
Max Thrust	$P := 163 lbf$	$P = 163 \cdot lbf$
Shear Stress in Bolt	$\tau_b := \frac{P}{A_b}$	$\tau_b = 8.42 \cdot ksi$
Factor of Safety of Bolt	$FS_b := \frac{\tau_{yb}}{\tau_b}$	$FS_b = 2.494$

Mounting Piece

Material: Brass

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Yellow Brass, Cold Rolled

Yield Stress of Mount	$\tau_{ym} := 32 ksi$	
Mount Thickness	$t_m := 0.0325 in$	
Bearing Stress of Mount	$\sigma_{bm} := \frac{\frac{P}{2}}{t_m \cdot d_b}$	$\sigma_{bm} = 15.973 ksi$
Factor of Safety of Mount	$FS_m := \frac{\tau_{ym}}{\sigma_{bm}}$	$FS_m = 2.003$

Thrust Calculations

Calculation Constants

Gas: Nitrogen

$$Ru := 8314\frac{J}{mol \cdot K} \qquad \gamma := 1.4 \qquad MW_N := 28.8\frac{gm}{mol}$$

Calculation Variables

$P_{exit} := 2700psi$	k-bottle assumed pressure
$P_a := 14.7psi$	ambient pressure
$T_{exit} := 273K$	assumed temperature at the exit of the flex hose

the thrust on the hose is calculated according to the rocket thrust equation which comes from the momentum equation. It is assumed the exit velocity is sonic, but the pressure and temperature are assumed to be stagnation conditions. No fanno effects are considered in the line. This is felt to be a conservative approach

$$\rho := \frac{P_{exit}}{\frac{Ru}{MW_N} \cdot T_{exit}}$$

the gas density at the exit is

$$\rho = 0.236\frac{kg}{m^3}$$

$$v := \sqrt{\gamma \cdot \frac{Ru}{MW_N} \cdot T_{exit}}$$

the sonic velocity is the effective exhaust velocity

$$P_A := 14.7psi$$

$$A_{exit} := \frac{(.19in)^2 \pi}{4}$$

the exit area is the tube exit area

The thrust is calculated according to

$$F := \left[\rho \cdot v^2 + \left(P_{exit} - P_a\right)\right] \cdot A_{exit}$$

$$F = 183.31lbf$$

Shear Stress Analysis for Nitrogen Flex Line

#10 Bolt

Material: Steel

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Structural Steel

Bolt Diameter Source: http://www.gizmology.net/nutsbolts.htm accessed 9/21/2010

Yield Stress of Bolt	$\tau_{yb} := 21\,ksi$	
Root Diameter of Bolt	$d_b := 0.1570\,in$	
Cross Sectional Area of Bolt	$A_b := \frac{\pi}{4} \cdot d_b^{\,2}$	
Max Thrust	$P := 184\,lbf$	$P = 184\,lbf$
Shear Stress in Bolt	$\tau_b := \frac{P}{A_b}$	$\tau_b = 9.504\,ksi$
Factor of Safety of Bolt	$FS_b := \frac{\tau_{yb}}{\tau_b}$	$FS_b = 2.209$

Mounting Piece

Material: Brass

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Yellow Brass, Cold Rolled

Yield Stress of Mount	$\tau_{ym} := 32\,ksi$	
Mount Thickness	$t_m := 0.0325\,in$	
Bearing Stress of Mount	$\sigma_{bm} := \frac{\frac{P}{2}}{t_m \cdot d_b}$	$\sigma_{bm} = 18.03\,ksi$
Factor of Safety of Mount	$FS_m := \frac{\tau_{ym}}{\sigma_{bm}}$	$FS_m = 1.775$

Thrust Calculations

Calculation Constants

Gas: Oxygen

$Ru := 8314 \frac{J}{mol \cdot K}$ $\gamma := 1.4$ $MW_N := 32.0 \frac{gm}{mol}$

Calculation Variables

$P_{exit} := 2500psi$ k-bottle assumed pressure

$P_a := 14.7psi$ ambient pressure

$T_{exit} := 273K$ assumed temperature at the exit of the flex hose

the thrust on the hose is calculated according to the rocket thrust equation which comes from the momentum equation. It is assumed the exit velocity is sonic, but the pressure and temperature are assumed to be stagnation conditions. No fanno effects are considered in the line. This is felt to be a conservative approach

$$\rho := \frac{P_{exit}}{\frac{Ru}{MW_N} \cdot T_{exit}}$$ the gas density at the exit is

$$\rho = 0.243 \frac{kg}{m^3}$$

$$v := \sqrt{\gamma \cdot \frac{Ru}{MW_N} \cdot T_{exi}}$$ the sonic velocity is the effective exhaust velocity

$P_A := 14.7psi$

$$A_{exit} := \frac{(.28in)^2 \pi}{4}$$ the exit area is the tube exit area

The thrust is calculated according to

$$F := \left[\rho \cdot v^2 + \left(P_{exit} - P_a\right)\right] \cdot A_{exi}$$

$F = 368.546lbf$

Shear Stress Analysis of Oxygen Flex Line

#12 Bolt

Material: Steel

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Structural Steel

Bolt Diameter Source: http://www.gizmology.net/nutsbolts.htm accessed 9/21/2010

Yield Stress of Bolt	$\tau_{yb} := 21\,ksi$	
Root Diameter of Bolt	$d_b := 0.1722\,in$	
Cross Sectional Area of Bolt	$A_b := \frac{\pi}{4} \cdot d_b^{\,2}$	
Max Thrust	$P := 369\,lbf$	
Shear Stress in Bolt	$\tau_b := \frac{P}{A_b}$	$\tau_b = 15.844\,ksi$
Factor of Safety of Bolt	$FS_b := \frac{\tau_{yb}}{\tau_b}$	$FS_b = 1.325$

Mounting Piece

Material: Brass

Mechanical Properties Source: Mechanics of Materials, 5th Ed., Beer, et al.
Appendix B, Yellow Brass, Cold Rolled

Yield Stress of Mount	$\tau_{ym} := 32\,ksi$	
Mount Thickness	$t_m := 0.0490\,in$	
Bearing Stress of Mount	$\sigma_{bm} := \frac{\frac{P}{2}}{t_m \cdot d_b}$	$\sigma_{bm} = 21.866\,ksi$
Factor of Safety of Mount	$FS_m := \frac{\tau_{ym}}{\sigma_{bm}}$	$FS_m = 1.463$

Chain Factors of Safety

Note: All factors of safety are conservative due to the thrusts being calculated from a more conservative view

Maximum Thrusts

Oxygen Thrust $F_{ox} := 369\,lbf$

Hydrogen Thrust $F_h := 170\,lbf$

Methane Thrust $F_m := 163\,lbf$

Nitrogen Thrust $F_n := 183\,lbf$

Chain Weight Ratings

Chain 1 $W_1 := 340\,lbf$

Chain 2 $W_2 := 255\,lbf$

Factors of Safety

Oxygen FS $FS_{ox} := \frac{2 \cdot W_1}{F_{ox}}$ $FS_{ox} = 1.843$

Hydrogen FS $FS_h := \frac{W_1}{F_h}$ $FS_h = 2$

Methane FS $FS_m := \frac{W_2}{F_m}$ $FS_m = 1.564$

Nitrogen FS $FS_n := \frac{W_2}{F_n}$ $FS_n = 1.393$

APPENDIX H

PLC Valve Timing Sequence

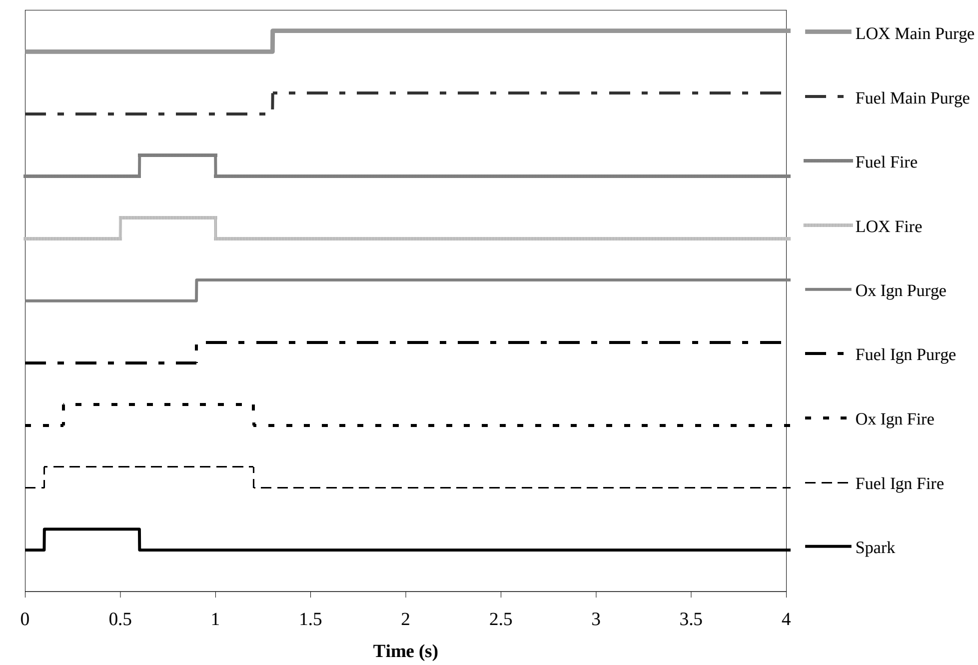


Figure H.1 LOX – GCH_4 0.5 second test valve sequence - 0.5 second

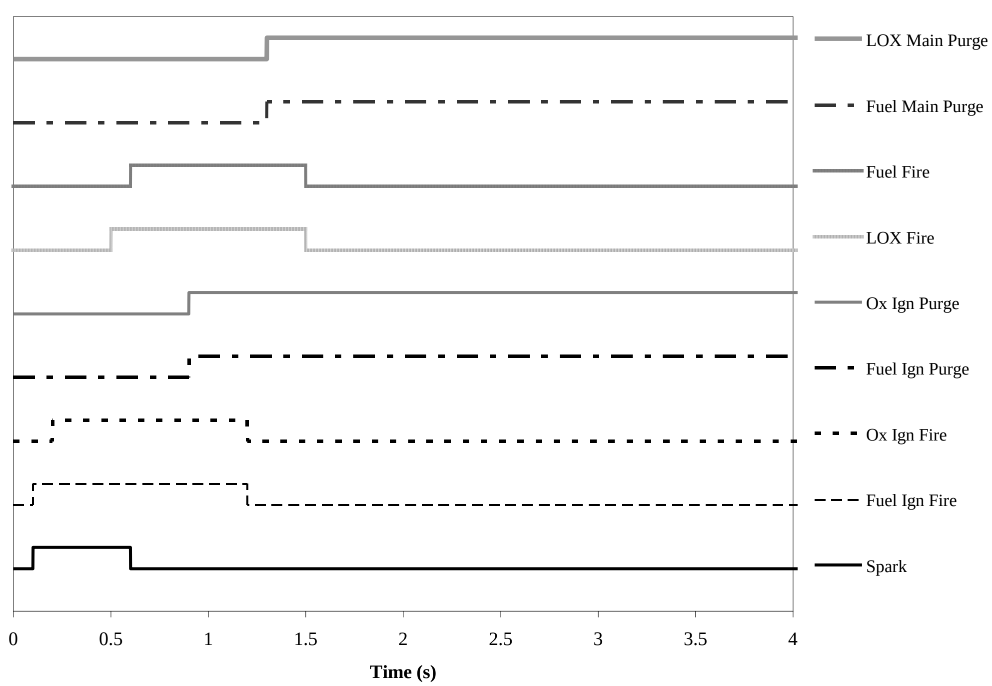


Figure H.2 LOX – GCH_4 test valve sequence - 1 second

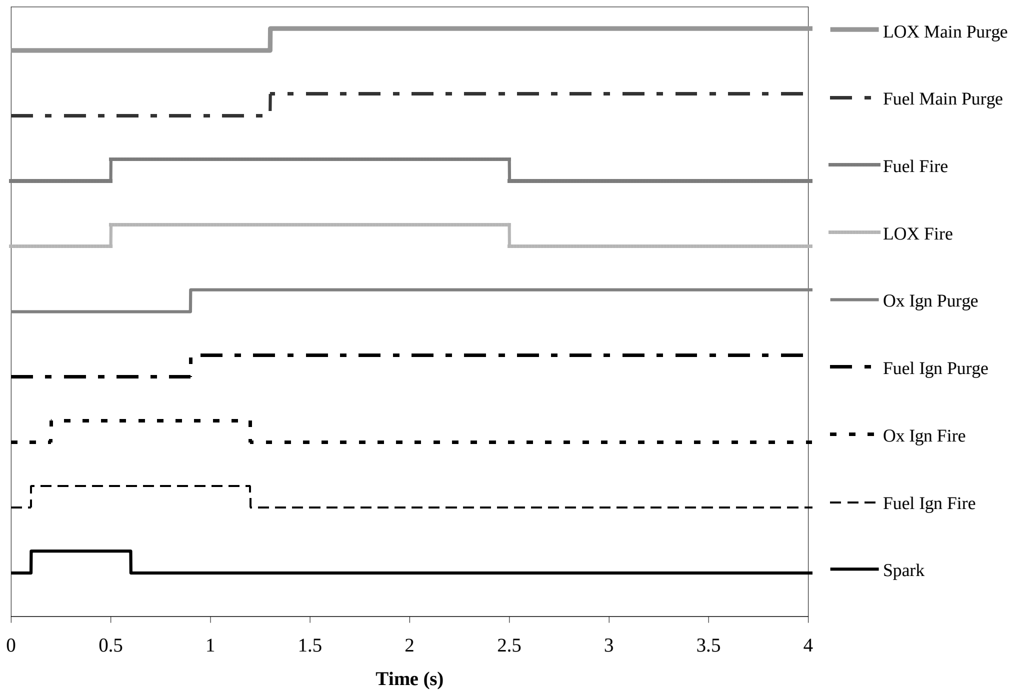


Figure H.3 LOX – GCH_4 test valve sequence - 2 second

APPENDIX I

Detailed Uncertainty Analysis

Taylor Series Detailed Uncertainty Analysis

Detailed Uncertainty Analysis - Measurement of C*
LOX-GCH_4 Rocket Engine

Measured Variables	Systematic Standard Unceratinty
Chamber Pressure	Uncertainty associated Chamber Pressure
$P_C := 1.5065 \cdot MPa$ $\quad P_C = 218.5 \cdot psi$	$b_{PC} := 0.021 \cdot MPa$ $\quad b_{PC} = 3 \cdot psi$
Nozzle Diameter	Uncertainty associated Nozzle Diameter
$D_T := 1.135 \cdot cm$ $\quad D_T = 0.447 \cdot in$	$b_{DT} := 0.0254 \cdot mm$ $\quad b_{DT} = 0.001 \cdot in$
GCH_4 Orifice Discharge Coeff	Uncertainty associated GCH_4 Discharge Coeff
$C_G := 0.91$	$b_{CG} := 0.015$
Fuel Orifice Pressure	Uncertainty associated Fuel Orifice Pressure
$P_F := 8.629 \cdot MPa$ $\quad P_F = 1251.5 \cdot psi$	$b_{PF} := 0.021 \cdot MPa$ $\quad b_{PF} = 3 \cdot psi$
Fuel Orifice Diameter	Uncertainty associated Fuel Orifice Diameter
$D_F := 0.16 \cdot cm$ $\quad D_F = 0.063 \cdot in$	$b_{DF} := 0.0254 \cdot mm$ $\quad b_{DF} = 0.001 \cdot in$
Fuel Orifice Temperature	Uncertainty associated Fuel Orifice Temperature
$T_F := 301.5 \cdot K$ $\quad T_F = 542.7 \cdot R$	$b_{TF} := 2.5 \cdot K$ $\quad b_{TF} = 4.5 \cdot R$
LOX Orifice Discharge Coeff	Uncertainty associated LOX Discharge Coeff
$C_D := 0.65$	$b_{CD} := 0.015$
LOX Orifice Diameter	Uncertainty associated LOX Orifice Diameter
$D_{LOX} := 0.119 \cdot cm$ $\quad D_{LOX} = 0.047 \cdot in$	$b_{DLOX} := 0.0254 \cdot mm$ $\quad b_{DLOX} = 0.001 \cdot in$
LOX Orifice Pressure	Uncertainty associated LOX Orifice Pressure
$P_{LOX} := 6.272 \cdot MPa$ $\quad P_{LOX} = 909.7 \cdot psi$	$b_{PLOX} := 0.021 \cdot MPa$ $\quad b_{PLOX} = 3 \cdot psi$
LOX Orifice Temperature	Uncertainty associated LOX Orifice Temperature
$T_{LOX} := 117.5 \cdot K$ $\quad T_{LOX} = 212 \cdot R$	$b_{TLOX} := 2 \cdot K$ $\quad b_{TLOX} = 3.6 \cdot R$

LOX Vapor Pressure and Density from LOX Temperature Measurement from NIST

LOX Vapor Pressure

$P_V := 0.882 \cdot MPa \qquad P_V = 127.9 \cdot psi$

LOX Density

$\rho_{LOX} := 1014.3 \cdot \frac{kg}{m^3} \qquad \rho_{LOX} = 63.321 \cdot \frac{lbm}{ft^3}$

NIST Data Uncertainty estimates

Uncertainty associated Vapor Pressure

$U_{Pv} := 2\% \cdot P_V \qquad U_{Pv} = 0.018 \cdot MPa \qquad U_{Pv} = 2.558 \cdot psi$

Uncertainty associated LOX Density Measurement

$U_\rho := 0.1\% \cdot \rho_{LOX} \qquad U_\rho = 1.0143 \cdot \frac{kg}{m^3} \qquad U_\rho = 0.063 \cdot \frac{lbm}{ft^3}$

$Pv_{Data} :=$

	0	1
0	116	116.66
1	116.1	117.38
2	116.2	118.11
3	116.3	118.84
4	116.4	...

$\Delta T := \left(Pv_{Data}^{\langle 0 \rangle}\right) \cdot K$

$\Delta Pv := \left(Pv_{Data}^{\langle 1 \rangle}\right) \cdot psi$

$\Delta T =$

	0
0	116
1	116.1
2	116.2
3	...

$\Delta Pv =$

	0
0	0.804
1	0.809
2	0.814
3	...

$\cdot MPa$

$\Delta Pv_{LOX} := slope(\Delta T, \Delta Pv) \qquad \Delta Pv_{LOX} = 0.054 \cdot \frac{MPa}{K} \qquad \Delta Pv_{LOX} = 4.389 \cdot \frac{psi}{R}$

Systematic Uncertainty associated Vapor Pressure

$b_{PvLOX} := \sqrt{U_{Pv}^2 + \left[\left(\Delta Pv_{LOX}^2\right) \cdot b_{TLOX}^2\right]} \qquad b_{PvLOX} = 0.11 \cdot MPa$

$b_{PvLOX} = 16.008 \cdot psi$

$\rho_{Temp} :=$

	0	1
0	116	63.853
1	116.1	63.818
2	116.2	63.782
3	116.3	63.747
4	116.4	...

$\Delta\rho_T := \left(\rho_{Temp}^{\langle 0 \rangle}\right) \cdot K$

$\Delta_{\rho Temp} := \left(\rho_{Temp}^{\langle 1 \rangle}\right) \cdot \frac{lb}{ft^3}$

$\Delta\rho_T =$

	0
0	116
1	116.1
2	116.2
3	...

K

$\Delta_{\rho Temp} =$

	0
0	1022.83
1	1022.27
2	1021.69
3	...

$\frac{kg}{m^3}$

$\Delta\rho T := \mathrm{slope}(\Delta\rho_T, \Delta_{\rho Temp})$ $\quad \Delta\rho T = -5.787 \cdot \frac{kg}{m^3 \cdot K}$ $\quad \Delta\rho T = -0.201 \cdot \frac{lbm}{ft^3 \cdot R}$

$\rho_{press} :=$

	0	1
0	906	63.312
1	906.1	63.312
2	906.2	63.313
3	906.3	...

$\Delta\rho_P := \left(\rho_{press}^{\langle 0 \rangle}\right) \cdot psi$

$\Delta\rho_{Press} := \left(\rho_{press}^{\langle 1 \rangle}\right) \cdot \frac{lb}{ft^3}$

$\Delta\rho_P =$

	0
0	6.247
1	6.247
2	6.248
3	...

$\cdot MPa$

$\Delta\rho_{Press} =$

	0
0	1014.16
1	1014.16
2	1014.18
3	...

$\Delta\rho P := \mathrm{slope}(\Delta\rho_P, \Delta\rho_{Press})$ $\quad \Delta\rho P = 4.09 \cdot \frac{kg}{m^3 \cdot MPa}$ $\quad \Delta\rho P = 0.00176 \cdot \frac{lbm}{ft^3 \cdot psi}$

Systematic Uncertainty associated Density

$$b_{\rho LOX} := \sqrt{U_\rho^{\,2} + \left[\left(\Delta\rho T^2\right) \cdot b_{TLOX}^{\,2}\right] + \left(\Delta\rho P^2\right) \cdot b_{PLOX}^{\,2}}$$

$b_{\rho LOX} = 11.619 \cdot \frac{kg}{m^3}$

$b_{\rho LOX} = 0.725 \cdot \frac{lbm}{ft^3}$

Propellant mass flow rates

Constants for Methane Gas

$\gamma_F := 1.305$

$R_F := 518 \cdot \frac{J}{kg \cdot K}$

$R_F = 96.277 \cdot \frac{lbf \cdot ft}{lbm \cdot R}$

GCH4 Mass Flow

$$m_{GCH4} := \left[\frac{C_G \cdot P_F \cdot \frac{\pi \cdot D_F^{\,2}}{4} \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F + 1}{\gamma_F - 1}}}}{\sqrt{\gamma_F \cdot R_F \cdot T_F}}\right]$$

$m_{GCH4} = 0.0267 \frac{kg}{s}$ $\quad m_{GCH4} = 0.0588 \cdot \frac{lb}{s}$

LOX Mass Flow

$$m_{LOX} := C_D \cdot \frac{\pi \cdot D_{LOX}^2}{4} \cdot \sqrt{2 \cdot ((\rho_{LOX})) \cdot (P_{LOX} - P_V)} \qquad m_{LOX} = 0.0756 \cdot \frac{kg}{s} \qquad m_{LOX} = 0.1667 \cdot \frac{lb}{s}$$

Nominal Measured C* Calculation

$$C_{Star} := \frac{P_C \cdot \frac{\pi \cdot D_T^2}{4}}{m_{GCH4} + m_{LOX}} \qquad C_{Star} = 1490.1 \cdot \frac{m}{s} \qquad C_{Star} = 4888.9 \cdot \frac{ft}{s}$$

$$C_{Th} := 1860.8 \cdot \frac{m}{s} \qquad C_{Th} = 6104.99 \cdot \frac{ft}{s}$$

$$\eta_{Cstar} := \frac{C_{Star}}{C_{Th}} = 0.8$$

Derivatives for the UMF's

1) Chamber Pressure

$$\theta_{PC} := \frac{\pi \cdot D_T^2}{\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F + 1}{\gamma_F - 1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}}$$

2) Nozzle Throat Diameter

$$\theta_{DT} := \frac{2 \cdot \pi \cdot D_T \cdot P_C}{\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot (P_V - P_{LOX})} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F + 1}{\gamma_F - 1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}}$$

3) Fuel Orifice Discharge

$$\theta_{CG} := -\frac{\pi^2 \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot \left(P_V - P_{LOX}\right)} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

4) Pressure at Fuel Orifice

$$\theta_{PF} := -\frac{\pi^2 \cdot C_G \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot \left(P_V - P_{LOX}\right)} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

5) Fuel Orifice Diameter

$$\theta_{DF} := -\frac{2 \cdot \pi^2 \cdot C_G \cdot D_F \cdot D_T^2 \cdot P_C \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot \left(P_V - P_{LOX}\right)} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \sqrt{R_F \cdot T_F \cdot \gamma_F}}$$

6) Temperature at Fuel Orifice

$$\theta_{TF} := \frac{\pi^2 \cdot C_G \cdot D_F^2 \cdot D_T^2 \cdot P_C \cdot P_F \cdot R_F \cdot \gamma_F^2 \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{2 \cdot \left[\pi \cdot \sqrt{2} \cdot C_D \cdot D_{LOX}^2 \cdot \sqrt{-\rho_{LOX} \cdot \left(P_V - P_{LOX}\right)} + \frac{\pi \cdot C_G \cdot D_F^2 \cdot P_F \cdot \gamma_F \cdot \sqrt{\left(\frac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F \cdot T_F \cdot \gamma_F}}\right]^2 \cdot \left(R_F \cdot T_F \cdot \gamma_F\right)^{\frac{3}{2}}}$$

7) LOX Orifice Discharge Coeff

$$\theta_{CD} := -\frac{\sqrt{2}\cdot\pi^2\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}{\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2}$$

8) LOX Orifice Diameter

$$\theta_{DLOX} := -\frac{2\cdot\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}\cdot P_C\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}{\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2}$$

9) Pressure at LOX Orifice

$$\theta_{PLOX} := -\frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot\rho_{LOX}}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}$$

10) LOX Density

$$\theta_{\rho LOX} := \frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^2\cdot D_{LOX}^2\cdot P_C\cdot(P_V - P_{LOX})}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})} + \frac{\pi\cdot C_G\cdot D_F^2\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\frac{2}{\gamma_F + 1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V - P_{LOX})}}$$

11) LOX Vapor Pressure

$$\theta_{PVLOX} := \frac{\sqrt{2}\cdot\pi^2\cdot C_D\cdot D_T^{\,2}\cdot D_{LOX}^{\,2}\cdot P_C\cdot\rho_{LOX}}{2\cdot\left[\pi\cdot\sqrt{2}\cdot C_D\cdot D_{LOX}^{\,2}\cdot\sqrt{-\rho_{LOX}\cdot(P_V-P_{LOX})}+\dfrac{\pi\cdot C_G\cdot D_F^{\,2}\cdot P_F\cdot\gamma_F\cdot\sqrt{\left(\dfrac{2}{\gamma_F+1}\right)^{\frac{\gamma_F+1}{\gamma_F-1}}}}{\sqrt{R_F\cdot T_F\cdot\gamma_F}}\right]^2\cdot\sqrt{-\rho_{LOX}\cdot(P_V-P_{LOX})}}$$

Systematic Standard Uncertainty - with coorelated errors from the Pressure Transducers

$$\begin{aligned}b_{squared1} :=& \left[(\theta_{PC})^2\cdot(b_{PC})^2\right]+\left[(\theta_{DT})^2\cdot(b_{DT})^2\right]+\left[(\theta_{CG})^2\cdot(b_{CG})^2\right]+\left[(\theta_{PF})^2\cdot(b_{PF})^2\right]\ldots\\&+\left[(\theta_{DF})^2\cdot(b_{DF})^2\right]+\left[(\theta_{TF})^2\cdot(b_{TF})^2\right]+\left[(\theta_{CD})^2\cdot(b_{CD})^2\right]\ldots\\&+\left[(\theta_{DLOX})^2\cdot(b_{DLOX})^2\right]+\left[(\theta_{PLOX})^2\cdot(b_{PLOX})^2\right]+\left[(\theta_{\rho LOX})^2\cdot(b_{\rho LOX})^2\right]\ldots\\&+\left[(\theta_{PVLOX})^2\cdot(b_{PvLOX})^2\right]+\left[2\cdot(\theta_{PC}\cdot\theta_{PF})\cdot(b_{PC}\cdot b_{PF})\right]\ldots\\&+\left[2\cdot(\theta_{PF}\cdot\theta_{PLOX})\cdot(b_{PF}\cdot b_{PLOX})\right]+\left[2\cdot(\theta_{PLOX}\cdot\theta_{PC})\cdot(b_{PLOX}\cdot b_{PC})\right]\end{aligned}$$

$b_C := \sqrt{b_{squared1}}$ $\quad b_C = 59.8\cdot\frac{m}{s}$ $\quad b_C = 196.2\cdot\frac{ft}{s}$

Systematic Standard Uncertainty - with out coorelated errors from the

Pressure Transducers

$$\begin{aligned}b_{squared2} :=& \left[(\theta_{PC})^2\cdot(b_{PC})^2\right]+\left[(\theta_{DT})^2\cdot(b_{DT})^2\right]+\left[(\theta_{CG})^2\cdot(b_{CG})^2\right]+\left[(\theta_{PF})^2\cdot(b_{PF})^2\right]\ldots\\&+\left[(\theta_{DF})^2\cdot(b_{DF})^2\right]+\left[(\theta_{TF})^2\cdot(b_{TF})^2\right]+\left[(\theta_{CD})^2\cdot(b_{CD})^2\right]\ldots\\&+\left[(\theta_{DLOX})^2\cdot(b_{DLOX})^2\right]+\left[(\theta_{PLOX})^2\cdot(b_{PLOX})^2\right]+\left[(\theta_{\rho LOX})^2\cdot(b_{\rho LOX})^2\right]\ldots\\&+\left[(\theta_{PVLOX})^2\cdot(b_{PvLOX})^2\right]\end{aligned}$$

$b_{Unc} := \sqrt{b_{squared2}}$ $\quad b_{Unc} = 60.83\cdot\frac{m}{s}$ $\quad b_{Unc} = 199.58\cdot\frac{ft}{s}$

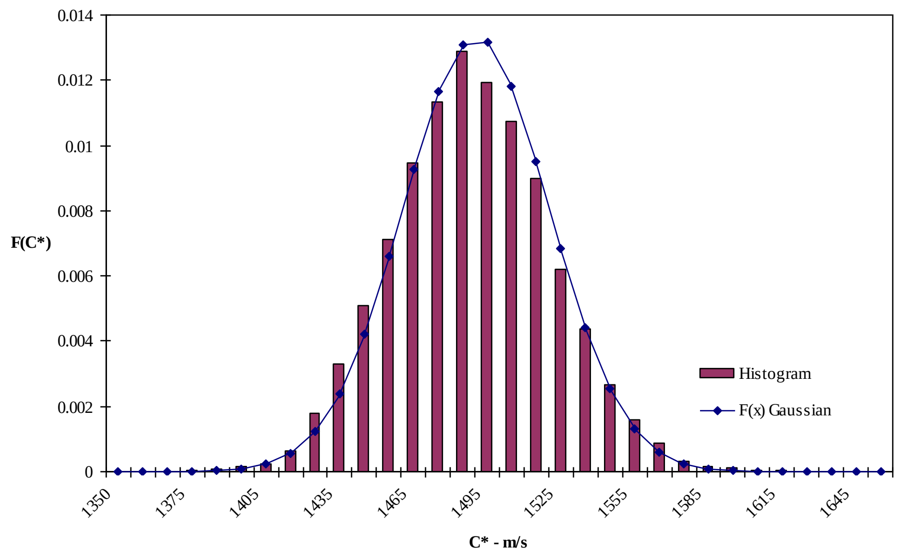


Figure I.1: Monte Carlo Simulation (Pressure transducers calibrated to the same standard) [Normalized Histogram of 10,000 generated random influenced $\overline{C}^*$ compared to Gaussian distribution with $\overline{C}^* = 1490.5$ m/s and $2\,S_{C^*} \approx 60.0$ m/s which is calculated from the 10,000 measurements]

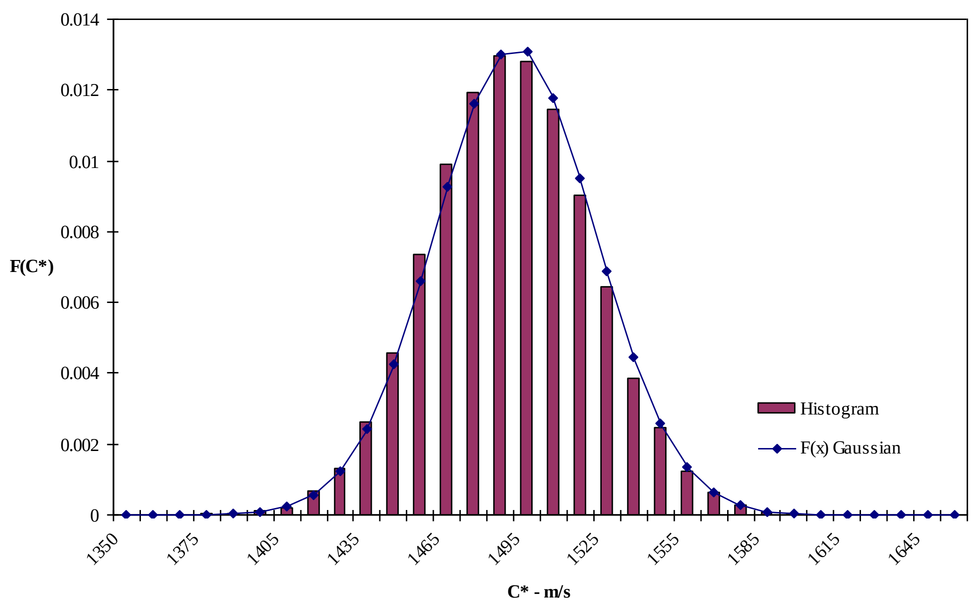


Figure I.2: Monte Carlo Simulation (Pressure transducers not calibrated to the same standard) [Normalized Histogram of 10,000 generated random influenced $\overline{C}^*$ compared to Gaussian distribution with $\overline{C}^* = 1490.5$ m/s and $2\,S_{C^*} \approx 60.3$ m/s which is calculated from the 10,000 measurements]

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