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Ames Hybrid Combustion Facility

Greg Zilliac
Ames Research Center
Moffett Field, California

Mustafa A. Karabeyoglu and Brian Cantwell
Stanford University
Stanford, California

Rusty Hunt and Shane DeZilwa
Ames Research Center
Moffett Field, California

Mike Shoffstall
White Sands Test Facility
Las Cruces, New Mexico

Paul T. Soderman
Ames Research Center
Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

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ABBREVIATIONS

AIT	auto ignition temperature
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BNC	Bayonet Neil-Concelman (connector)
CGA	Compressed Gas Association
EIA	Electronics Industry Association
FMEA	Failure Modes and Effects Analysis
GOX	gaseous oxygen
GUI	Graphical User Interface
HCF	Hybrid Combustion Facility
HMI	Human-Machine Interface
i.d.	inside diameter
IPS	iron pipe size
IST	integrated system test
L_{AE}	day-night noise level
LOX	liquid oxygen
MAWP	maximum allowable working pressure
MNPT	male national pipe thread
NEMA	National Electrical Manufacturers Association
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
OARF	Outdoor Aerodynamics Research Facility
o.d.	outside diameter
O/F	oxidizer-to-fuel ratio
OHA	Operational Hazard Analysis
OSHA	Occupational Safety and Health Administration
PID	proportional integral-differential
PLC	Programmable Logic Controller
RTG	ring-type joint
SCF	standard cubic feet
SCFH	standard cubic feet per hour
SCFM	standard cubic feet per minute
SOP	standard operating procedure
UBC	Uniform Building Code
WOG	water, oil, gas
WSTF	White Sands Test Facility

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AMES HYBRID COMBUSTION FACILITY

Greg Zilliac, Mustafa A. Karabeyoglu,[*] Brian Cantwell,[†] Rusty Hunt,
Shane DeZilwa, Mike Shoffstall,[‡] and Paul T. Soderman

Ames Research Center

SUMMARY

The report summarizes the design, fabrication, safety features, environmental impact, and operation of the Ames Hybrid-Fuel Combustion Facility (HCF). The facility is used in conducting research into the scalability and combustion processes of advanced paraffin-based hybrid fuels for the purpose of assessing their applicability to practical rocket systems. The facility was designed to deliver gaseous oxygen at rates between 0.5 and 16.0 kg/sec to a combustion chamber operating at pressures ranging from 300 to 900 psi. The required run times were of the order of 10 to 20 sec. The facility proved to be robust and reliable and has been used to generate a database of regression-rate measurements of paraffin at oxygen mass flux levels comparable to those of moderate-sized hybrid rocket motors.

BACKGROUND

Hybrid rockets, which typically use a liquid oxidizer (such as liquid oxygen) and a solid fuel (often a form of rubber), have traditionally been poor performers that have limited applications because they require complicated grain geometry in order to achieve useful thrust levels. Recently, researchers at Stanford University have demonstrated that paraffin and oxygen combusts at a rate of approximately three times that of conventional hybrid fuels, thus eliminating the need for complicated and inefficient grain geometries (ref. 1). In addition, the products of combustion, namely carbon dioxide and water, are nontoxic and less harmful to the environment than most rocket propellants.

Stanford University approached Ames Research Center to collaborate in this research effort to (1) assess the scalability of the laboratory results obtained at Stanford and (2) investigate the fluid mechanics phenomena associated with this hybrid fuel combustion process. To achieve these objectives, Ames built a facility that is significantly larger than that used by Stanford in their pioneering research. The NASA facility (fig. 1) consists of a gaseous oxygen delivery system, an igniter, and a combustion chamber with a nozzle. The purpose of the gaseous oxygen system (GOX system) is to deliver oxygen to the combustion chamber at a specified mass-flow rate and pressure. The GOX is created from liquid oxygen (LOX) that is pumped through a heat exchanger and is stored in a large pressure vessel until it is used as an oxidant during a firing of the facility. The gas-gas igniter (methane and oxygen) is essentially a high-pressure torch that heats the primary oxygen flow and ignites the fuel in the combustion chamber. Most tests are 10 sec or less in duration.

Two interchangeable combustion chambers support the overall research effort. The first is a 47-in-long cylinder used to assess the regression-rate characteristics of the hybrid fuel. The second is a slab burner (rectangular in cross section) that has optical viewing ports to allow detailed fluid mechanics measurements to be made. The details of the cylindrical combustion chamber are contained in this report. The two-dimensional version is still under development.

Prior to undertaking the construction of a new test facility at Ames, consideration was given to other government or commercial test sites that are commonly used for rocket testing. The obvious advantages of these sites are the built-in infrastructure for LOX/GOX delivery and the potential for thrust measurement.

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[*] Research Associate, Stanford University, Stanford, California.
[†] Professor, Stanford University, Stanford, California.
[‡] Oxygen Systems Analyst, White Sands Test Facility, White Sands, New Mexico.

After reviewing the technical, operational, and cost characteristics of candidate facilities, it became apparent that, for a variety of reasons, these facilities were not appropriate for the research aspects of the project. First, the motor size required to demonstrate the regression-rate law is small (~5,000 lb thrust) compared with the motors that are normally tested at these sites. Second, the cost and limited occupancy time would have put unacceptable constraints on the number of test points to be obtained and would have prohibited their use for conducting the detailed fluid mechanics measurements. Using a number of expensive, but surplus, components available at Ames, along with in-house expertise, the facility was designed and constructed for approximately $150,000, which was much less than the estimated occupancy cost at other existing facilities. Finally, the physical proximity to Ames and Stanford was also important for cost and research productivity reasons, since costs and travel time would be minimized for the duration of the test program. Locating the facility at Ames was also critical for the fluid mechanic measurements, since the sophisticated instrumentation and expertise was located at Ames and would have to be transported off-site, if a commercial facility was used.

Significant safety measures have been incorporated into the facility. These measures include proper material and component selection, an oxygen system hazard analysis, an operational hazard analysis (OHA), and reviews and training. Codes and standards have been followed, when applicable, including the American Society of Mechanical Engineers (ASME) pressure codes and the NASA "Safety Standard for Oxygen and Oxygen Systems," NSS 1740.15 (ref. 2). The project was subject to and has benefited from extensive oversight from safety organizations within Ames and oxygen system experts from NASA's White Sands Test Facility (WSTF) at White Sands, New Mexico.

Another major concern, which was addressed, is the environmental impact of the project. Although the facility is sited at a remote location within Ames, Ames is located close to an urban area. The Jet Noise 7 computer code was used to perform noise predictions for the surrounding area. The predicted yearly day-night noise levels (L_{AE}) at the closest point of noise exposure by the general public, is 51 dB (with no sound barrier in place). At the location of the fence surrounding the OARF, the L_{AE} level is 75 dB. Given the short duration of the tests, it was considered highly unlikely that Ames personnel or the neighboring communities would be significantly affected, given that there are numerous other noise sources within Ames that typically generate comparable noise levels but of longer duration.

The design and fabrication and review phases of this project have involved approximately 40 people with expertise that includes design, fabrication, safety, controls, instrumentation and measurement systems, operations, fluid mechanics, and rocket science. The result is a safe, environmentally sound, and cost-effective test rig (figs. 1 and 2). To date, 41 successful tests have been conducted using the HCF. The initial goal of the research program, namely obtaining a database of regression-rate measurements of paraffin at oxygen mass flux levels comparable to those of a moderate-size hybrid rocket motor, has been accomplished.

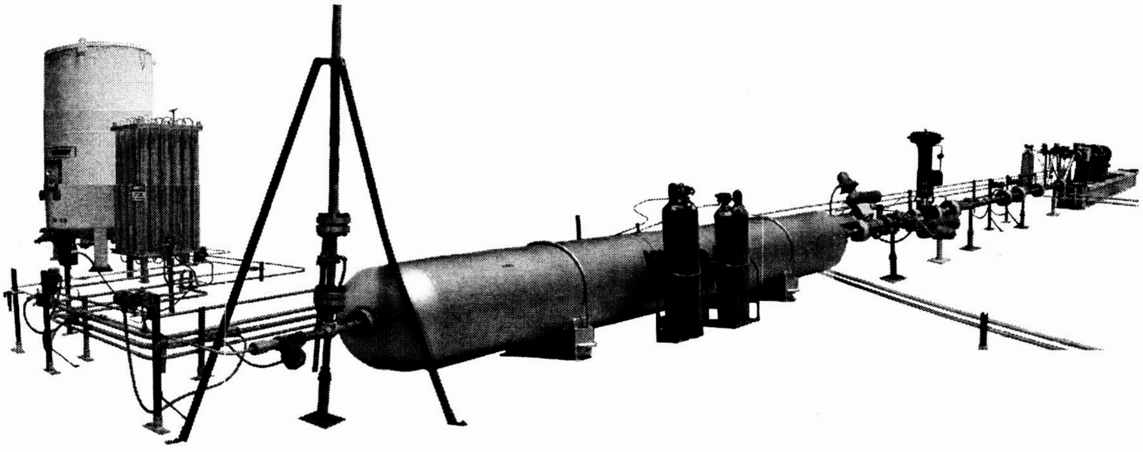


Figure 1. Ames Hybrid Combustion Facility.

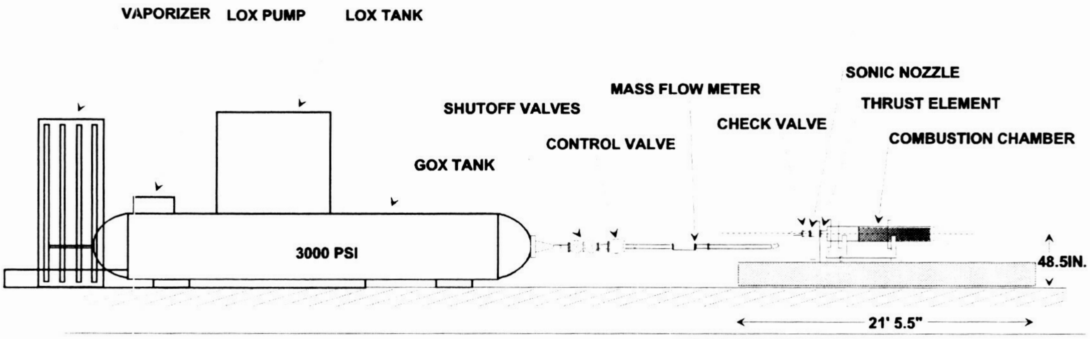


Figure 2. Ames Hybrid Combustion Facility (side view).

FACILITY SITE

The HCF is located at the Outdoor Aerodynamics Research Facility (OARF) at Ames. The OARF was originally developed as an air-breathing engine test site and has a below-ground control room, is fenced off from the surrounding wetlands, and has the required utilities. The OARF provides a safe, isolated environment for the test rig. The existing concrete pad provides an ideal foundation for the facility and the isolated location reduces the exposure of Ames employees to high noise levels. The community noise impact is small because the combustion chamber is pointed toward the bay and the tests have short run times. Aside from a few environmental concerns (see the Environmental Impact section) the OARF is an ideal site. The combustion facility is positioned at the OARF as shown in figure 3.

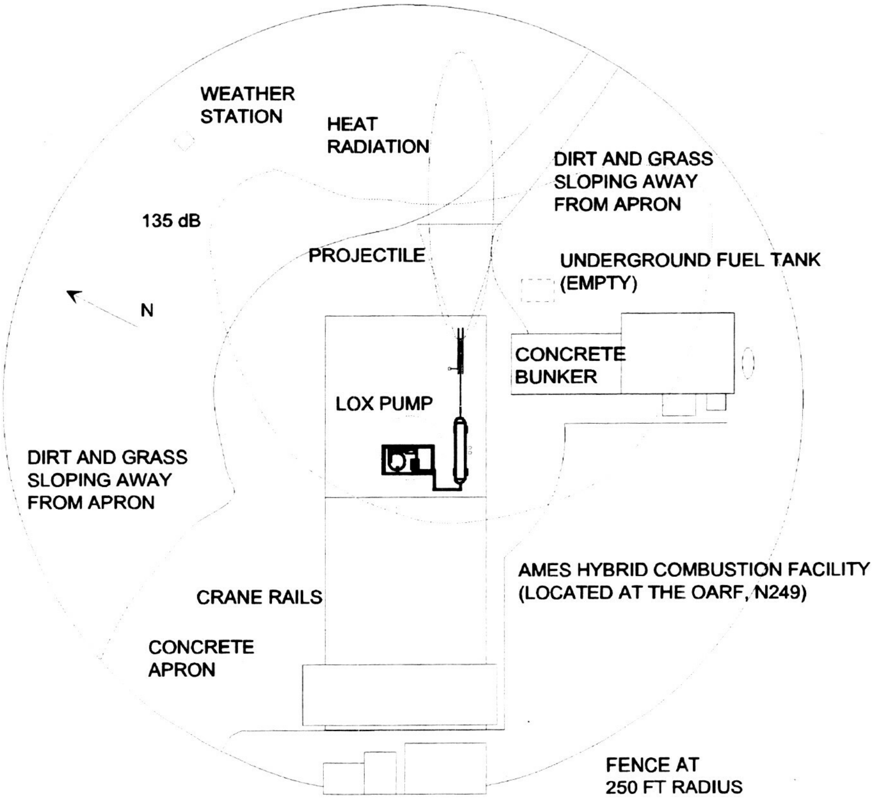


Figure 3. Outdoor Aerodynamics Research Facility site for HCF.

Figure 4 shows the positioning of the components relative to the south crane rail at the OARF (crane rail on the right of fig. 3). The areas shown in gray are access panels to the OARF support structure.

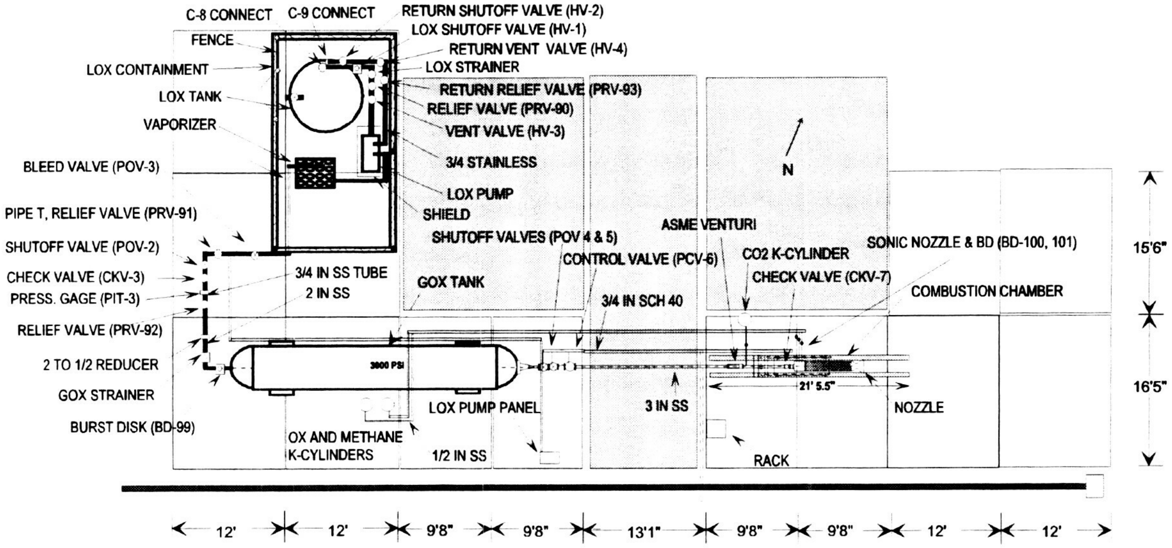


Figure 4. Layout of HCF at the OARF.

Specific quantity-distance guidelines are given in NSS 1740.15 (ref. 2) concerning the positioning of LOX and GOX tanks and their proximity to fuel sources. In this guideline, barricades are recommended to prevent unauthorized personnel from encroaching on the minimum distance requirements. The OARF has a fence at approximately 250 ft from the HCF that is used for this purpose. Concerning the LOX and GOX tanks, all relevant NSS 1740.15 guidelines have been met.

Containment is provided to capture spilled LOX in the event that the LOX tank were to split a seam. The containment walls are 8 in. high and are constructed of cement blocks attached to the pad using mortar. The confinement zone can contain approximately half of the LOX volume of the LOX tank. The LOX pump is mounted within this confinement zone on a steel pedestal that is 2 in. high and shielded from the GOX tank by a barrier constructed of ceramic board.

In choosing the site for the HCF, consideration of the potential hazards was paramount. The factors considered included the following:

1. The greatest potential energy associated with the facility is that contained by the gaseous oxygen pressure vessel. In the vessel, 70 ft^3 of oxygen gas is held at pressures of up to 2,900 psi. This vessel has 6-in.-thick walls, was originally designed for 15,000 psi, and is currently certified to 4,000 psi.

2. The HCF is not a rocket in the traditional sense and therefore is not nearly as hazardous. In liquid rockets, liquid fuel and liquid oxygen are injected into combustion chambers that have wall thickness as of the order of 0.33 in. If, for some reason, the liquid oxygen and fuel mixture does not ignite or burn properly, an explosion can result (as has happened many times in the past). Solid rockets have fuel and oxidizer in direct contact with each other at a molecular level throughout the grain. Solid rocket propellants are usually classified as Department of Transportation (DOT) 1.2 or 1.3 materials and are explosive. In contrast, the HCF injects gaseous oxygen into a combustion chamber that has a wall thickness of 1.25 in., protected by burst disks, and uses a fuel (paraffin) that is in contact with the oxidizer only at the surface of the grain. Paraffin is not an explosive material and is not listed on the CFR 172.101 list of hazardous materials.

3. The effect of the worst-case probable failure mode that is envisioned by the safety analysts is a fire. There is the possibility that either a valve or the combustion chamber could partially burn. Many steps have been taken to engineer out such possibilities, but the reality is that, despite the best efforts of the designers, fires do occur in oxygen systems.

4. A literature search for hybrid rocket explosions was conducted and only one of significance was identified. The explosion occurred when liquid oxygen was fed into a combustion chamber that contained tar as the fuel. The researchers could not get the rocket to ignite. The liquid oxygen and the tar formed a gel that subsequently exploded after the researchers attempted another ignition sequence. This accident could not happen in the HCF because we use gaseous oxygen and have procedures to eliminate this hazard in the case of a failed ignition (purge with CO^2, etc.)

In addition to the inherent safety features of the HCF design, a standard operating procedure (SOP) is our first line of defense against the possibility of injury. The primary procedural control specified in the SOP is that all personnel must be inside the blockhouse at the OARF, during combustion tests, or outside the locked fence that surrounds the OARF at a distance of 250 ft from the facility. In order to avoid startling people outside the 250 ft radius but within hearing range, a klaxon-warning siren has been installed. In addition, a closed circuit television system with three cameras mounted 50 ft above the ground is monitored to verify that nobody is in the vicinity of the OARF during tests.

A hazard diagram (fig. 3) has been established based on considerations of heat radiation, noise, exhaust plume, particulate ejection, and possible failure modes.

OXYGEN DELIVERY SYSTEM

Oxygen System Description

The oxygen delivery system (fig. 5) consists of a 3,000-gal cryogenic LOX storage tank, a LOX pump, a GOX pressure vessel, and the associated piping and valves.

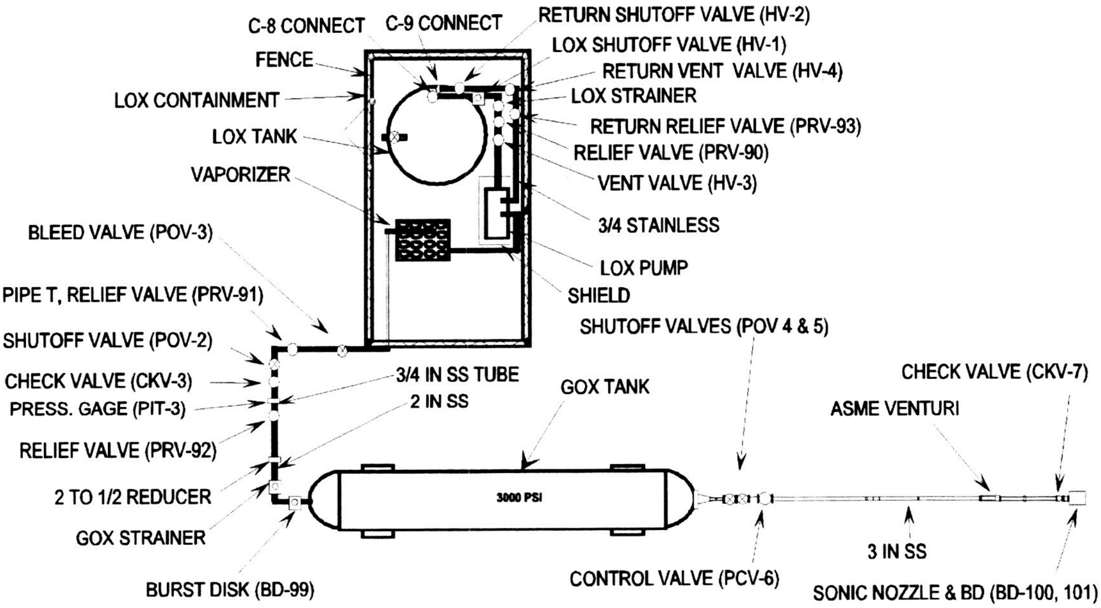


Figure 5. HCF oxygen delivery system.

This system is designed to deliver up to 16 kg/sec of ambient-temperature gaseous oxygen to the combustion chamber at pressures of 300 psi to 1,000 psi (although the facility has been run at chamber pressures as low as 150 psi). During the integrated systems tests (ISTs), the extremes of the delivery system operating envelope were tested (using nitrogen) and verified. To date, the maximum oxygen mass-flow established in an actual test (with combustion) is 6 kg/sec. The oxygen system was sized to allow for possible future tests with larger combustion chambers. The system functions as follows:

1. With the main shutoff valves POV-4 and POV-5 closed and LOX shutoff valve HV-1 and shutoff valve POV-2 in the line between the vaporizer and the GOX tank open, LOX is pumped through the vaporizer and is gasified.

2. Over a period of up to an hour, the pressure rises in the GOX tank until it reaches a pre-set level (typically in the range of 1,900 to 2,500 psi) depending on the desired mass-flow rate and injector inlet pressure. At this point, the LOX pump is turned off and LOX shutoff valve HV-1 and shutoff valve POV-2 in the line between the vaporizer and the GOX tank are closed.

3. The operator then sets the desired initial control-valve position. The initial set point is dependent on the desired pressure upstream of the sonic nozzle (at least twice the combustion-chamber pressure).

4. Main shutoff valves POV-4 and POV-5 are then opened (100% open) and GOX flows through the 3-in. line to the combustion chamber.

5. The igniter is turned on and the facility runs for up to 12 sec. During this time, the delivery pressure is maintained constant through a feedback loop based on the pressure measured in the oxygen feed line upstream of check valve CK-7. At the end of the run, shutoff valves POV-4 and POV-5 are closed.

Oxygen System Modeling

The oxygen mass-flow rate and delivery pressure are established by the size of the sonic nozzle, the control valve PCV-6 setting, and GOX tank initial pressure. During a run, the control valve continuously opens to maintain a constant oxygen delivery pressure. The purpose of the sonic nozzle is to isolate the oxygen feed system from pressure variations in the combustion chamber. The delivery pressure is chosen such that the flow through the sonic nozzle remains choked for the duration of the run. A choke margin of at least 10% is typically maintained so that pressure perturbations in the combustion chamber do not unchoke the sonic nozzle. It should be noted that the combustion chamber pressure is established by the area of the combustion chamber nozzle and is essentially independent of the delivery pressure. The pressure downstream of the sonic nozzle can be no greater than 1,532 psi under any conditions, short of an exhaust-nozzle blockage, because the flow through the sonic nozzle is choked and the maximum pressure that the pump can generate is 2,900 psi.

Three analytical models of the gaseous oxygen portion (between the GOX tank and combustion chamber) of the oxygen delivery system were developed during the course of this project. These include a steady-state model based on standard loss calculations for compressible flow systems, a Simulink dynamic model that makes use of the measured time response of the various components in the system, and a dynamic model that was derived from first principles. Each model has it strengths and weaknesses. The steady-state model is not very useful for control system tuning but is quite useful for determining pressure levels in the various components and for estimating the control valve initial position and range required. The Simulink model was developed after the hardware was in place and cold-flow runs were possible. This model turned out to be the most useful from the control system tuning point of view. Its shortcoming is that it is based on observed response as opposed to component models derived from abstractions of the physics of fluid flow. The "first principles" model was derived from a control volume thermodynamic approach. This model was most helpful in the analysis of the oxygen delivery system during the ignition portion of the run. Using this model, it was possible to schedule the control valve during ignition to minimize time lags in the oxygen delivery system.

Described in detail in the following pages is the steady-state model. The model was developed using product literature and information gleaned from the "Handbook of Hydraulic Resistance" by Idelchik (ref. 3). The main goal of this modeling effort was to determine the initial and final control valve positions for a run of a specified duration, GOX tank initial pressure level, and desired delivery pressure. Most of the components that make up the oxygen delivery system are analyzed individually (with some lumped together). The logic flow of the model starts with the sonic orifice. The pressure just upstream of the orifice is chosen. Knowing the orifice diameter, the mass-flow through the orifice may be determined. By continuity, this must be the mass-flow through the rest of the components. The desired delivery pressure is then used as a starting point and the losses through each component are computed upstream to the control valve (to the downstream side of control valve). The pressure losses are then computed starting inside the GOX tank and progressing to the upstream side of the control valve. The position of the control valve is then adjusted to match the pressure on the upstream and downstream sides of this valve. In the standard notation, P is pressure, $\dot{m}$ is the mass-flow rate, A is area, T is temperature, M is Mach number, R is the ideal gas constant, ρ is the density, k is the ratio of specific heats, ζ is a loss coefficient, and subscript t refers to stagnation or total conditions. On a component-by-component basis, the main modeling equations are shown below.

GOX tank model: isentropic expansion

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$P_{t_{in}} = P_{t_{out}}$ (Isentropic)

$P_{in} = P_{t_{in}}, M_{in} = 0$ (Low Mach approx.)

$V_{in} = \dfrac{\dot{m}_{in} R T_{T_{in}}}{P_{t_{in}} A_{in}}$ (ideal gas & $\dot{m} \equiv \rho A V$)

Constraints at output station:
(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\left(1+\frac{k-1}{2}M^2\right)^{\frac{k+1}{2(1-k)}} = \frac{\dot{m}}{P_t A}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P_t, T_t, A, R, k$

=> Find M

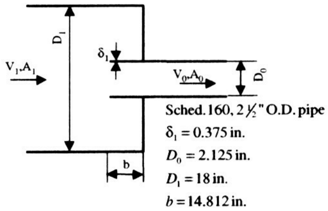
$$P = P_t \Big/ \left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$$

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

$$V = M\sqrt{kRT}$$

$$\rho = \frac{P}{RT}$$

GOX tank exit model: sudden contraction, Borda mouthpiece



Sched. 160, 2 ½" O.D. pipe

$\delta_1 = 0.375$ in.

$D_0 = 2.125$ in.

$D_1 = 18$ in.

$b = 14.812$ in.

$$\zeta \equiv \frac{\Delta p}{\frac{1}{2}\rho V_0^2} = \zeta'\left(1-\frac{A_0}{A_1}\right)^m = 0.49$$

$$\zeta' = f\left(\frac{\delta_1}{D_h}, \frac{b}{D_h}\right) = 0.5$$

$$m = f\left(\frac{b}{D_h}\right) = 1$$

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$P_{out} = P_{in} - \zeta \frac{1}{2}\rho V_0^2$

Constraints at output station:
(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

=> Find M

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

Shutoff valve model: Norriseal Valve Sizing Reference Guide (ISA)

$$x = \frac{P_1 - P_2}{P_1} \quad \text{limit } x \le x_T = 0.25$$

$$F_k = \tfrac{k}{1.4}, F_P = 1$$

$$Y = 1 - \frac{x}{3F_k x_T}$$

$$C_V = 322$$

$$Q = \tfrac{1360}{60} C_V F_P P_1 Y \sqrt{\frac{x}{G_g T Z}} \quad \text{[SCFM]}$$

$$\dot{m} = \tfrac{1.33}{60 \times 3.28^3} Q \quad \text{[kg/sec]}$$

Know $\dot{m}, T, Z = \mathrm{f(M)}, \mathrm{P}_1$

=> Find P_2

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

If valve is closed, $\dot{m} = 0$

Constraints at output station:
(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1 + \frac{k-1}{2} M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

=> Find M

$$T = T_t \Big/ \left(1 + \frac{k-1}{2} M^2\right)$$

Control valve model: same as shutoff valve

Pressure losses propagated from GOX tank downstream to control valve entrance
=> P_1
Pressure losses propagated from sonic orifice upstream to control valve exit
=> P_2

$$x_T = 0.7$$

$$Q = \tfrac{1360}{60} C_V F_P P_1 Y \sqrt{\frac{x}{G_g T Z}} \quad \text{[SCFM]}$$

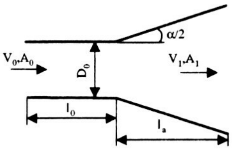
$$\dot{m} = \tfrac{1.33}{60 \times 3.28^3} Q \quad \text{[kg/sec]}$$

Know mass flow, use outlet conditions for T, Z and solve for $\mathrm{C_V}$

$$C_V = f(\%\ \text{open})$$

%open	0	10	20	30	40	50	60	70	80	90	100
Cv	0	1.51	4.87	11	20.3	30.9	41.5	50.2	57	61.4	64.8

Diffuser model: free discharge from a circular straight wall diffuser



$n_1 = \frac{A_1}{A_0}; \mathrm{Re} = \frac{V_0 D_0}{\upsilon}$

Sched. 160, 2" O.D. pipe
to sched. 160, 3" O.D. pipe
$D_0 = 1.689$ in.
$D_1 = 2.626$ in.
$\alpha = 30^\circ$

$$\zeta \equiv \frac{\Delta p}{\frac{1}{2}\rho V_0^2} = \zeta_{tot} = f(\alpha, n_1, \mathrm{Re}) = 0.635$$

assumption: uniform velocity at entrance

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$\rho = \frac{P_{t_{out}}}{RT_{t_{out}}}$ (Incompressible)

$V_0 = V_{out} A_{out} / A_{in}$ (Incompressible)

$P_{in} = P_{out} + \zeta \frac{1}{2}\rho V_0^2$

Constraints at input station:

(isentropic, perfect gas mass flow relation)

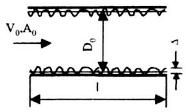
$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

=> Find M

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

Pipe model: circular tube with walls of uniform roughness



Sched. 160, 3" O.D. pipe
$D_0 = 2.626$ in.

$$\zeta \equiv \frac{\Delta p}{\frac{1}{2}\rho V_0^2} = \lambda \frac{l}{D_0}$$

$$\lambda \equiv f\left(\mathrm{Re}, \frac{\Delta}{D_0}\right) = 0.035 \text{ (turbulent)}$$

assumption: use aggregate pipe length

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$\rho = \frac{P_{t_{out}}}{RT_{t_{out}}}$ (Incompressible)

$V_0 = V_{out}$ (Approx.; friction will increase V)

$P_{in} = P_{out} + \zeta \frac{1}{2}\rho V_0^2$

Constraints at input station:

(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

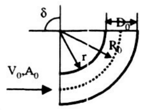
=> Find M

$$P_t = P\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$$

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

$$V = M\sqrt{kRT}$$

45 ° elbow model



$$\zeta \equiv \frac{\Delta p}{\frac{1}{2}\rho V_0^2} = k_\Delta k_{\mathrm{Re}} \zeta_{loc} + 0.0175\delta\lambda \frac{R_0}{D_0} = 0.1$$

$$\zeta_{loc} = f\left(\delta, \frac{R_0}{D_0}\right)$$

$$k_\Delta = f\left(\frac{\Delta}{D_0}\right), \quad k_{\mathrm{Re}} = f(\mathrm{Re})$$

$$\lambda \equiv f\left(\mathrm{Re}, \frac{\Delta}{D_0}\right) = 0.035 \text{ (turbulent)}$$

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$\rho = \dfrac{P_{t_{out}}}{RT_{t_{out}}}$ (Incompressible)

$V_0 = V_{out}$ (Approx.; friction will increase V)

$P_{in} = P_{out} + (2)\zeta \frac{1}{2}\rho V_0^2$

Constraints at input station:

(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

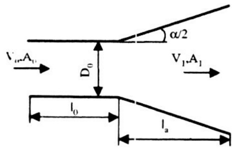
=> Find M

$$P_t = P\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$$

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

$$V = M\sqrt{kRT}$$

ASME Venturi model: free discharge from a circular straight wall diffuser



$n_1 = \dfrac{A_1}{A_0}; \mathrm{Re} = \dfrac{V_0 D_0}{\upsilon}$

$\beta = \dfrac{D_0}{D_1} = 0.749$

$D_0 = 1.967$ in.

$D_1 = 2.626$ in.

$\alpha = 30°$

$$\zeta \equiv \frac{\Delta p}{\frac{1}{2}\rho V_0^2} = \zeta_{tot} = f(\alpha, n_1, \mathrm{Re}) = 0.635$$

assumptions: uniform velocity at entrance, losses in diffuser section only

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

$\rho = \dfrac{P_{t_{out}}}{RT_{t_{out}}}$ (Incompressible)

$V_0 = V_{out} \, {A_{out}} \big/ {A_{throat}}$ (Incompressible)

$P_{in} = P_{out} + \zeta \frac{1}{2}\rho V_0^2$

Constraints at input station:

(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

=> Find M

$$P_t = P\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$$

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

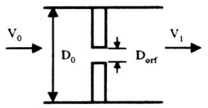
$$V = M\sqrt{kRT}$$

Check valve model: same as shutoff valve

$x_T = 0.3$

$C_V = 240$

Sonic orifice model: choked flow



$$\beta = \frac{D_{orf}}{D_0}$$

$$r = \frac{P_1}{P_0}$$

if $r < r_c$ where: $r_c^{\frac{1-k}{k}} + \frac{k-1}{2}\beta^4 r_c^{2/k} = \frac{k+1}{2}$

=> choked

$$\dot{m} = C_d \sqrt{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \frac{P_0 A}{\sqrt{RT_t}}$$

Constraints:

$\dot{m}_{in} = \dot{m}_{out}$ (Continuity)

$T_{t_{in}} = T_{t_{out}}$ (Adiabatic)

Constraints at input station:
(isentropic, perfect gas mass flow relation)

$$f(M,k) = M\sqrt{1+\frac{k-1}{2}M^2} = \frac{\dot{m}}{PA}\sqrt{\frac{RT_t}{k}}$$

Know $\dot{m}, P, T_t, A, R, k$

=> Find M

$$T = T_t \Big/ \left(1+\frac{k-1}{2}M^2\right)$$

Figure 6 show the performance of the oxygen delivery system (with a worst-case choke margin of zero) as predicted by the steady-state model. The plot on the left shows the velocity levels in the main pipe (3 in. nominal). The plot on the right shows the sonic nozzle diameter required to achieve a desired mass-flow rate as a function of pressure downstream of the sonic nozzle (essentially the combustion chamber pressure assuming that an exhaust nozzle of proper area is installed).

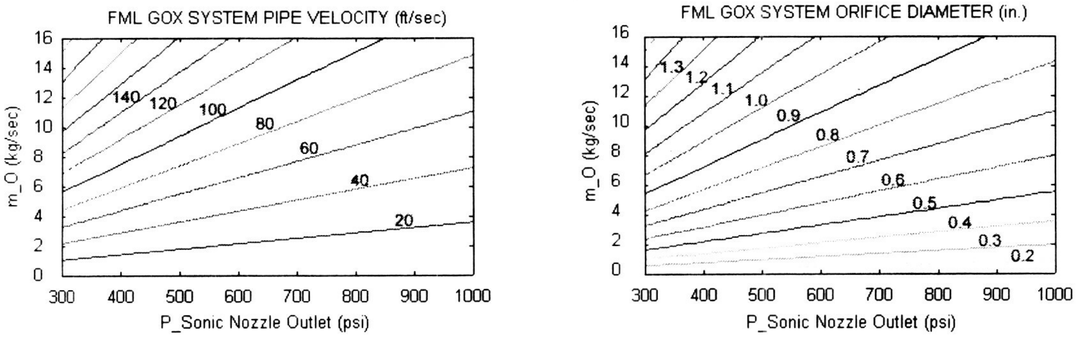


Figure 6. Performance of the GOX delivery system.

The components in the GOX portion of the oxygen delivery system were further analyzed to ensure that they were sized properly and also to provide data for the oxygen system hazards analysis. Presented in figures 7-10 is a series of plots showing the velocity, pressure, Mach number, and cross-sectional area at the extremes of the oxygen system operation envelope. Plotted are the values at the inlet, minimum area, and outlet for each component (grid lines indicate the entrance and exit for a component). Values at the beginning of a run are shown in green and values at the end of a run are shown in red. These plots overlap downstream of the sonic nozzle (flow is right to left), because control valve PCV-6 opens up during the run to maintain constant delivery pressure. These results were computed using the component manufacture's C_V data. The initial GOX tank pressure was set to achieve a run duration of at least 10 sec.

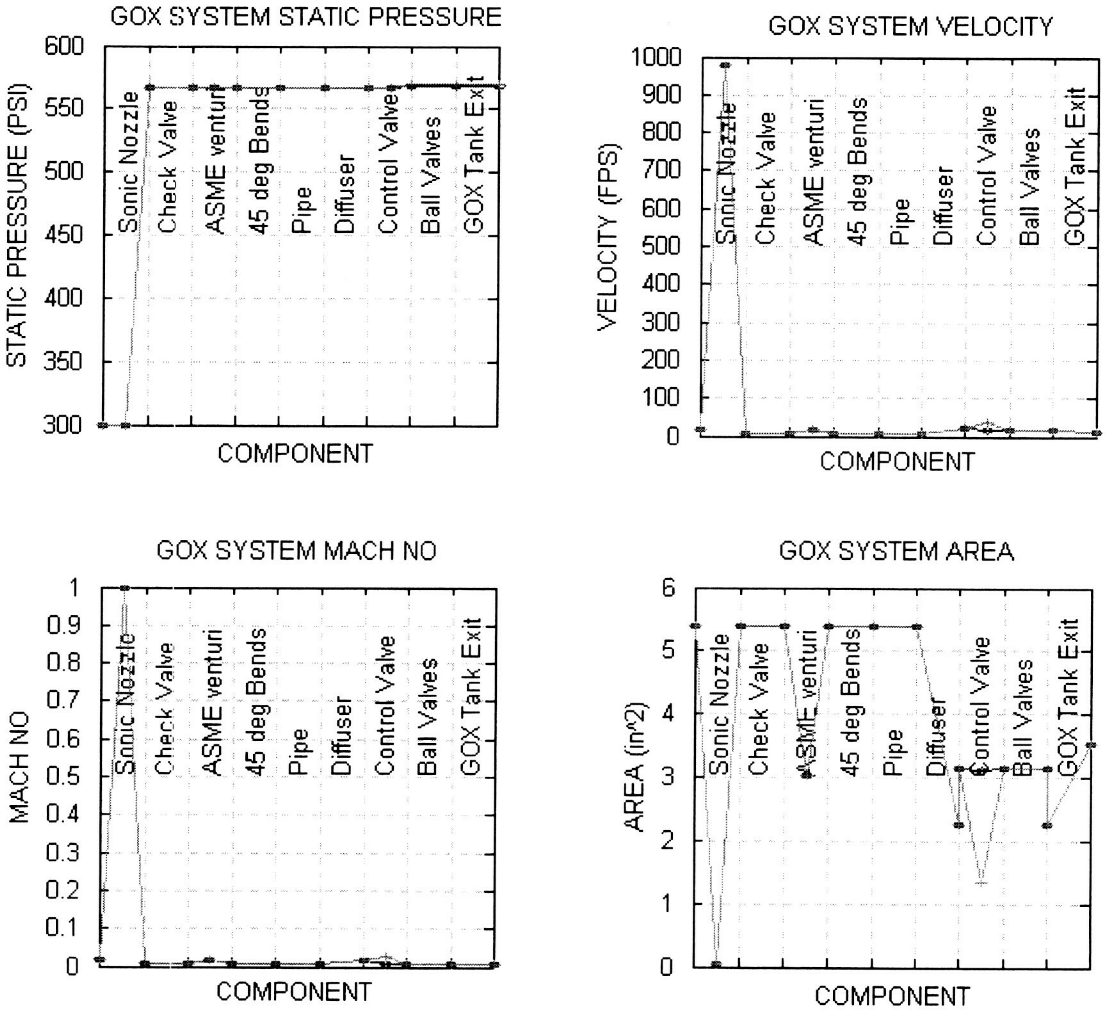


Figure 7. Component analysis for mass-flow rate of 0.5 kg/sec and pressure of 300 psi.

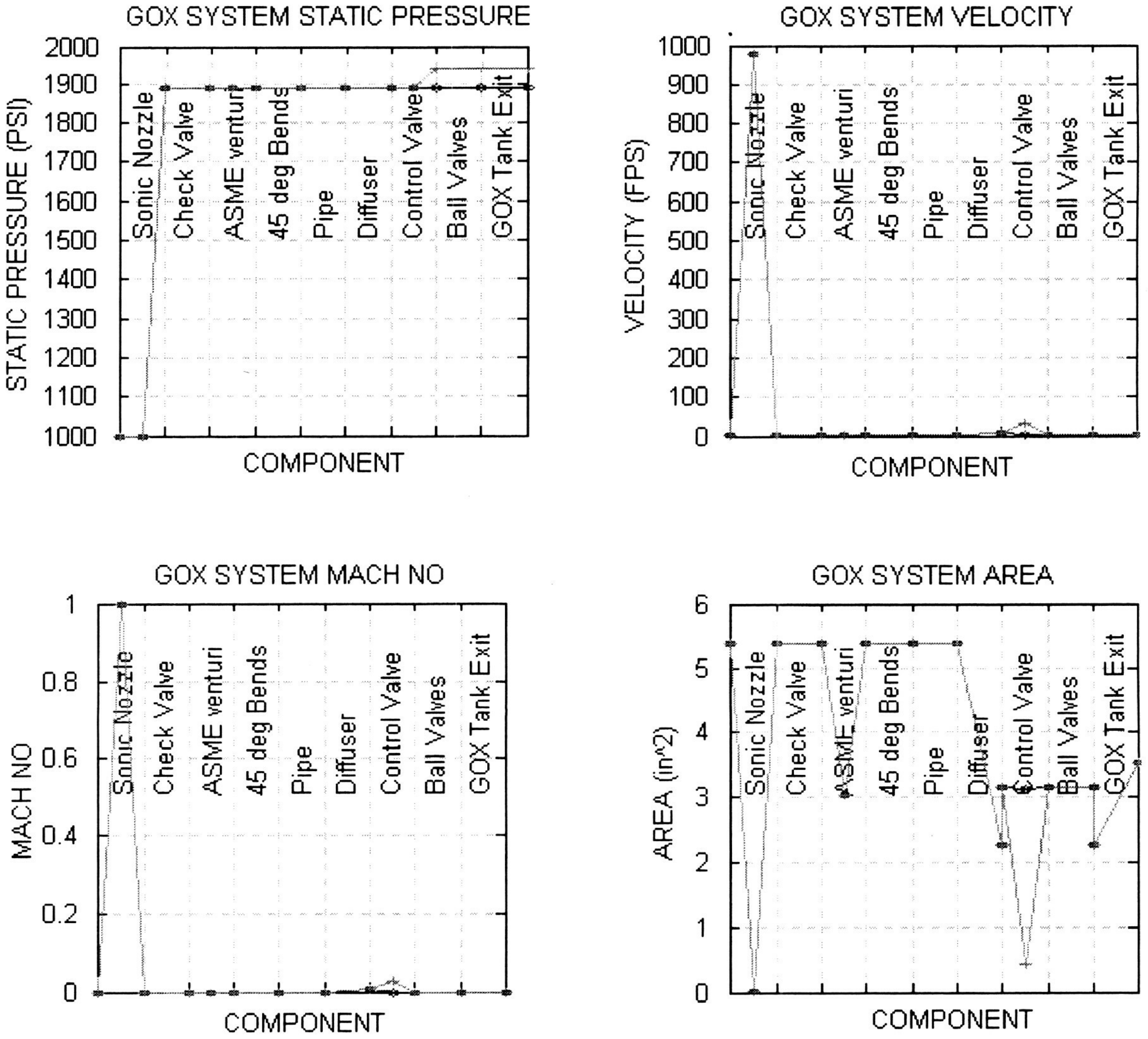
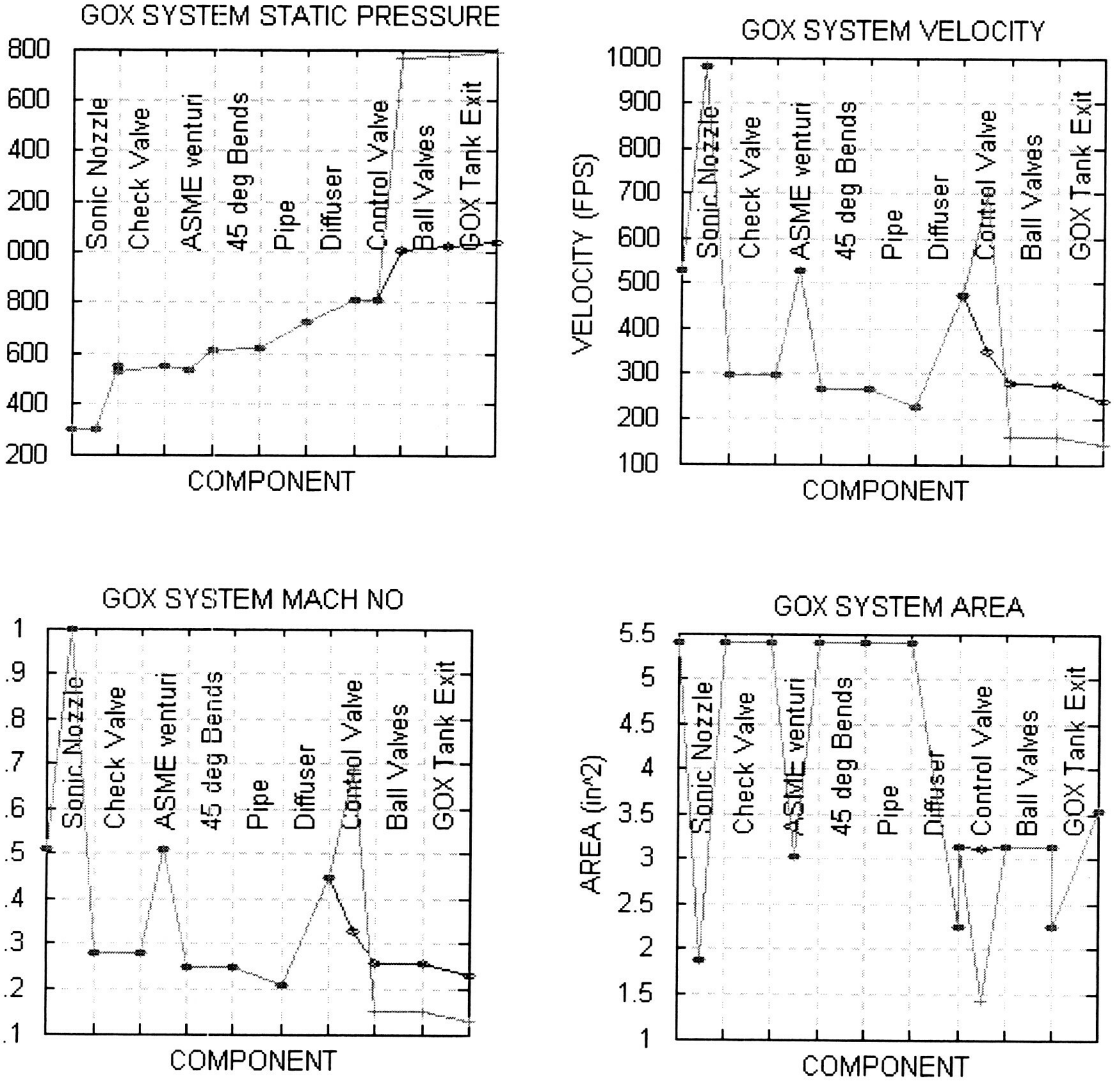


Figure 8. Component analysis for mass-flow rate of 0.5 kg/sec and pressure of 1,000 psi.



GOX SYSTEM STATIC PRESSURE

GOX SYSTEM VELOCITY

GOX SYSTEM MACH NO

GOX SYSTEM AREA

Figure 9. Component analysis for mass-flow rate of 16 kg/sec and pressure of 300 psi.

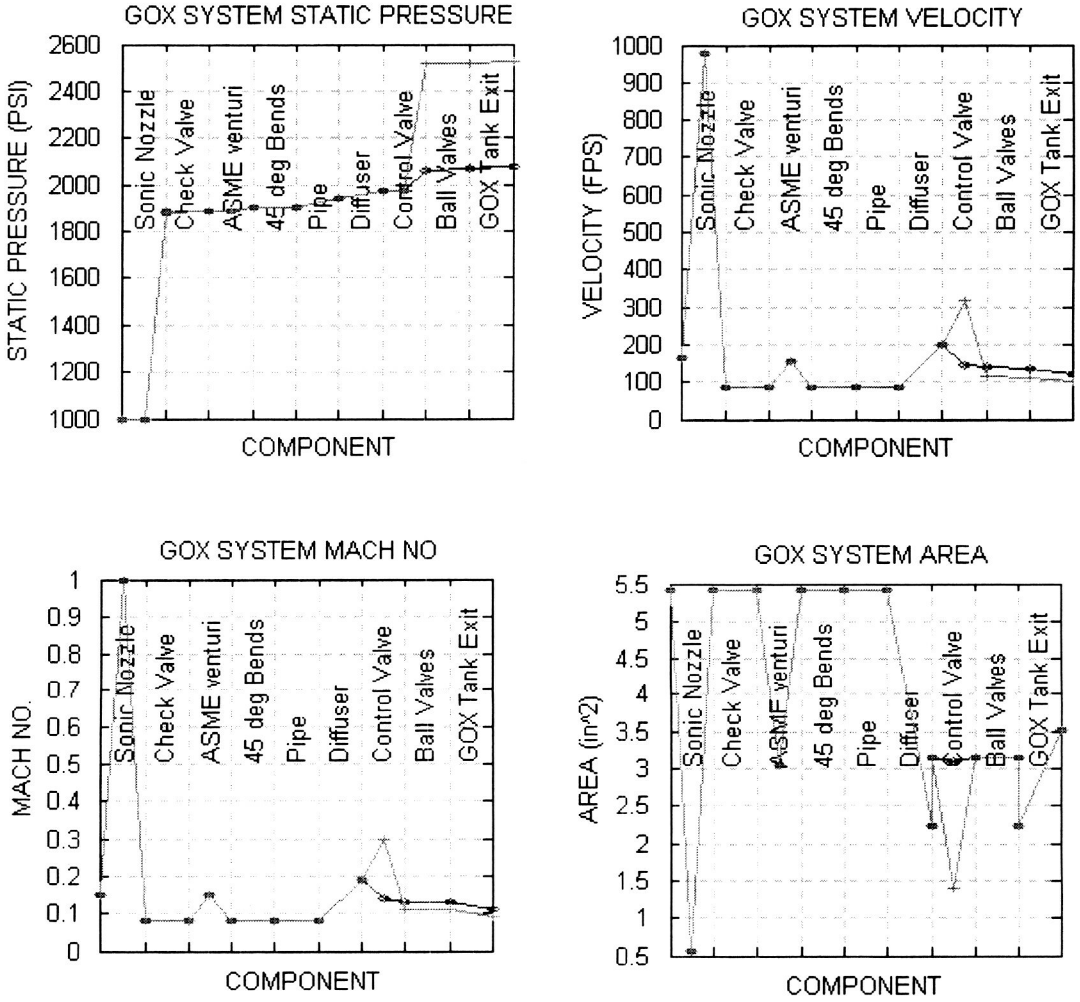


Figure 10. Component analysis for mass-flow rate of 16 kg/sec and pressure of 1,000 psi.

The following conclusions can be drawn from the loss analysis results presented above:

1. Four components can have flow velocities greater than 300 ft/sec; hence, the materials used in these components must be resistant to ignition by particle impact in a pure oxygen environment. These are the sonic nozzle, the ASME venturi (FE-101), the control valve PCV-6, and check valve CKV-7.

2. From an oxygen safety point of view, the low-pressure, high-mass-flow case is the case that the greatest attention should be given to because of the high velocities in several of the components.

To minimize the flow velocity through control valve PCV-6, the initial GOX tank pressure should be set just slightly above what is required to maintain the sonic nozzle choke margin during the run. This pressure level is dependent on the desired mass-flow rate, run time, and chamber pressure. Limiting the initial GOX tank pressure has the effect of reducing the pressure drop required across control valve PCV-6 and, correspondingly, the peak velocity in control valve PCV-6, thereby increasing the safety and valve longevity and reducing the noise. The maximum velocity in control valve PCV-6 was found to be 705 ft/sec, and this occurs at a mass-flow rate of 16 kg/sec and at a nozzle pressure of 300 psi. The required initial GOX tank pressure level as a function of oxygen mass-flow rate and chamber pressure is shown in figure 11 and the maximum possible run time (with a choke margin of 0) is shown in figure 12.

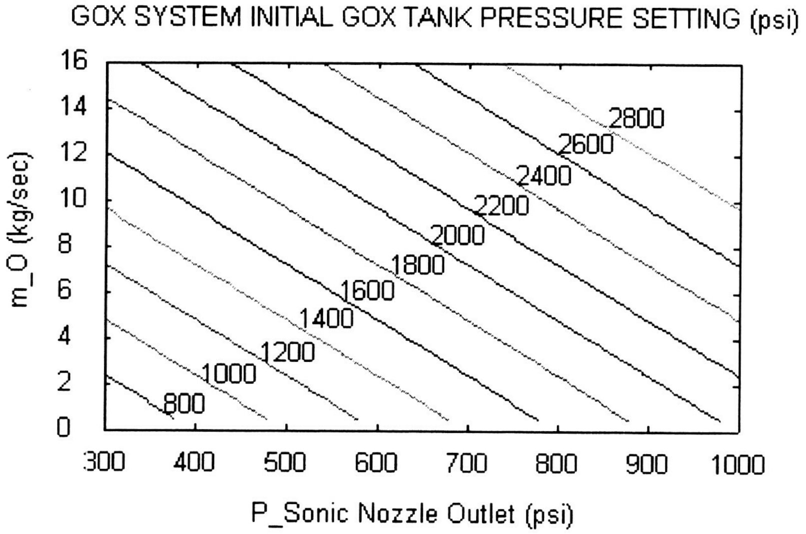


Figure 11. Required initial GOX tank pressure.

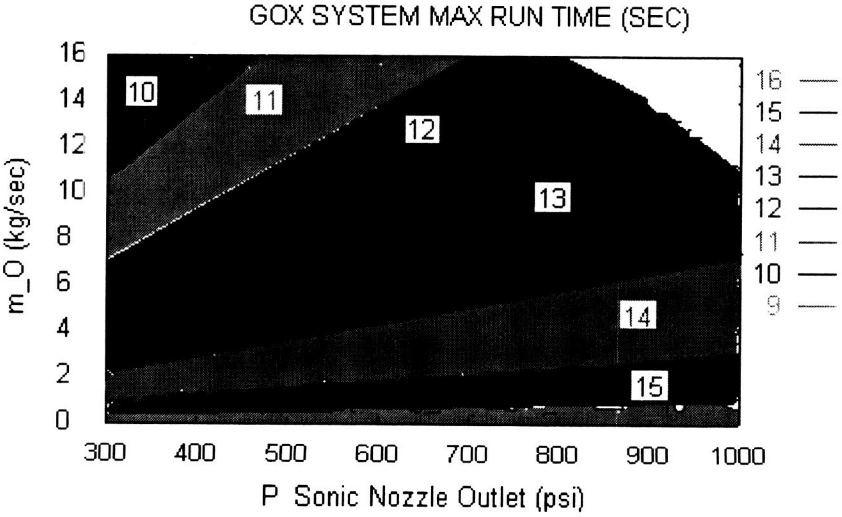


Figure 12. Maximum facility run times.

To minimize the off-condition time, control valve PCV-6 should be pre-positioned as shown in figure 13.

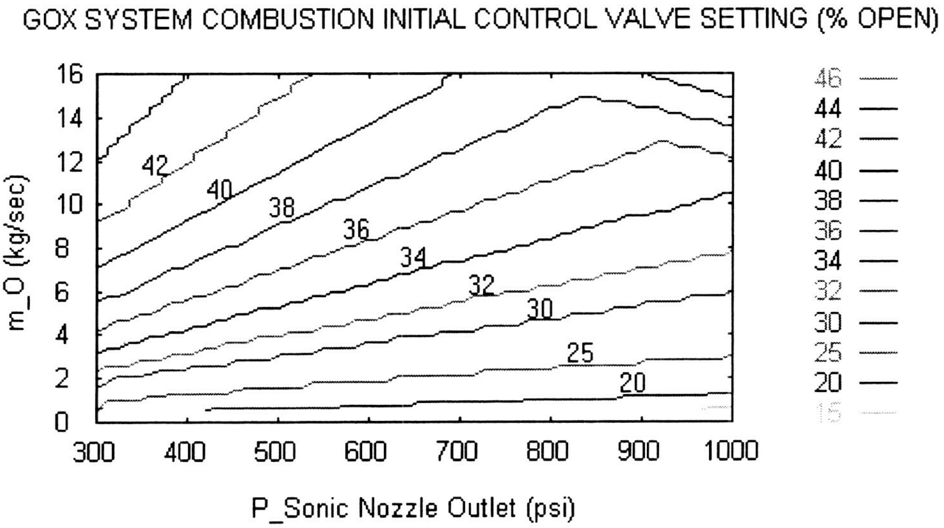


Figure 13. Initial control valve PCV-6 setting.

Oxygen System Components

In the following sections, the specifications of the oxygen system components are described. This information was supplied to the oxygen system safety experts at WSTF as a starting point for their analysis. In many of the figures in these sections, the oxygen flow paths and oxygen-whetted parts are shown in green. This information was also supplied to the pressure system safety group at Ames to assist them in their certification of the facility.

LOX Tank

The LOX tank (figs. 14 and 15) is a pre-existing component that was purchased for a project that was ultimately canceled. It was manufactured by MVE Incorporated in 1988 and has never been used. Its specifications are as follows:

Weight (full): 28,090 lb
Weight (empty): 16,200 lb
Outside diameter: 8 ft.
Internal volume (estimated) 168 ft^3
Capacity: 3,000 gal
Max pressure: maximum allowable working pressure (MAWP) 250 psi
Fabrication date: 1988
Serial No.: 1705
Inner vessel: VCS-3000-SP-250
Tank No: 345-1289

This tank was certified by Minnesota Valley Engineering (MVE) (National Board number of 19878). It was purged with dry nitrogen and then put into service. The connection for liquid withdraw is made at point C-8 that has a 0.5-in. male national pipe thread (MNPT), outlet and the vapor return line from the pump to the LOX tank is made at C-9 with a 1.25-in. MNPT (fig. 15). It should be noted that the piping between the LOX pump and the LOX tank was installed so that it slopes downward from the tank to the pump. This is most critical for the vent return line to the tank. Flat (or parallel to the ground) tube segments in the LOX feed line are permissible. The tank has all of the required and desired safety features including vent valves, check valves, drain valve, a liquid level meter, burst disks, and relief valves, as shown on the diagram in figure 15.

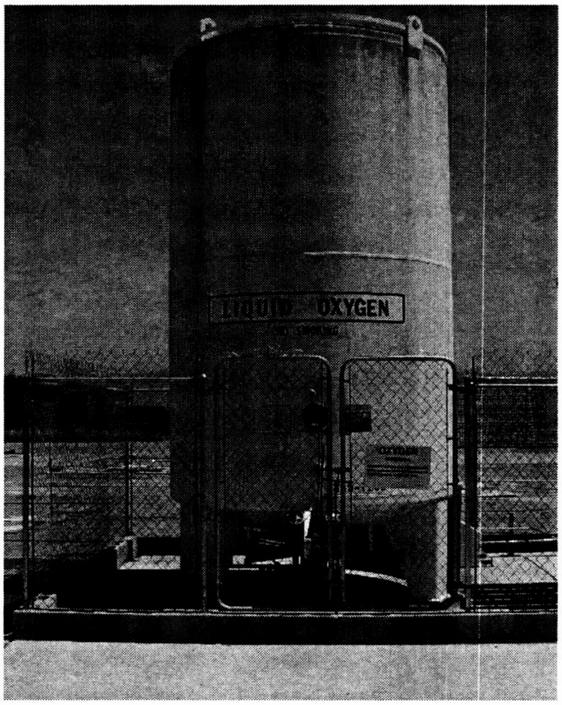


Figure 14. LOX tank.

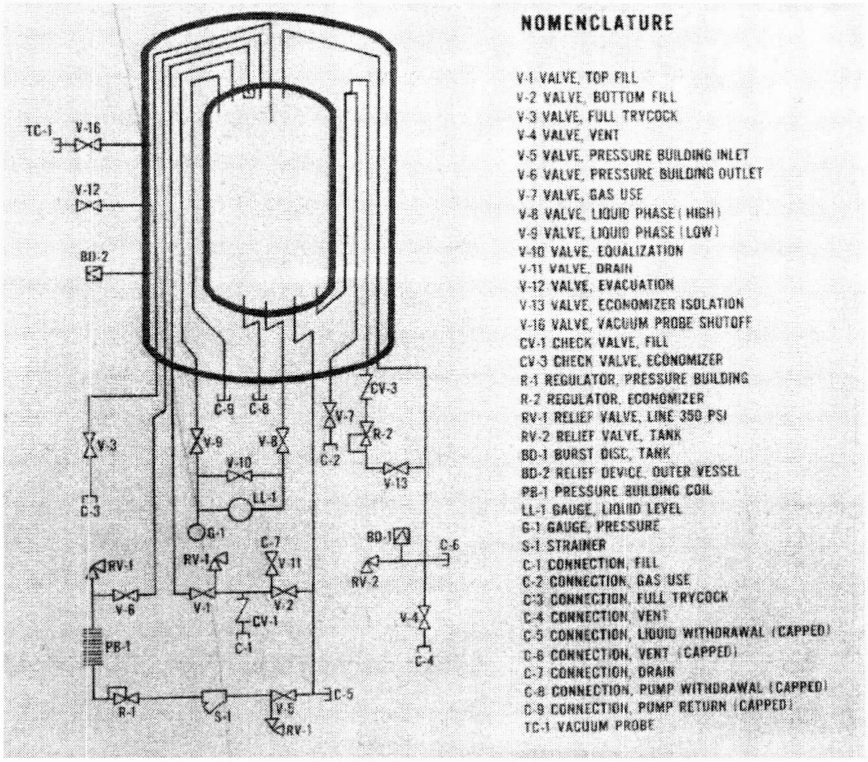


Figure 15. LOX tank piping and valve diagram.

During the IST, the vacuum level of the warm LOX tank was checked (using a Hastings DV6 meter) and found to be 280 microns. A vacuum pump was then attached and the tank's vacuum lining was pulled down to 150 microns. MVE ships the tank with readings of 10 microns, although levels below 200 microns are considered satisfactory for a warm tank.

Liquid nitrogen was used initially to run a series of tests of the oxygen system (it is safer than oxygen). This tank was designed to hold either liquid oxygen or nitrogen, although the correct Compressed Gas Association (CGA) filling adapter is required to fill with liquid nitrogen.

LOX Shutoff Valve HV-1

LOX shutoff valve HV-1 is a globe valve that is located in the stainless steel LOX line immediately after the LOX tank connection point C-8 (fig. 5). The purpose of HV-1 is to start and stop the flow of LOX from the LOX tank. The valve is made by Circle Seal Controls Inc, Model ES2-084-OWPG1; it has a 14-in. extended stem, an operating pressure of 300 psi (max), and an operating temperature range of –400°F to 150°F. The body is made of bronze, with 0.5-in. iron pipe size (IPS) (F) thread connections. The valve seats are Kel-F. It was shipped from the factory cleaned for oxygen service (fig. 16). Valve data are shown in table 1.

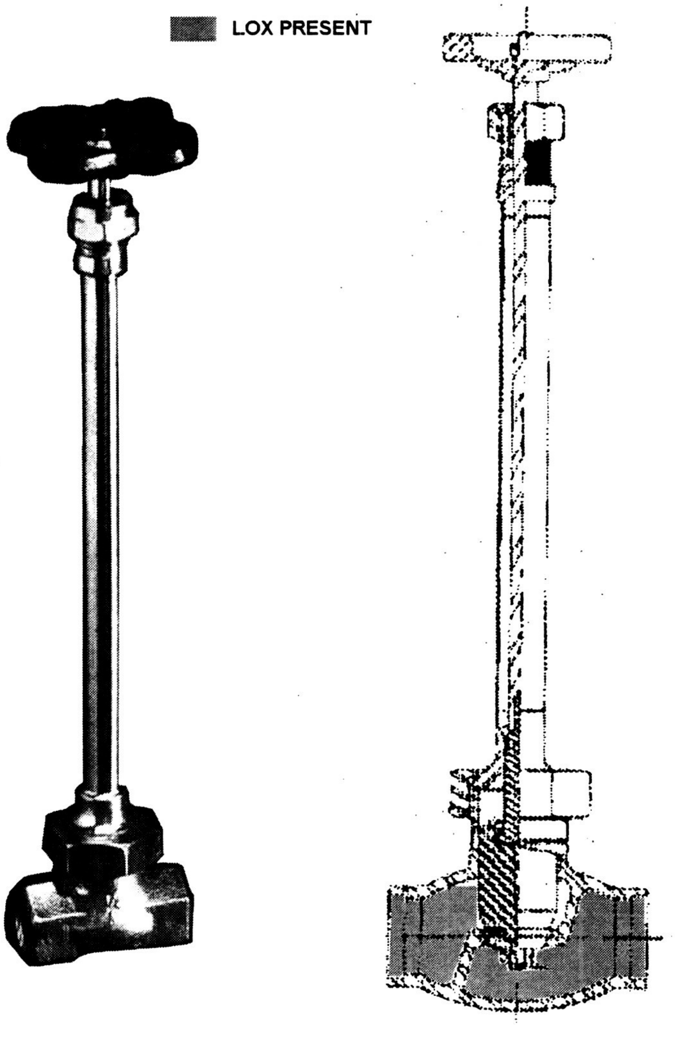


Figure 16. LOX shutoff valve (HV-1).

Table 1. Operating range and component materials for HV-1.

Component name: LOX shutoff valve HV-1	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to 3.67 ft/sec LOX velocity (at inlet and exit of valve)

Component name: LOX shutoff valve HV-1	Circle seal controls	ES2-084-OWPG1
	Material	Remarks
Body	Bronze	
Valve packing	Teflon	
Seat	Kel-F	

LOX Strainer

The Model 861-SS 0.5-in. National Pipe Thread (NPT) female LOX Strainer (fig. 17) is manufactured by Mueller-Steam and is a Y-type strainer with a 100 mesh (wire *D*= 0.0045-in.) Monel screen. The strainer body is made of 316 SS. The maximum pressure rating is 1,440 psi. This strainer will remove particulate greater than 0.0055 in. (140 micron). It is cleaned on an as-needed basis. The condition of the strainer is determined by monitoring the rate at which the pressure in the GOX tank increases during LOX pumping. Under normal operating conditions, the GOX tank pressure increases at a rate of 1 psi per second during pumping. Strainer data are shown in table 2.

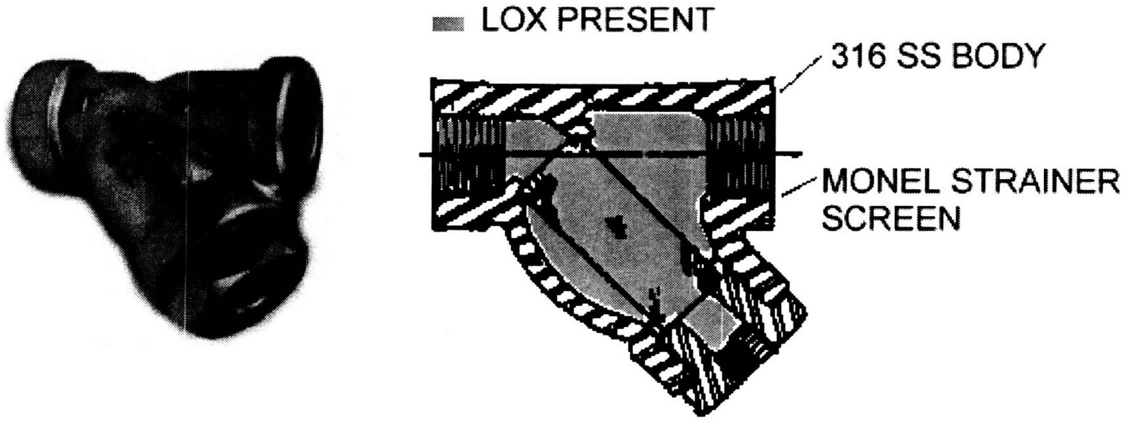


Figure 17. LOX strainer cutaway view.

Table 2. Operating range and component materials for LOX strainer.

Component name: LOX strainer	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to 3.67 ft/sec LOX velocity (at inlet and exit of strainer)

Component name: LOX strainer	Muller-Steam	861-SS
	Material	Remarks
Body	316SS	
Wire Mesh	Monel	100 mesh, *D*=0.0045-in

Relief Valve PRV-90

Relief valve PRV-90 relieves pressure that can build up in the 0.75-in. stainless steel line between the LOX tank and the LOX pump after the LOX pumping is complete and the LOX flow has been shut off by LOX shutoff valve HV-1. The pressure rise in this tube segment (estimated maximum possible with no relief is 417 psi) is caused by heat exchange between the ambient air and LOX trapped in the tube segment. In practice, this valve does not open, because return-line valve HV-2 is left open for approximately 1 hr after LOX pumping to allow the GOX in the LOX lines to return to the LOX tank.

As will be discussed in a later section, the 0.75-in. stainless steel tube that runs between the LOX tank and the LOX pump has a maximum allowable internal pressure rating of over 2,500 psi (based on the ASME B31.3 code). The relief valve cracking pressure is set to the same cracking pressure as the relief valve on the LOX tank, which is set to 250 psi (the MAWP of the vessel).

The capped valve (fig. 18) is mounted to a tee in the 0.75-in. stainless steel LOX line. It is made by Generant, Model CRVD-500B-K-250 and has male 0.5-in. NPT pipe threads on one end. It is constructed of brass with an extrusion-resistant encapsulated Teflon O-ring seal. It was shipped from the factory cleaned for oxygen service. Relief valve data are shown in table 3.

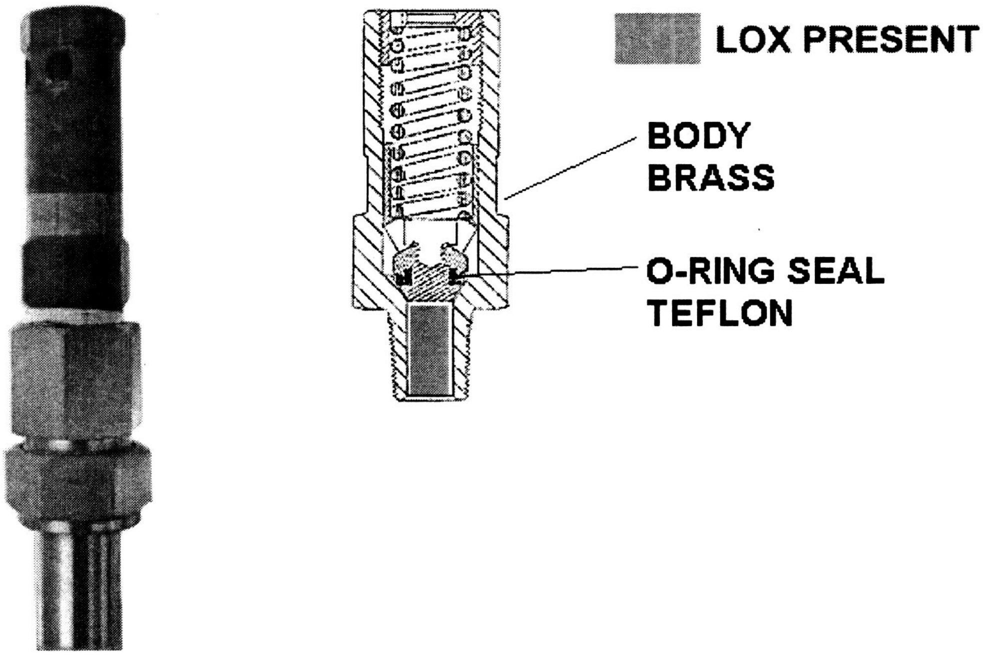


Figure 18. Relief valve PRV-90.

Table 3. Operating range and component materials for PRV-90.

Component name: Relief valve PRV-90	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to <100 GOX velocity (at inlet and exit of valve)

Component name: Relief valve PRV-90	Generant	CRVD-500B-K-250
	Material	Remarks
Body	Brass	
O-ring seal	Teflon	

Vent Valve HV-3

The HV-3 vent valve is mounted on a tee in the 0.75-in. stainless steel LOX line immediately after relief valve PRV-90. The purpose of this valve is to allow the line to be depressurized for servicing purposes. It is a brass globe valve made by Rego, Inc., Model 9454DA, with a maximum working pressure of 600 psi, and with 0.5-in. (F) NPT connections. It has Teflon elastomers on the valve spindle to ensure zero leakage and Kel F seats. It was shipped from the factory cleaned for oxygen service (fig. 19). Valve data are shown in table 4.

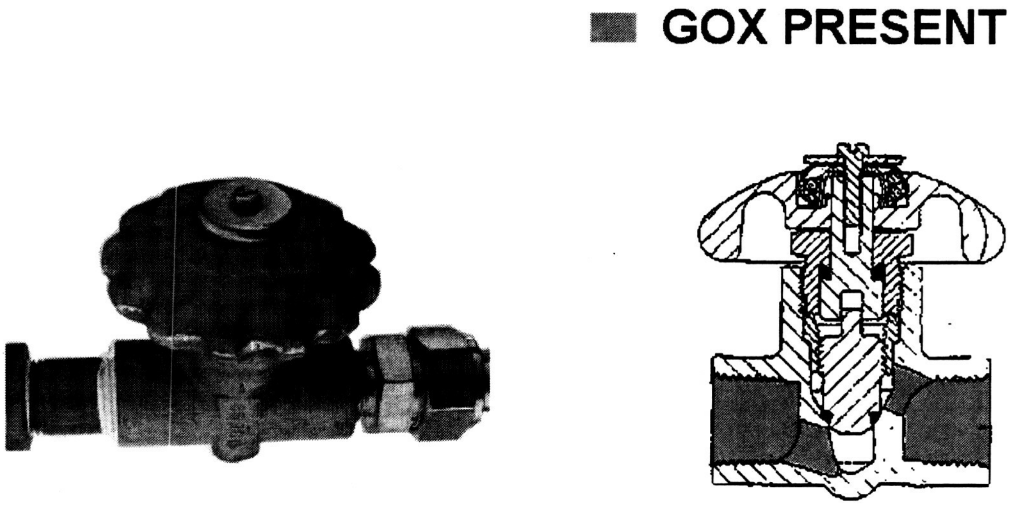


Figure 19. Vent valve (HV-3).

Table 4. Operating range and component materials for HV-3.

Component name: Vent valve HV-3	
Temperature range, °F	-320 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Vent valve HV-3	Rego	9454DA
	Material	Remarks
Body	Brass	
Valve packing	Teflon	
Seat	Kel F	
Lower stem	Manganese bronze	

Return Shutoff Valve (HV-2)

The purpose of the HV-2 return shutoff valve is to shut off the vapor return piping after LOX pumping has been completed. This Goddard Valve (Model B-222-4T) is a long-stem, 0.5-in. NPT (F) cryogenic globe valve that has a 300-psi water, oil, gas (WOG) rating (fig. 20). The lower service temperature limit is –325°F. The valve was shipped from the factory cleaned for oxygen service.

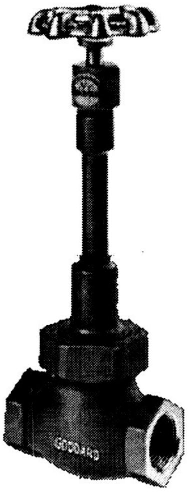


Figure 20. Return shutoff valve HV-2.

Table 5. Operating range and component materials for HV-2.

Component name: Return shutoff valve HV-2	
Temperature range, °F	-320 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to <50 (GOX velocity at inlet and exit of valve)

Component name: Return shutoff valve HV-2	Goddard	B-222-4T
	Material	Remarks
Body	Brass	
Valve packing	Flurocarbon	
Seat	Kel F	

Return Relief Valve PRV-93

The purpose of return relief valve PRV-93 is to relieve pressure that may build up in the vapor return piping. It is set to open at 250 psi and it is the same valve as relief valve PRV-90. Valve data are shown in table 6.

Table 6. Operating range and component materials for PRV-93.

Component name: Return relief valve PRV-93	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to <100 GOX velocity (at inlet and exit of valve)

Component name: Return relief valve PRV-93	Generant	CRVD-500B-K-250
	Material	Remarks
Body	Brass	
O-ring seal	Teflon	

Return Vent Valve HV-4

The purpose of return vent valve HV-4 is to purge the gaseous oxygen in the vapor return piping for maintenance purposes. This valve is the same as vent valve HV-3. Valve data are shown in table 7.

Table 7. Operating range and component materials for HV-4.

Component name: Return vent valve HV-4	
Temperature range, °F	-320 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Return vent valve HV-4	Rego	9454DA
	Material	Remarks
Body	Brass	
Valve packing	Teflon	
Seat	Kel F	
Lower stem	Manganese bronze	

LOX Pump

The ACD Model WDPD reciprocating LOX pump (figs. 21-23) is designed to pump 2.2 gal/min of LOX at a pressure of up to 2,900 psi. The first time the GOX tank (internal volume of 75 ft^3) was pumped to a pressure of 2,200 psi, the LOX pump pumped 97 gal of LOX through the ambient draft vaporizer into the tank. This resulted in 11,244 standard cubic feet (SCF) of GOX (Note: 1 gal LOX produces 115 SCF of GOX) being stored in the GOX tank. The pump operates at a rate of 2.2 gal/min so it operates for approximately 45 min when pumping from ambient to full GOX tank pressure. During the actual running of the combustion facility, the GOX tank is depleted by, at most, 7,000 SCF (60 gal of LOX). Therefore, after the initial pump up, the time required to bring the GOX tank up to pressure is typically less than 30 min.

The pump has a 1.2-in. stroke and a bore of 1.26 in. It comes with a standard suction adapter and Monel strainer, and is driven by a 10 hp motor that requires 230 Vac, 3-phase, 60 Hz power.

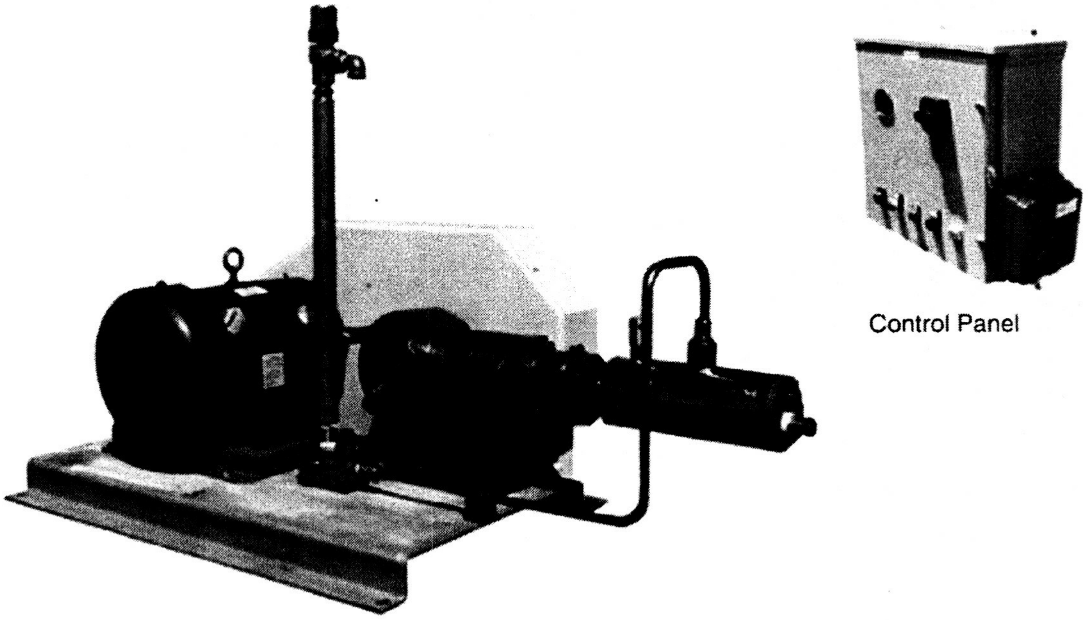


Figure 21. LOX pump.

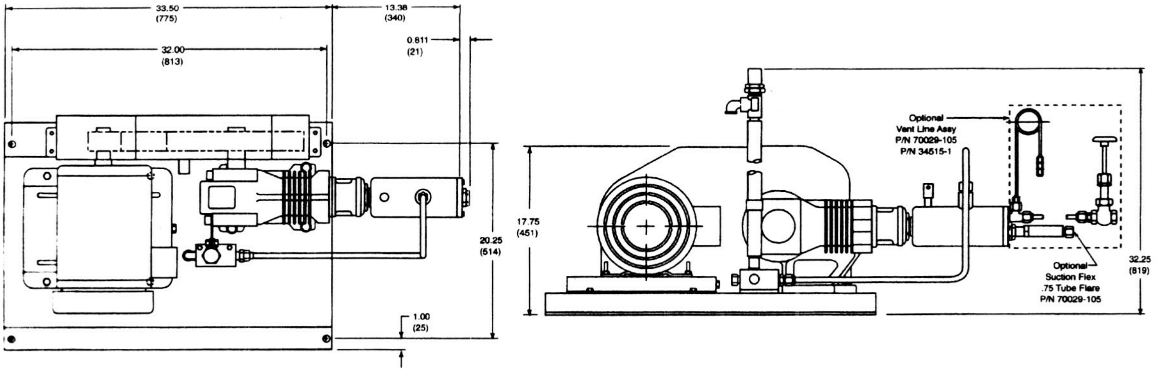


Figure 22. The WDPD LOX pump top and plan view.

The suction end of the pump has a 0.75-in. NPT (F) attachment fitting and the discharge end has a 0.5-in. NPT (F) fitting. As required by CGA G4.7 (ref. 4) the LOX pump has the following features:

1. A remote on/off switch
2. A high-pressure switch that will shut off the pump in the unlikely event of an overpressurization.
3. A relief valve that will vent if the pressure exceeds 3,250 psi.

A loss-of-prime detection sensor was not deemed necessary because of the relatively short duration of the pump operation (approximately 30 min/day, maximum) and also because the pump will not be operated unattended. There is an audible change when pumps of this type loose prime. This is an acceptable loss-of-prime detection approach as given in CGA G-4.7.

The installation of the LOX pump was in accordance with CGA G4.7 and included establishment of a 15-ft-radius hazard zone not to be entered during pump operation. A nonflammable shield constructed of Hardibacker board was placed between the pump and the LOX tank to shield the LOX tank in case of a fire. This Hardibacker board is an inflammable (a test was performed using an oxy-acetylene torch and the board did not ignite) ceramic-based board and is quite strong. Pump data are shown in table 8.

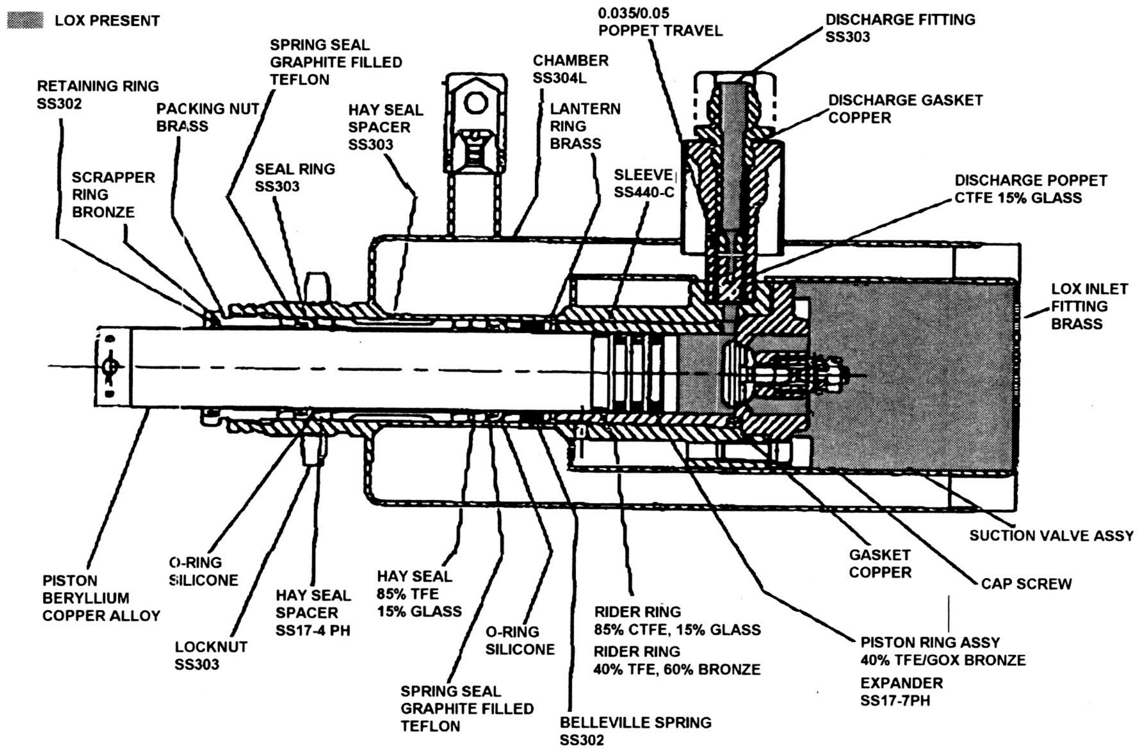


Figure 23. WDPD LOX-pump cold end.

Table 8. Operating range and component materials for LOX pump.

Component name: LOX pump	
Temperature range, °F	-360 to ambient
Pressure range, psi	250 at inlet 2,900 at exit
Velocity range, ft/sec	0 to 3.67 (LOX velocity at inlet and exit)

Component name: LOX pump	ACD	WDPD
	Material	Remarks
Cold end chamber	SS304L	
Suction strainer	Monel	
Pump piston	Beryllium-copper alloy	
Pump cylinder	SS440-C	
Discharge pipe	SS303	
Piston rings	CTFE, Glass, Bronze and TFE	
O-ring seal	Silicone	
Suction valve assembly		

Vaporizer

The ambient draft vaporizer is a Model HAI 824 S40 manufactured by Cryoquip (fig. 24). This vaporizer is capable of vaporizing liquid oxygen at a rate of 7,500 standard cubic feet per hour (SCFH) to within 30° of the ambient air temperature for periods of up to 8 hr. In the HCF, the vaporizer is required to vaporize at a higher rate (nearly double) but for up to only 1 hr per day. It has been found in practice to have more than adequate capacity. Its specifications follow:

Weight: 710 lb
Max pressure (MAWP): 4,000 psi
Material: aluminum lined with 304 stainless steel liner
L x W x H: 54.75 in. x 36.25 in. x 115.25 in.
End connections: 0.5 in NPT (F)

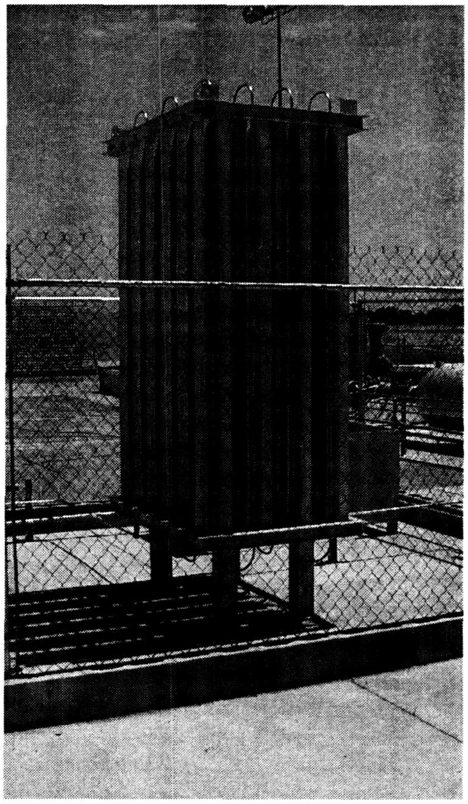


Figure 24. Ambient-draft vaporizer.

The design of this unit is in accordance with the Uniform Building Code (UBC) and applicable sections of the American National Standards Institute (ANSI) A 58.1. The unit is supported by four legs each with four 0.75-in. diameter anchor bolts and is mounted within the liquid oxygen containment area no closer than 3 ft to any other component (to promote good air circulation).

The vaporizer has 24 aluminum-finned, stainless steel tube (304 stainless steel tube with wall thickness of 0.065 in.) elements connected in series. The manufacturer ran a prediction code that predicted a pressure drop of 53 psi across the vaporizer when 2.2 gal of LOX (15,220 SCFH) is pumped at 2,900 psi.

Since the pressure can be as high as 2,900 psi in the vaporizer, the piping between the LOX pump and the vaporizer and also the piping between the vaporizer and the GOX tank is 0.75-in. stainless steel tube with Swagelok tube fittings. LOX flows in the tube segments between the pump and the vaporizer at maximum velocities of 3.7 ft/sec and, as will be discussed later, stainless steel is a good oxygen-compatible material for these segments.

In the vaporizer, the temperature increases to the point where the LOX begins to gasify. Accompanying the gassification is a great reduction in the oxygen density and a correspondingly great increase in velocity (of the GOX). The CGA G-4.4 code (ref. 5) recommends that flow velocity, for stainless steel pipe, should be less than that given by a curve with the equation

$$V = 18,800\ P^{-1.292}$$

where V is GOX velocity in ft/sec and P is pressure in psig in the range of 0 to 1,000 psig. As shown in figure 25, this recommendation is not met by the current design. It is not deemed a hazard, however, because the gradual bends employed in this vaporizer minimize the likelihood of direct-hit particle impacts.

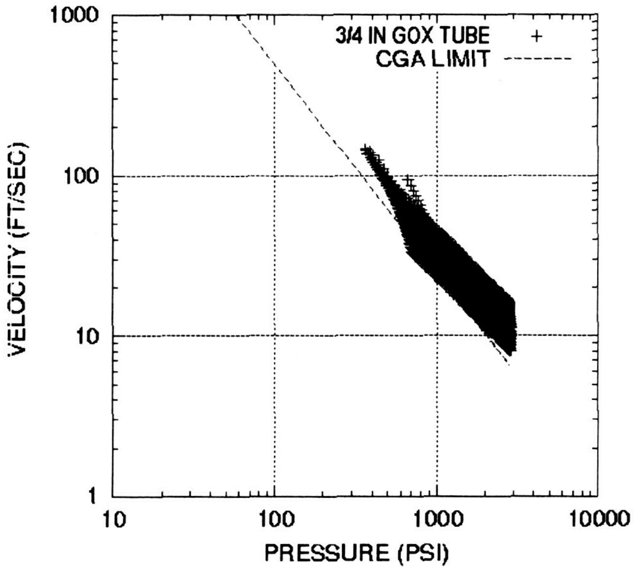


Figure 25. GOX velocity in the vaporizer and associated tubing.

A computer program was written to analyze the pressure losses between the LOX pump and the GOX tank; it generated figure 25. The program computes the pressure, velocity, and density at points in the vaporizer, assuming frictionless flow, and then adds in the pressure losses due to friction. It is assumed that the temperature variation along the vaporizer elements is linear and varies from –227°F at the vaporizer inlet to 30°F below ambient at the vaporizer outlet. The pump capacity (2.2 gal/min of LOX) is assumed independent of discharge pressure (as is usually the case for reciprocating pumps). Each + symbol in the figure represents a pressure-velocity pair reached at some point in the GOX line between the pump and GOX tank during the process of filling the GOX tank. Vaporizer data are shown in table 9.

Table 9. Operating range and component materials for vaporizer.

Component name: Vaporizer	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	10 to 200 (GOX velocity)

Component name: Vaporizer	Cryoquip	HAI 824 S40

	Material	Remarks
Vaporizer fins	Aluminum	
Liner	304 SS	0.065-in. thick

Relief Valve PRV-91

Relief valve PRV-91 relieves pressure that can build up in the 0.75-in. stainless steel line between the LOX pump and shutoff valve POV-2 after the valve has been closed. This valve is mounted to a tee in the 0.75-in. GOX line. Its cracking pressure is set to 2,900 psi. This is the primary oxygen delivery system relieving device and its cracking pressure is less than that of any other component between the LOX pump and the sonic orifice; hence the MAWP of the oxygen delivery system is 2,900 psi. This relief valve is made by Circle Seal Controls (Model 5332B-4PP-2900) and has female 0.5-in. NPT pipe threads on each end. It is constructed of brass with metal-to-metal seats and a Viton O-ring seal. It has a proof pressure of 16,000 psi and a burst pressure of over 30,000 psi (fig. 26). It was shipped from the factory cleaned for oxygen service. Relief valve PRV-91 has a calibrated setting of 2,900 psig. This is appropriate, because shutoff valve POV-2 is closed before a test run and the tube segments and vaporizer, which are protected by relief valve PRV-91, have ratings greater than 2,900 psig. Under normal facility operation, this valve should not open, because the pressure is vented from this line by actuation of vent valve POV-3. Value data are shown in table 10.

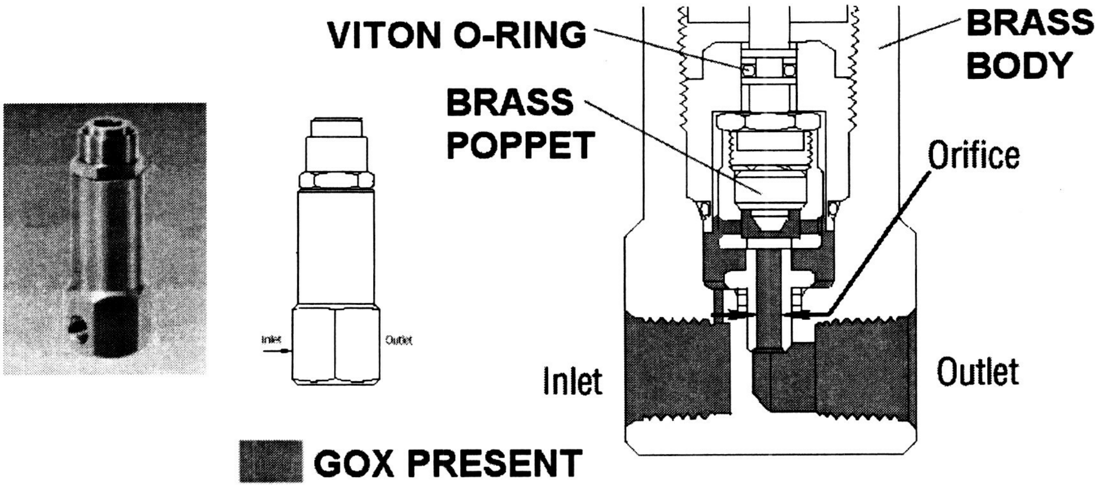


Figure 26. Relief valve PRV-91.

Table 10. Operating range and component materials for PRV-91.

Component name: Relief valve PRV-91	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Relief valve PRV-91	Circle seal controls	5332B-4PP-2900
	Material	Remarks
Body	Brass	
O-ring seals	Viton	

Shutoff Valve POV-2

The flow of oxygen through the 0.75-in. tube line between the vaporizer and the GOX tank is controlled by an air actuated 0.5-in. Monel ball valve (TBV Model 05511FSEM4M4M5XT2HP) with Teflon body seal and Arlon (Peek) seats rated at 3,000 psi MAWP. The valve was cleaned for oxygen service at the factory. It is shown in figure 27 with a pneumatic actuator. This is a normally closed 0.5-in. full port valve that has 0.5-in. NPT (F) connections. Valve data are shown in table 11.

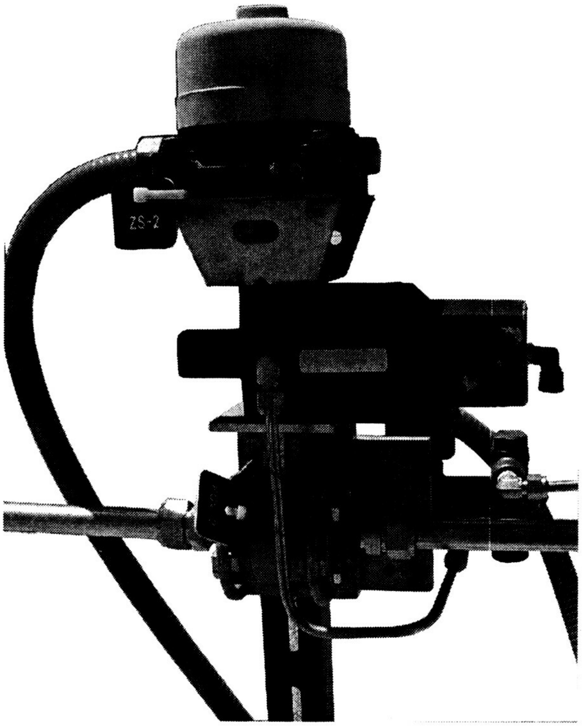


Figure 27: Shutoff valve POV-2.

Table 11. Operating range and component materials for POV-2.

Component name: Shutoff valve POV-2	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 3,000
Velocity range, ft/sec	0 to <200 (GOX velocity at inlet and exit of valve)

Component name: Shutoff valve POV-2	TBV	0551FSEM4M4M5XT2HP
	Material	Remarks
Body	Alloy 400	
Seat	Arlon (Peek)	
Body seal	Teflon	

Check Valve CKV-3

Check valve CKV-3 prevents reverse flow from the GOX tank from flowing into the LOX system. It is an in-line-type check valve that is mounted in the 0.75-in. stainless steel GOX line. Its cracking pressure is 8 psi. It is made by Circle Seal Controls Inc, Model 220B-4PP-8, and has female 0.5-in. NPT pipe threads on each end (fig. 28). The valve is constructed of brass and it has a Teflon O-ring seal. It has a proof pressure of 4,500 psi and a burst pressure of over 11,200 psi. It was shipped from the factory cleaned for oxygen service. Valve data are shown in table 12.

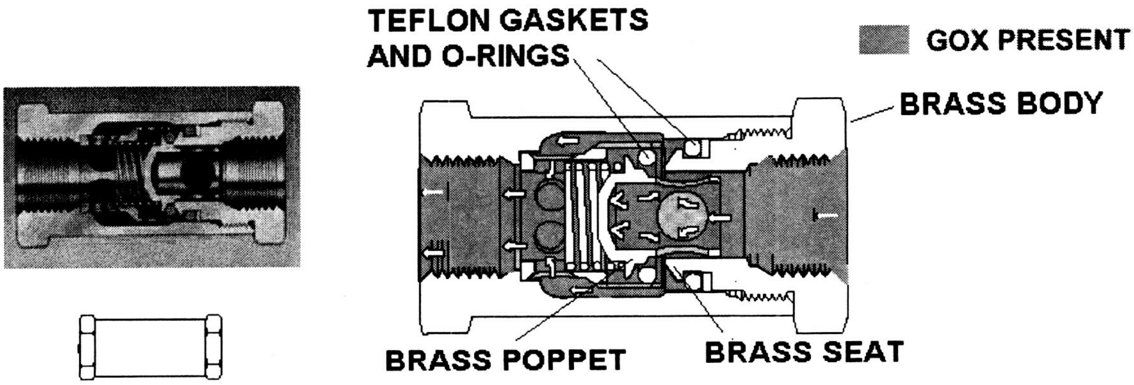


Figure 28. Check valve CKV-3 in open position.

Table 12. Operating range and component materials for CKV-3.

Component name: Check valve CKV-3	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <200 (GOX velocity at inlet and exit of valve)

Component name: Check valve CKV-3	Circle seal controls	220B-4PP-8
	Material	Remarks
Body	Brass	SS also available
O-ring seals	Teflon	

Relief Valve PRV-92

Relief valve PRV-92 relieves pressure that can build up in the GOX tank and in the 0.5-in. stainless steel line when shutoff valve POV-2 is closed. This relief valve is the same as relief valve PRV-91. The valve is mounted to a tee in the 0.75-in. GOX line. Its cracking pressure is set to 2,900 psi. It is made by Circle Seal Controls, Model 5332B-4PP-2900, and has female 0.5-in. NPT pipe threads on each end. It is constructed of brass with metal-to-metal seats and a Viton O-ring seal. It has a proof pressure of 16,000 psi and a burst pressure of over 30,000 psi. It was shipped from the factory cleaned for oxygen service.

Relief valve PRV-92 is set at 2,900 psig (MAWP of the ASME Venturi (FE-101) is 2,900 psi) which is the lowest MAWP of any component between shutoff valve POV-2 and the sonic nozzle. Valve data are shown in table 13.

Table 13. Operating range and component materials for PRV-92.

Component name: Relief valve PRV-92	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2900
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Relief valve PRV-92	Circle seal controls	5332B-4PP-2900
	Material	Remarks
Body	Brass	
O-ring seal	Viton	

GOX Strainer

The GOX Strainer (fig. 29) is a Mueller-Steam Model 863M-SS and is a class 1,500 Y-type strainer with a 100-mesh (wire *D* = 0.0045-in) Monel screen and 2-in. NPT (F) threads (very similar to the LOX strainer in construction). The strainer body is made of 316 SS. This strainer will remove particulate greater than 0.0055 in. (140 microns). The maximum GOX velocity through this component is 35 ft/sec. It is cleaned on an as-needed basis. The condition of the strainer is determined by monitoring the rate at which the pressure in the GOX tank increases during LOX pumping. Strainer data are shown in table 14.

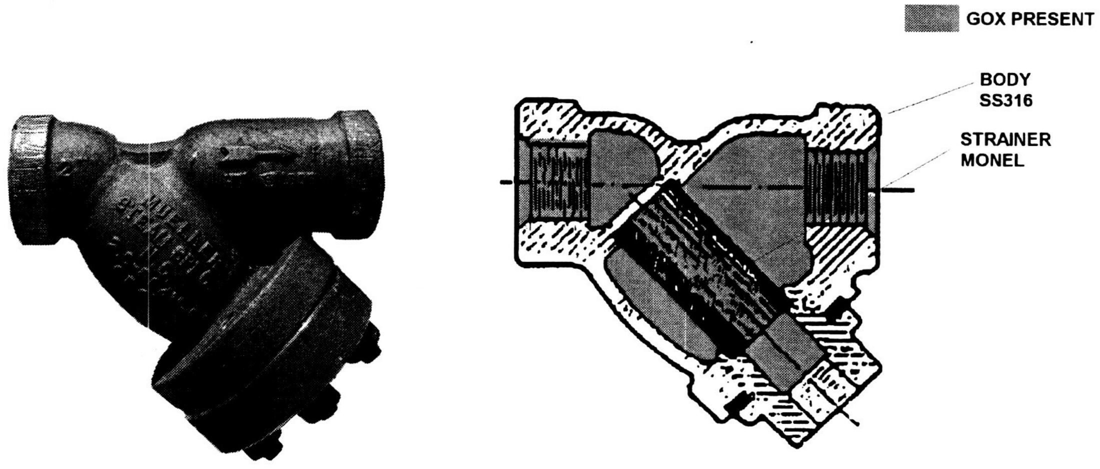


Figure 29. GOX strainer.

Table 14. Operating range and component materials for GOX strainer.

Component name: GOX strainer	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <200 (GOX velocity at inlet and exit of strainer)

Component name: GOX strainer	Muller-Steam	863M-SS
	Material	Remarks
Body	316SS	
Wire mesh	Monel	100 mesh, D=0.0045 in.

Burst Disk BD-99

Burst disk BD-99 (fig. 30) is located immediately upstream of the flange that feeds GOX into the GOX tank (directed upward). The purpose of this disk is to provide emergency pressure relief of the components between shutoff valve POV-2 and the sonic nozzle in the unlikely event of an unforeseen overpressurization. An Oseco 2.0-in. FAS disk held by a 2-in. Oseco Model. FRDH-2 316/316 threaded rupture disk holder is mounted on a tee in the 2-in, A312 F304 schedule 160 pipe segment immediately upstream of the GOX tank flange. (Note: A 2-in. by 0.5-in. pipe reducer is located upstream of the burst-disk pipe tee reduces the pipe to match the remainder of the piping between the vaporizer and the burst disk.) The holder is made of 316 stainless steel and the burst disks are made of Hastelloy C.

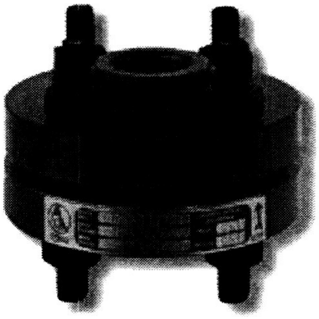


Figure 30. Burst-disk holder.

At the location immediately upstream of the GOX tank flange, the inside diameter (i.d.) of the GOX pipe is 1.689 in. The Oseco 2-in. Hastelloy disk is chosen to burst at a pressure of 3,045 psi, which is 5% above the maximum pressure rating of the ASME venturi (FE-101, the weakest component in the GOX system with a MAWP of 2,900 psi). Note: The manufacturer recommends that the actual pressure to which the disk is exposed be no higher that 90% of the pressure rating stamped on the disk.

The code (ASME Section VIII Div.1) says that when the required capacity is provided by more than one pressure relief device, (relief valve PRV-91 set at 2,900 psi) only one device need be set at or below the maximum allowable working pressure of the system (in this case Flanged ASME venturi (FE-101) with MAWP of 2,900 psig). The additional relief device may be set to open at higher pressures, but in no case at a pressure higher than 105% of the MAWP (hence: 1.05 × 2,900 = 3,045 psig).

It is advisable to operate at 10% below MAWP to avoid frequent opening of the relief device. Therefore, the suggested maximum operating pressure is 2,900/1.10 = 2,636 psig.

The Oseco Model number of the holder is 2-in. FRDH-2 1,500 lb inlet 316/316 outlet and the disks are 2-in. FAS series Hastalloy 3,045 psi. Following SME section VIII procedures for critical flow, the flow capacity of the burst disk can be computed as follows:

$$W = K_D\, C\, A\, P\, [(M / (Z \times T)]^{1/2}$$

where:

W = flow, lb/hr
K_D = discharge coefficient = 0.62 per ASME UG 127(a) (2) (a)
A = actual discharge area, (2-in, schedule 160 pipe area of 2.240 in^2)
C = constant based on specific heats (356 for gaseous oxygen)
P = (set pressure × 1.10) + 14.7, psia
M = molecular weight (32 for oxygen)
Z = compressibility factor (1.0 at P = 2,900 psia and T = 550°R)
T = absolute temperature, °F + 460

Therefore,

$$W = (0.62)\ (356)\ (2.240\ \text{in}^2)\ (3{,}364.2\ \text{psi})\ [(32/\ (1 \times 550)]^{1/2}$$
$$W = 4.0 \times 10^5\ \text{lb/hr}$$

and the mass flow is

$$\begin{aligned} \text{Mass flow} &= 4.0 \times 10^5\ \text{lb/hr} / (3{,}600\ \text{sec/hr} \times 32.2\ \text{ft/sec}^2) \\ &= 3.44\ \text{slugs/sec} \\ &= 3.44\ \text{slugs/sec} \times 14.5939\ \text{kg/slug} \\ &= 50.24\ \text{kg/sec} \end{aligned}$$

Hence, this burst disk should be adequate for all but the most extreme situations (i.e., for all but those associated with failure modes that have very low probability of happening). Disk data are shown in table 15.

Table 15. Operating range and component materials for BD-99 and holder.

Component name: Burst disk BD-99	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to sonic (GOX velocity at exit of burst disk housing)

Component name: Burst disk BD-99	Oseco	2"FRDH-2 316/316
	Material	Remarks
Burst disk	Hastelloy C	
Holder	316 SS	Threaded Monel pipe stud

The vent piping and burst-disk sensor holder (for BD-99) is to be configured as shown on the drawing in figure 31. ASME class 900 flanges with a MAWP of 2,200 psi are the weakest component in the vent piping (downstream of the burst disk). The GOX tank exit (i.d.=1.554 in) has a cross-sectional area that is 64% that of the class 900 flanges (MAWP of 2,220 psi, the only component that does not have a MAWP of at least 3,000 psi). The maximum pressure that the GOX tank can be raised to is 3,045 psi without blowing the burst disk (Note that relief valve PRV-92 will open at 2,900 psi). If the burst disk blows, the choke point will be at the GOX tank exit because all components between the GOX tank exit and the vent-pipe exit have cross-sectional areas greater than the GOX tank exit. Since the choke point is at the GOX tank exit, the maximum pressure in the vent pipe is 0.5283 × 3,045 psi = 1,609 psi where $P/P_{total} = 0.5283$ at Mach 1 (choke). Since the MAWP of 2,220 of the class 900 flanges is greater than 1,609 psi, the vent piping is safe. In reality, the pressure in the vent piping will be much less because the maximum true pressure level (above ambient) is equal to the frictional losses in the pipe. Just downstream of the choke point, the pressure will be reduced well below 1,609 psi through the under-expanded jet created at the choke point. Computation of the precise frictional losses is difficult, so the vent piping design errs on the side of caution.

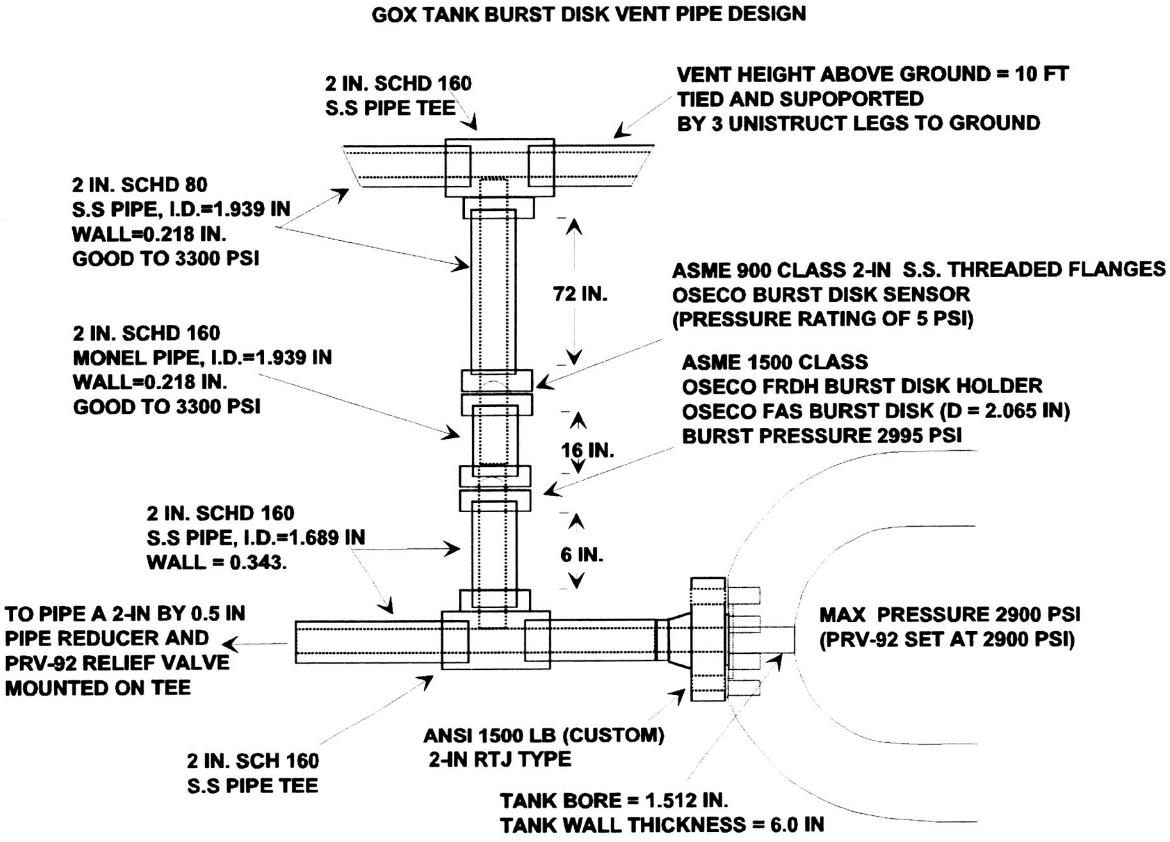


Figure 31. Burst-disk vent pipe configuration.

GOX Bleed Valve POV-3

The purpose of GOX bleed valve POV-3 is to vent the oxygen line downstream of the LOX pump. The LOX pump has a discharge valve (similar to a check valve) on the high-pressure end of the pump cylinder that prevents pressure from being transmitted through the pump to the low-pressure side. This discharge valve has elastomers in it that should not be exposed to high pressure for extended periods of time, because of the possibility that these elastomers will be extruded under the influence of pressure. In addition, it is not good practice to start the LOX pump with high pressure on the discharge side because the belts that drive the pump may slip. A remotely operated bleed valve has been installed between the vaporizer and shutoff valve POV-2 to permit the 0.75-in. line to be brought to low pressure after a LOX pumping operation.

The GOX bleed valve is a Monel ball valve manufactured by Whitey, Model M-43F4-SC11-33, with a MAWP of 3,000 psi and a 0.187-in. orifice (fig. 32). The valve body has 0.25-in. NPT (F) connections. This valve has a pneumatic actuator and was shipped cleaned for oxygen service from the factory. It is similar in appearance to shutoff valves POV-11, POV-21, POV-31, and POV-41. Valve data are shown in table 16.

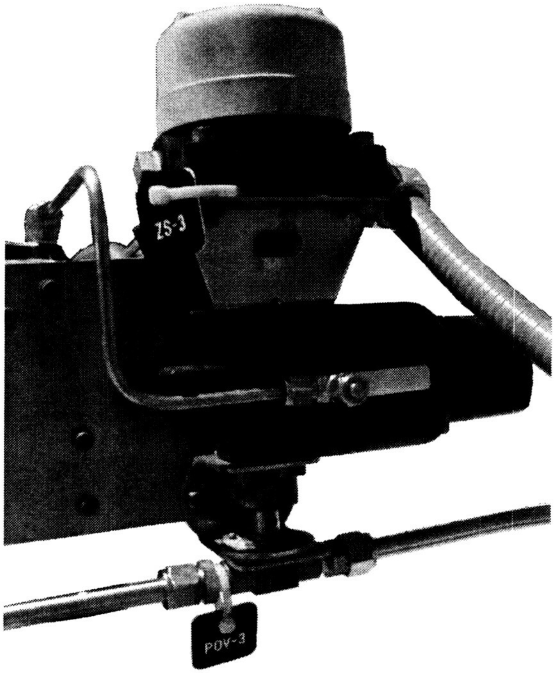


Figure 32. Bleed valve POV-3.

Table 16. Operating range and component materials for POV-3.

Component name: GOX bleed valve POV-3	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 3,000
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: GOX bleed valve POV-3	Whitey	M-43F4-SC11-33C
	Material	Remarks
Body	Alloy 400	
Seat	Alloy 400	
Soft goods	TFE/D1710	

LOX Tubing

The LOX tubing is the tube that runs between the LOX tank and the pump and is a 0.75-in. TP-316/TP-316L seamless stainless steel tube (ASME SA-213) with Swagelok fittings (fig. 33). The maximum pressure that the tube will experience is 250 psi (the MAWP of the LOX tank).

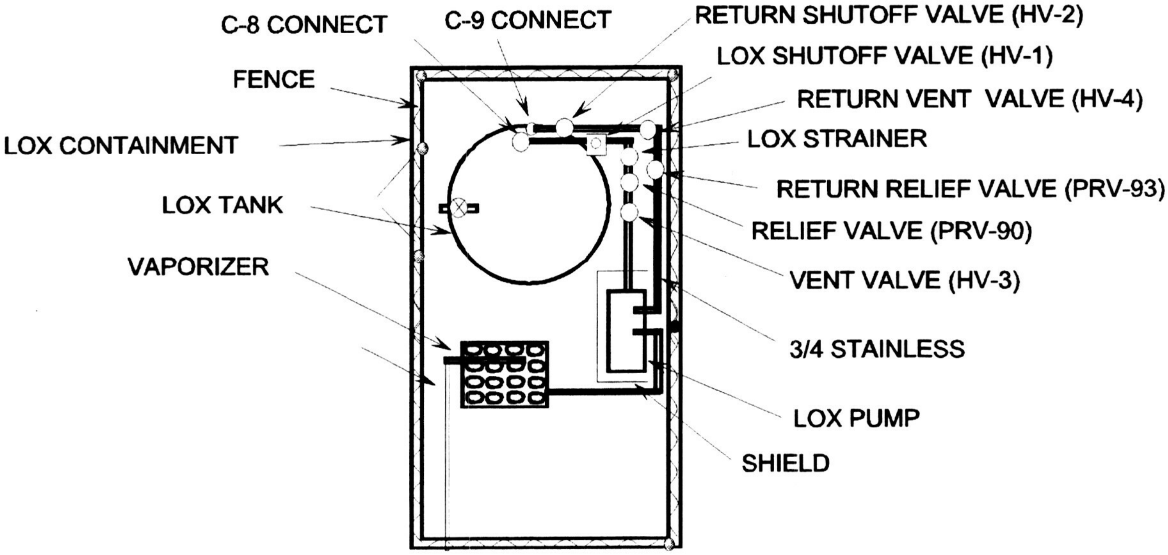


Figure 33. LOX tubing layout.

Following ASME B31.3, the minimum LOX tube wall thickness required can be determined from the following equation:

$$t_m = P\,D / [2\,(S\,E + P\,y)]$$

where:

P = maximum internal service pressure, psi
D = tube o.d., in.
S = max allowable stress due to pressure, psi, page 184, Table A-1 of ASME B31.3
E = quality factor
y = coefficient in Table 304.1.1 of ASME B31.3

For the 0.75-in. stainless steel tube, the following wall thickness analysis applies:

$$t_m = (250 \text{ psi})(0.750 \text{ in}) / [2\,(20{,}000 \text{ psi} \times 1.0 + 250 \text{ psi} \times 0.4)]$$
$$t_m = 0.005 \text{ in}$$

For the 0.75-in. stainless steel tube, P = 250 psi (the MAWP of LOX tank), D = 0.75 in., S = 20,000 psi, E = 1.0 (for seamless tube), and y = 0.4 resulting in a t_m = 0.005 in. The 0.75-in. stainless steel tube wall thickness is 0.065-in, thus, 0.065(0.875 wall tolerance) = 0.057 and since 0.057-in. > 0.005-in, the wall thickness is satisfactory.

In order to compensate for the contraction that will take place and without creating extreme stress in the pipe, stainless steel flexible couplings with AN fittings are used at the point where the tube attaches to the LOX pump. This line is protected from excessive pressure by relief valve PRV-90. Computing the pressure that would build up in the tube if trapped LOX was brought to 100°F, gives

$$P = mRT/V$$
$$P = (0.152 \text{ lbm})(1{,}554 \text{ ft-lb}_f\text{/mole-R} / 32 \text{ lbm/mole})(100{+}459.69 \text{ R})/(90.6 \text{ in}^3)(1/12^3 \text{ ft}^3/\text{in}^3)$$
$$P = 416.9 \text{ psi}$$

This is based on a 20-ft-long, 0.75-in. stainless steel tube filled with LOX. Thus, even without a relief valve in the line, the 0.75-in. stainless steel tube would withstand the maximum pressure that could develop.

The linear coefficient of thermal expansion for type 304 stainless steel is 9.6×10^{-6} in/in per °F. The total length of tube between the LOX tank and the LOX pump is 10 ft. The contraction in length that would occur if the tube were to reach a uniform temperature of –227°F on a 90°F day is (10 ft)(12 in/ft)(9.6×10^{-6} in/in per °F)(90+227°F) = 0.37 in. The flexible coupling in combination with the turns in the tubing ensures that the excessive stress caused by thermal contraction will not develop.

In order to ensure that liquid oxygen (as opposed to gaseous oxygen) reaches the pump, the 0.75-in. stainless steel tube is insulated using 4-in-thick Foamglas insulation (manufactured by Pittsburg Corning). This is a pure-glass insulation (chemically inert) that contains no binders or fillers and is inflammable.

The LOX pump can put out up to 2.2 gal/min, hence the velocity of LOX in the 0.75-in. line is 3.67 ft/sec maximum. (1 gal. of LOX has a volume of 0.134 ft^3) The LOX flow rate equates to 0.005 ft^3/sec. Using a tube cross-sectional area of 0.0014 ft^2 leads to a velocity of 3.67 ft/sec. Tubing data are shown in table 17.

Table 17. Operating range and component materials for LOX tubing.

Component name: LOX tube	
Temperature range, °F	-360 to ambient
Pressure range, psi	Ambient to 250
Velocity range, ft/sec	0 to 3. (LOX velocity)

Component name:		
	Material	Remarks
LOX tube	Stainless steel	ASTM A269 or equivalent

GOX Tank

The GOX tank (fig. 34) is a surplus tank that had previously been used to store air. The following is a list of details concerning the required GOX tank:

S/N: HTB2559-32954
Manufactured by: Babcock & Wilcox
Weight: 55,000 lb
Design pressure: 15,000 psi (down rated to 6,600 psi)
Overall length: 358.4 in
Outside diameter: 35 in
Wall thickness: 6 in
Internal volume: 75 ft^3
Material: SA-336-F22 H.T.
Opening at center of caps: D = 1.554-in. bore (nonstandard flange) in one end cap
Fabrication date: 1963
Last certification: 2/1992
Next certification: 2/2002

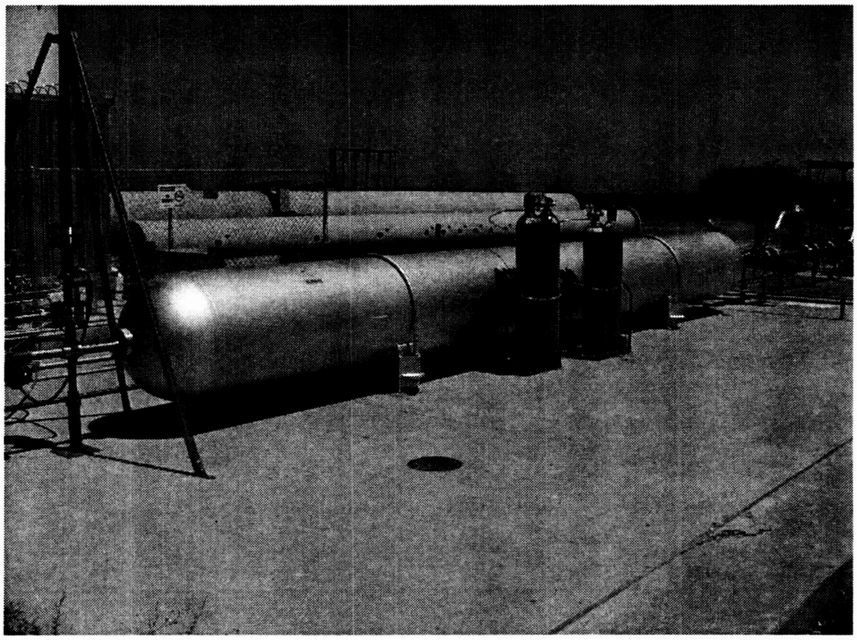


Figure 34. GOX tank.

As can be seen in figure 34, the GOX tank is supported by two saddles. Each saddle is held to the concrete pad by four 0.50-in. expansion-type concrete anchors.

The temperature of the metal shell of the GOX tank will drop a maximum of 0.66°C from the pumping of the cool gas into the tank. The specification on the vaporizer upstream of the tank is that the gas exits this unit at a temperature no lower than 30°F below ambient. A very conservative calculation of the temperature drop of the GOX tank would be to assume that the outside of the tank is insulated (no heat transfer to the ambient air) and to further assume that the total quantity of cool gas is instantaneously put into the GOX tank at 30°F (16.6°K) below ambient. Using the first law of thermodynamics and the definition of mean heat capacity, the following relation holds:

$$Q = m\,c\,(T_2 - T_1)$$

where:

Q = heat absorbed
m = mass (24,965 kg for steel tank, 500 kg for oxygen)
c = mean heat capacity (0.46 kJ/kg °K for steel, 0.92 kJ/kg °K for oxygen)

If it is assumed that all the heat transferred from the tank goes to the gas, then the following equality must be true:

$$(24{,}965 \text{ kg})(0.46 \text{ kJ/kg °K})(T_2 - T_1) = (500 \text{ kg})(0.92 \text{ kJ/kg °K})(16.6\text{°K})$$
$$T_2 - T_1 = 0.66\text{°K}$$

Given that the pumping takes some time, that the ambient air warms the tank during this time, and also that the pumping will take place during the daytime, pumping of the cool gas will not cause a significant change in the GOX tank wall temperature.

The expansion of the GOX inside the GOX tank will cause a significant GOX temperature reduction during a run. Assuming an adiabatic process and assuming that during a typical run, the final pressure in the tank is 80% of the original (for a worst-case, initial pressure is 3,045 psi) leads to a 34°F gas temperature reduction. Following the same analysis as above, this GOX temperature change will decrease the pressure shell average temperature by 0.7°C.

Regarding the strength factor of safety for the GOX vessel, standard practice is to determine the required thickness for the specified maximum pressure, and then compare it with the actual vessel wall thickness. For this vessel at 3,045 psi (the burst-disk setting), the required thickness is 2.17 in.; the actual vessel wall thickness 6 in. This implies an additional factor of safety of 6/2.17 = 2.76. Combined with the material factor of safety of 4, the total factor of safety for vessel strength is 11. GOX tank data are shown in table 18.

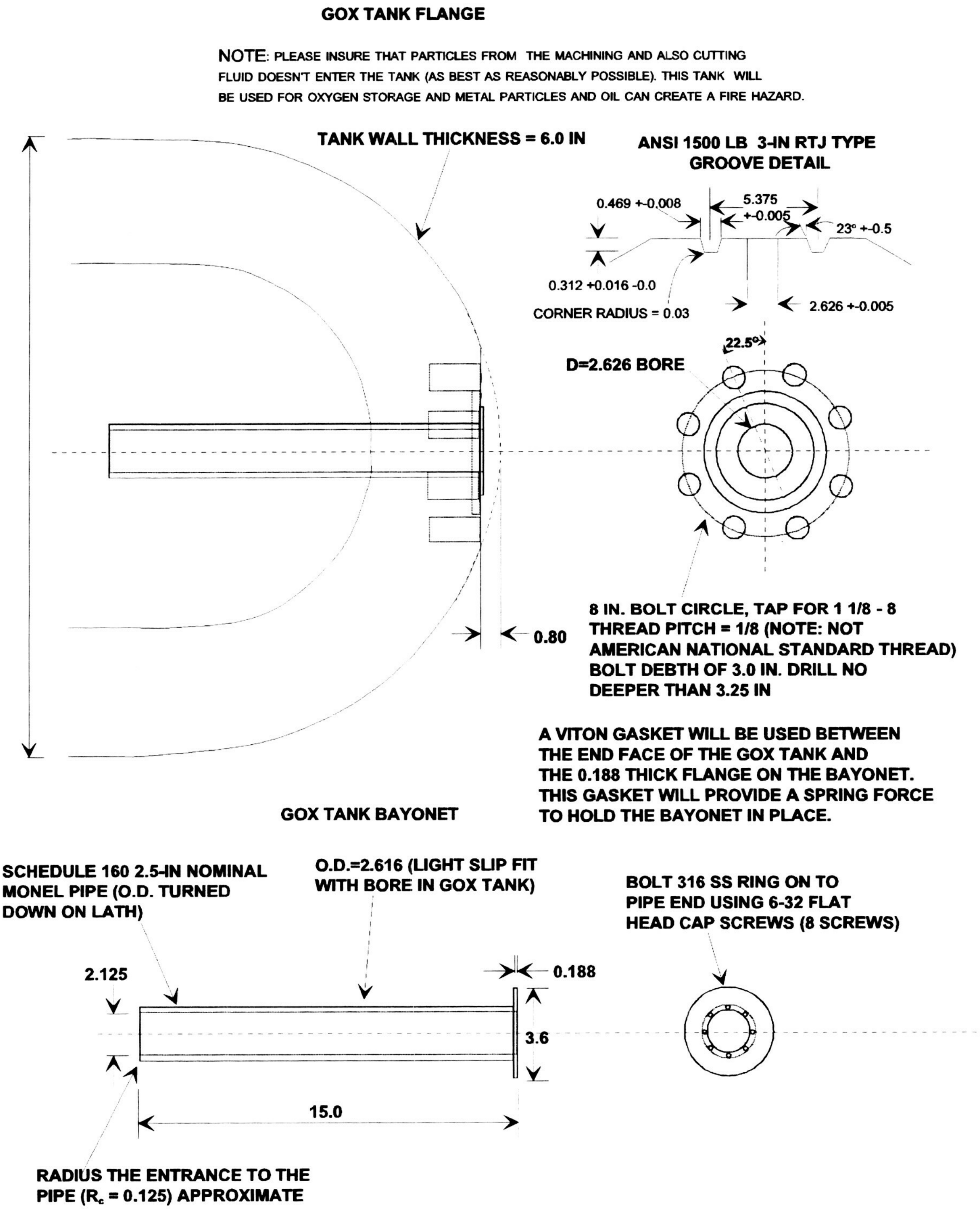
Table 18. Operating range and component materials for GOX tank.

Component name: GOX tank	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to 250 (GOX velocity in bayonet tank fitting)

Component name:		
	Material	Remarks
GOX tank	SA-336-F22 H.T.	
Bayonet inlet	Monel	See next section

GOX Tank Modifications

The possibility of particulates in the GOX tank entering the 3-in. GOX line was minimized by installing a Monel bayonet nozzle in the GOX tank at the point where the 3-in. gaseous oxygen line attaches to the tank. Note that in this line, there are some 2-in. (nominal) components including the pipe that forms the bayonet. The GOX tank bayonet configuration is shown in figure 35.



NOTE: PLEASE INSURE THAT PARTICLES FROM THE MACHINING AND ALSO CUTTING FLUID DOESN'T ENTER THE TANK (AS BEST AS REASONABLY POSSIBLE). THIS TANK WILL BE USED FOR OXYGEN STORAGE AND METAL PARTICLES AND OIL CAN CREATE A FIRE HAZARD.

8 IN. BOLT CIRCLE, TAP FOR 1 1/8 - 8 THREAD PITCH = 1/8 (NOTE: NOT AMERICAN NATIONAL STANDARD THREAD) BOLT DEBTH OF 3.0 IN. DRILL NO DEEPER THAN 3.25 IN

A VITON GASKET WILL BE USED BETWEEN THE END FACE OF THE GOX TANK AND THE 0.188 THICK FLANGE ON THE BAYONET. THIS GASKET WILL PROVIDE A SPRING FORCE TO HOLD THE BAYONET IN PLACE.

SCHEDULE 160 2.5-IN NOMINAL MONEL PIPE (O.D. TURNED DOWN ON LATH)

O.D.=2.616 (LIGHT SLIP FIT WITH BORE IN GOX TANK)

BOLT 316 SS RING ON TO PIPE END USING 6-32 FLAT HEAD CAP SCREWS (8 SCREWS)

RADIUS THE ENTRANCE TO THE PIPE (R_c = 0.125) APPROXIMATE

Figure 35. GOX tank bayonet nozzle.

The bayonet nozzle is made from Monel pipe. The pipe extends 9 in. into the interior of the GOX tank. This pipe portion of the bayonet is constructed from schedule 160 2.5 in. nominal pipe with the o.d. turned down to 2.624-in. (a light slip fit with the 2.626-in. bore in the tank. The wall thickness of the bayonet is 0.25 in., which is ample, given that the pressure loading on this component is virtually zero. It should be noted that the flange attachment machined into the end of the GOX tank is standard ASME 3-in. 1500 class RTJ. A Viton O-ring is placed between the lip of the bayonet and the face of the GOX tank to prevent the bayonet from rattling. The RTJ rings are API number R35 and are made out of 304L stainless steel. The 1.554-in. opening on the GOX tank has a nonstandard flange. A custom flange was manufactured out of A479 F304 bar stock.

Gaseous Pressure Piping and Tubing

The GOX pressure piping and tubing consists of two runs. These include a run of 0.75-in. tube (with a very short segment of A312 TP304 stainless steel, schedule 160 2-in. nominal pipe), between the LOX pump and the GOX tank and a run of 3 in., schedule 160 stainless steel pipe that runs from the GOX tank to the flange upstream of the precombustion chamber. Following ASME B31.3, the minimum wall thickness required for the 3-in. nominal A312 F304 schedule 160, stainless steel pipe can be determined from the following:

$$t_m = P\,D\,/\,[2\,(S\,E + P\,y)]$$

$$t_m = (2{,}900 \text{ psi})(3.5 \text{ in.}) \,/\, [2\,(20{,}000 \text{ psi} \times 1.0 + 2{,}900 \text{ psi } \times 0.4)]$$

$$t_m = 0.240 \text{ in.}$$

In the above equation, P = 2,900 psi (relief valve setting), D = 3.5 in., S = 20,000 psi, E = 1.0 (for seamless pipe), and y = 0.4, resulting in a t_m = 0.301 in. Schedule 160 pipe (3 in.) has a wall thickness of 0.437 in.; thus, 0.437 (0.875 wall tolerance) = 0.382, and since 0.382-in. > 0.240-in, the wall thickness is satisfactory. The 3-in. pipe will experience pressure levels of up to 2,900 psi and oxygen velocities of up to 200 ft/sec at temperatures near ambient.

For the 0.75-in. seamless stainless steel tube, P = 2,900 psi (relief valve setting), D = 0.75 in., S = 20,000 psi, E = 0.8, y = 0.4, resulting in:

$$t_m = P\,D\,/\,[2\,(S\,E + P\,y)]$$

$$t_m = (2{,}900 \text{ psi})(0.750 \text{ in.}) \,/\, [2\,(20{,}000 \text{ psi} \times 1.0 + 2{,}900 \text{ psi } \times 0.4)]$$

$$t_m = 0.051 \text{ in.}$$

The 0.75-in. ASTM A269 seamless stainless steel tube has a wall thickness of 0.065; thus, 0.065(0.875 wall tolerance) = 0.057 in. and since 0.058 in. > 0.051 in., the tube wall thickness is satisfactory.

If relief valve PRV-91 fails and shutoff valve POV-2 is closed, pressure may build up in the 0.75-in. tube. The maximum pressure (worst case) that the 0.75-in. stainless steel tube, vaporizer, and cold end of the LOX pump would reach is 3,470 psi. This pressure level is that caused by a 90°F temperature increase and assuming that the initial pressure in this line is 2,900 psi. This pressure is still less than the proof pressure of the components in this pipe segment.

The joint on the GOX tank is for a flange that is welded to a 2-in. schedule 160 pipe. The piping transitions to 0.75-in. stainless steel seamless tube through a 2-in. by 0.5-in. pipe reducer that is located upstream of the burst-disk pipe T. For this short segment of 2-in. nominal, schedule 160, stainless steel pipe, P = 2,900 psi (relief valve setting), D = 2.375-in, S = 20,000 psi, E = 0.8, y = 0.4, resulting in:

$$t_m = P\,D\,/\,[2\,(S\,E + P\,y)]$$

$$t_m = (2{,}900 \text{ psi})(2.375 \text{ in.}) \,/\, [2\,(20{,}000 \text{ psi} \times 1.0 + 2{,}900 \text{ psi } \times 0.4)]$$

$$t_m = 0.163 \text{ in.}$$

Schedule 160 A312 F304 pipe (2.0 in.) has a wall thickness of 0.343 in.; thus, 0.343 (0.875 wall tolerance) = 0.300-in, and since 0.300-in. > 0.163-in, the wall thickness is satisfactory.

The 3-in. pipe segments and valves are connected by weld-neck-type class 1500 flanges made of A182 F316L or F304L with ring-type joints (RTJs). The rings are octagonal, API number R35 (standard for 3-in. class 1500 RTJ flanges). Class 1500 flanges have a working pressure limit of 3,600 psi for spec A105 material and a temperature range of –20°F to 100°F (ASME B16.5). The pipe will never experience a flow that exceeds this temperature range unless the ambient temperature exceeds 100°F (the facility would not be run on such days).

The RTJ gaskets are manufactured in accordance with API-6A and ANSI B16.2 specifications. API ring joints come in two basic types, oval and octagonal. These basic shapes are used in pressures up to 10,000 psi. The dimensions are standardized and require specially grooved flanges. The octagonal cross section has a higher sealing efficiency than the oval and is the preferred gasket. The newer flat-bottom groove design will accept either the oval or the octagonal cross section. The sealing surfaces on the ring joint grooves must be smoothly finished to 63 microinches and be free of objectionable ridges or tool or chatter marks. RTJs have "R" numbers assigned to them for pipe size and pressure class identification. Ideally, the hardness of the ring should be less than the hardness of the flanges, although in practice, because of material compatibility issues, pressure limitations, or availability, rings of similar hardness are often used. Rings made of 304L (Brinell hardness of 140) have been used in the HCF. Ring data are shown in table 19.

Table 19. Ring-type joint sealing rings required.

Component	Quantity	Type	API ring size
3-in. pipe	10	Octagonal	R35
2-in. pipe	5	Octagonal	R24

The studs used to bolt the pressure components together are ASTM A193 grade B7 1.125-in. studs with ASTM A194 heavy hex nuts. Stud data are shown in table 20.

Table 20. Required B7 studs.

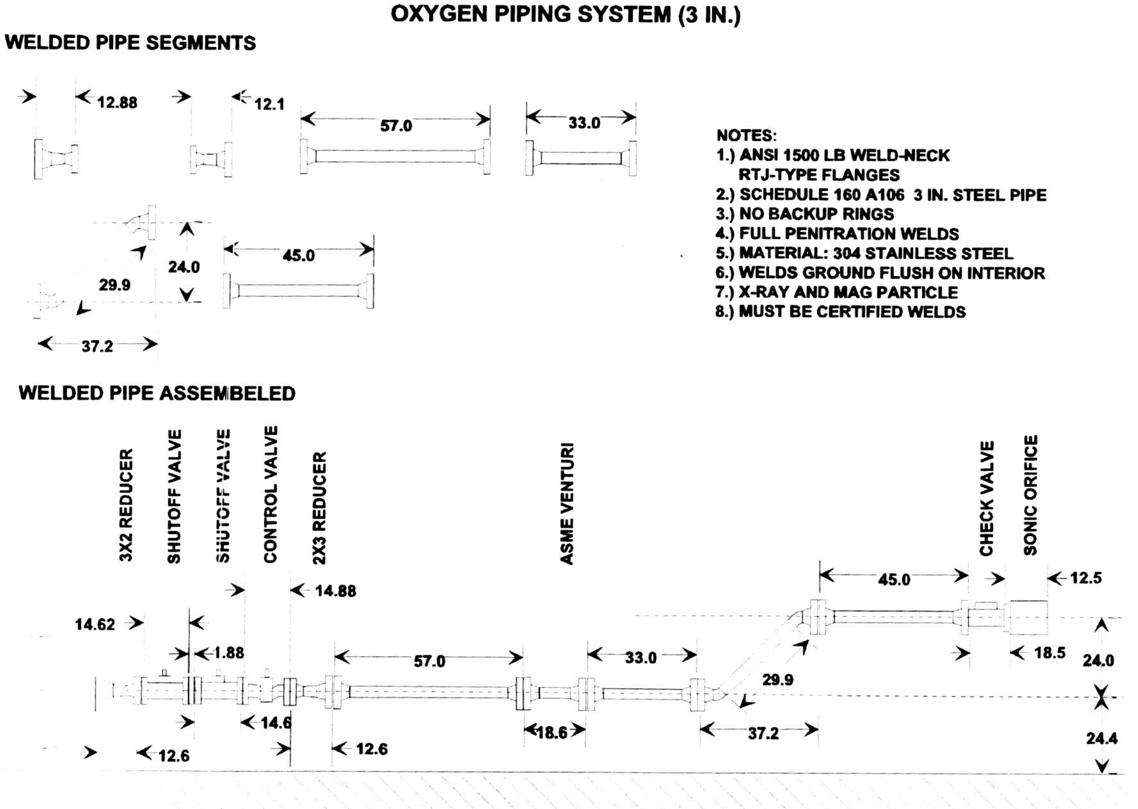
Quantity	Size	Remarks
48	1.125 in. × 7.25 in.	For ASME class 1500 3-in. flanges
32	1.125 in. × 5.5 in.	For ASME class 1500 3-in. flanges bolted to machined components
24	0.875 in. × 6.0 in.	For ASME class 1500 2-in. flanges
16	0.875 in. × 8.5 in.	For ASME class 1500 2-in. flanges with bleed rings
8	1.375 in. × 20 in.	For precombustion chamber 10 in flanges
8	1.375 in. × 46 in.	For aftcombustion chamber 10 in flanges

As mentioned in another part of this document, the 3-in. pipeline will expand and contract with ambient temperature variations. The concrete pad, on which the pipe is supported (and essentially fixed to at its ends), will also expand and contract. Initially, it was thought that the stress that developed in the pipeline, from ambient temperature variations, would be small because the coefficients of thermal expansion of concrete and that of steel differ by only 30% (9.6×10^{-6} in./in. per °F for type 304 stainless steel and 6.0×10^{-6} in./in. per °F for concrete). A dial gauge was used to measure the pipeline thermal elongation over a 20-hr period during which the ambient temperature varied by 30°F. During this test, the combustion chamber end of the pipeline was allowed to roll. The result was surprising. The relative movement between the end of the 280-in. long pipe and the concrete pad was 0.10-in. This is about 10 times the expected relative movement and nearly twice the level that would be measured if the concrete pad did not expand or contract at all (i.e., constrained at its edges). An explanation for this is that the thermal mass of the concrete pad is so high that its thermal response significantly lags that of the pipe. During the day, the pipe and concrete pipe heat up and at night, the pipe cools off rapidly, whereas the pad remains warm. This process could account for a 0.10-in. differential.

A commercial pipe analysis computer program (Caesar II) was run to analyze the stress levels that would arise in the 3-in. piping system as a result of a 0.1-in. elongation, including the effects of the support stanchions and the end constraints. The maximum stress was found to be 33 ksi, and this level was calculated to occur at the upstream end of the 45-deg segment that rises up to the level of the combustion chamber (fig. 36).

The practical implication of these results is that allowances must be made for axial expansion and contraction of the pipeline to avoid overstressing fasteners. The HCF standard operating procedure states that the bolts on the thrust plate should be left in a loosened state at all times, except when the facility is running, in order to allow for thermal expansion and contraction of the main oxygen line.

Flexible links connect the 0.75-in. seamless stainless steel tube to the cold end of the LOX pump. The links allow the tube to contract without causing excessive temperature-induced stress. The total length of pipe between the vaporizer and the GOX tank is 38 ft. Since the linear coefficient of thermal expansion for type 304 stainless steel is 9.6 $\times 10^{-6}$ in/in per °F, the contraction in length, that would occur if the tube were to reach a uniform temperature of 30 °F below ambient, in addition to the normal annual temperature variation of 60°F, would be (38 ft)(12 in/ft)(9.6 $\times$ 10^{-6} in/in per °F)(30 + 60°F) = 0.39 in. Because this tube has four 90-deg bends between the vaporizer and the GOX tank and because it is not firmly clamped, the stress rise caused by thermal contraction is minimal.



NOTES:
1.) ANSI 1500 LB WELD-NECK RTJ-TYPE FLANGES
2.) SCHEDULE 160 A106 3 IN. STEEL PIPE
3.) NO BACKUP RINGS
4.) FULL PENITRATION WELDS
5.) MATERIAL: 304 STAINLESS STEEL
6.) WELDS GROUND FLUSH ON INTERIOR
7.) X-RAY AND MAG PARTICLE
8.) MUST BE CERTIFIED WELDS

Figure 36. GOX pipe layout (3-in. nominal).

The choice of ASTM A269 stainless steel for the 0.75-in. tube between the LOX pump and the vaporizer is based on the –325°F minimum temperature rating of 304 and the ignition resistance of stainless steel. In the 0.75-in. tube, the temperature of the LOX (emanating from the pump) is approximately –227°F at pressure levels of up to 2,900 psi and a maximum LOX velocity of 3.7 ft/sec. Under these conditions, the use of stainless steel is a reasonable choice (see CGA G4.4) for oxygen service. The 0.75-in. tube between the vaporizer and the GOX tank is also ASTM A269 stainless steel.

The components in the 0.75-in. tube line are, for the most part, threaded (NPT type) with Swagelok adapters. The threaded components include relief valves PRV-91 and PRV-92, shutoff valve POV-2, vent valve POV-3, check valve CKV-3, and pressure transducer PIT-3. Relief valves PRV-91 and PRV-92, vent valve POV-3 and the pressure transducer (described in a later section), are plumbed into Swagelok tube tees in the line. GOX pipe data are shown in table 21.

Table 21. Operating range and component materials for GOX pipe.

Component name: 0.75-in. tube, 2- and 3-in. GOX piping	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to 200 (GOX velocity in 0.75-in. tube) 0 to 100 (GOX velocity in 2-in. pipe) 0 to 200 (GOX velocity in 3-in. pipe)

Component name:		
	Material	Remarks
0.5, 2- and 3-in. GOX piping	SA304	

Shutoff Valves POV-4 and POV-5

Two shutoff ball valves (for redundancy) are present in the 3-in. line located just downstream of the GOX tank exit. The valves, POV-4 and POV-5, are mounted back-to-back and rotated about the longitudinal axis, relative to each other. These stainless steel shutoff valves (figs. 37-40), manufactured by TK Valve, Inc, are 2- by 2-in, ASME class 1500 with RTJ flanges. These valves were fabricated in full compliance with ASME B16.34 and they were hydro-tested to 5,400 psi at the factory and supplied with a certification. Note that fire-safe valves are not required and were not to be used because graphite, typically in the fire seals, is not oxygen compatible. The face-to-face dimension of the valve is 14.625 in.

Shutoff valves POV-4 and POV-5 are soft-seated valves with bubble-tight shutoff (Model OS228JBCCCCVP). They have Viton O-rings and PEEK seats and were cleaned for oxygen service during the IST. These valves are of two-piece construction with stainless steel body (A351-CF8M or A182-F316), stainless steel ball and trun (all 17-4PH), and Viton O-rings. These valves do not have packing glands. The torque, required for these valves at full differential pressure (3,600 psi), is 4,388 in-lb (break torque). At 3,000 psi, the torque required is 3,818 in-lb. TK recommends that a 15% safety factor be applied to these numbers.

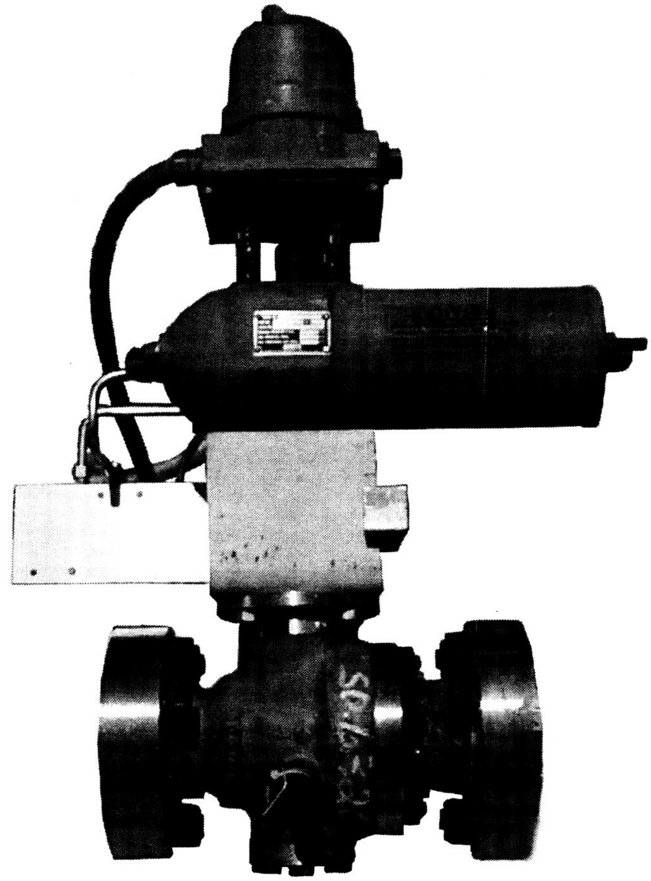


Figure 37. TK ball valve (shutoff valves POV-4 and POV-5).

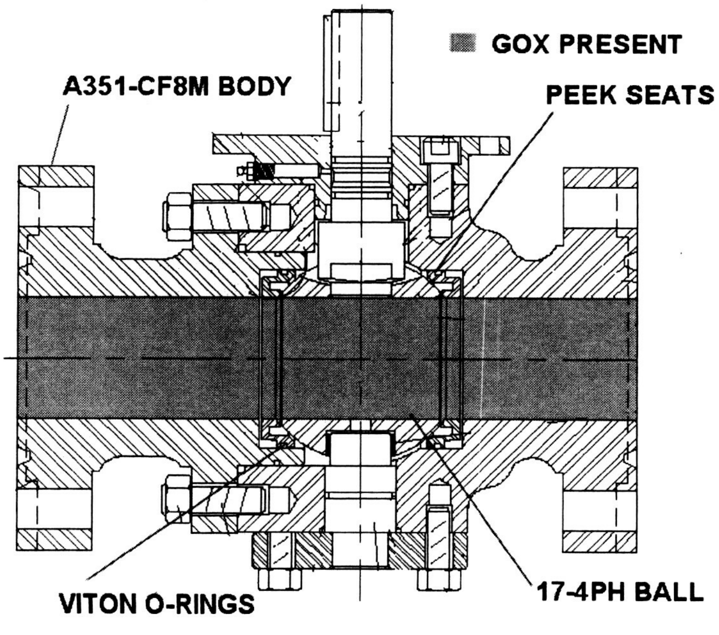


Figure 38. Ball valve (shutoff valves POV-4 and POV-5).

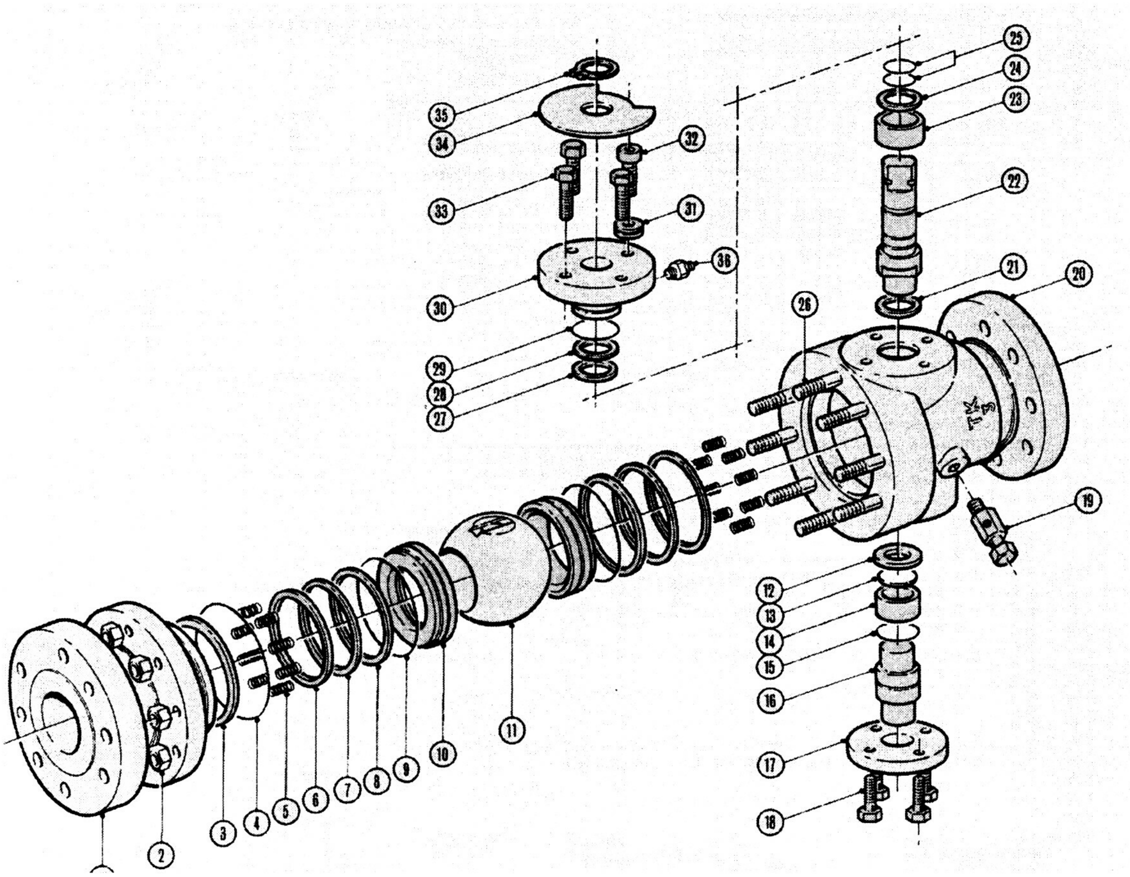


Figure 39. Exploded view of TK ball valves POV-4 and POV-5.

1	ADAPTER	19	BLEED VALVE
2	NUT	20	BODY
3	ADAPTER FIRESEAL	21	BONNET FIRESEAL
4	ADAPTER O-RING	22	STEM
5	SPRING	23	STEM BUSHING
6	SEAT ACTIVATOR RING	24	THRUST WASHER
7	SEAT SPACER	25	STEM O-RING
8	SEAT FIRESEAL	26	STUDS
9	SEAT O-RING	27	COMPRESSION RING
10	SEAT HOLDER	28	STEM FIRESEAL
11	BALL	29	BONNET O-RING
12	TRUNNION FIRESEAL	30	BONNET
13	THRUST DISK	31	STOP SPACER
14	TRUNNION BUSHING	32	STOP
15	TRUNNION O-RING	33	BOLT
16	TRUNNION	34	STOP PLATE
17	TRUNNION FLANGE	35	RETAINING RING
18	TRUNNION BOLT	36	GREASE FITTING

Figure 40. Key for TK-valve exploded view.

A double-acting actuator is used on POV-4 (GHBettis Model CB525). On POV-5, a spring return actuator (GHBettis Model CB725 SR) is used. These actuators are scotch-yoke type with a Model 5R041 ABC WT00 enclosure that contains four single-position double-throw snap switches (figs. 41and 42). These switches will close or open accordingly as the valve is closed or open (depending on how they are wired). The one-quarter turn dual-acting CB 525 pneumatic actuator has a recommended maximum operating pressure of 120 psi and a MAWP of 200 psi. The spring return CB 725 pneumatic actuator has a maximum operating pressure of 120 psi and a MAWP of 160 psi. ASCO solenoid valves are used to control the actuator supply air. The pneumatic actuators are configured in a fail-closed configuration.

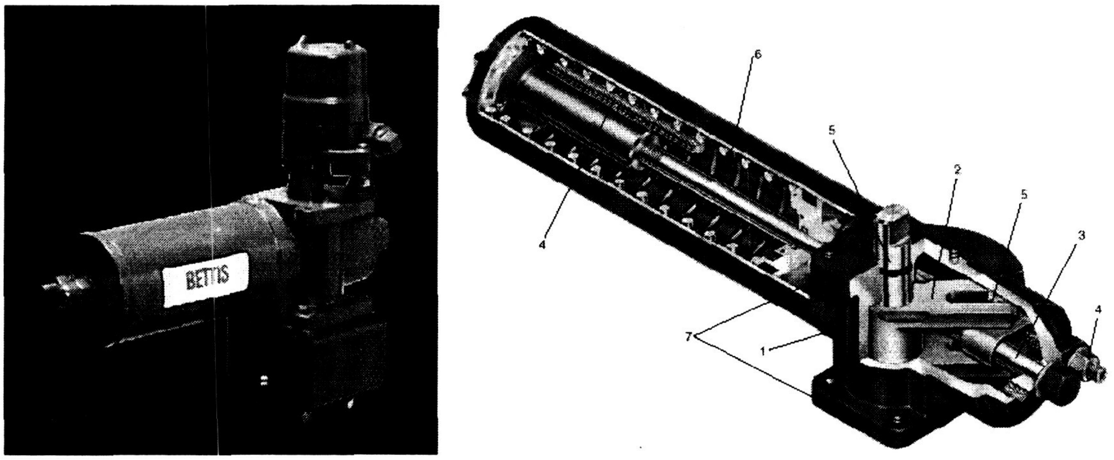
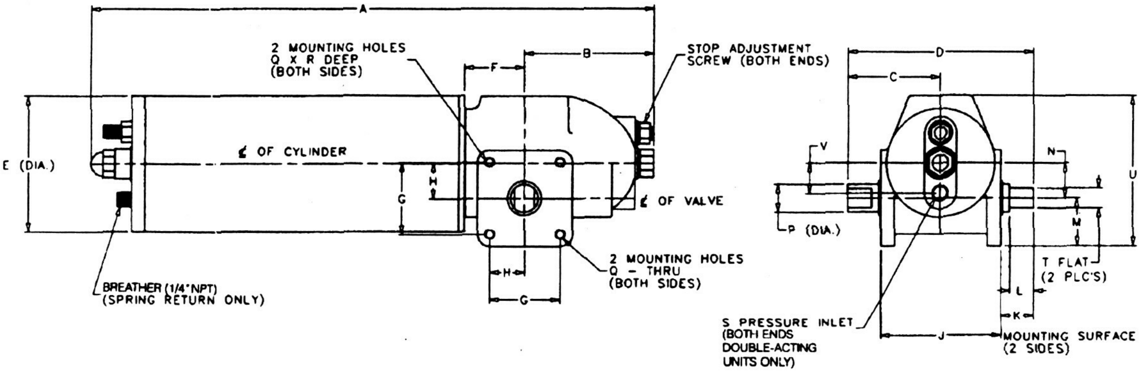


Figure 41. Pneumatic actuator for shutoff valves POV-4 and POV-5.



Actuator Model	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U	V	W	X	Y	Z
CB 525 DA	18.88	6.31	4.38	8.75	5.38	2.56	3.50	1.75	5.75	1.50	1.13	2.31	1.69	1.500 1.497	1/2-13 UNC	0.75	3/8" NPT	1.120 1.115	7.09	1.13	N/A	N/A	N/A	N/A
CB 525 SR	27.78	5.88																			N/A	N/A	N/A	N/A
CB 525 SR-M-XX	See "Z" Dim.	5.88																			1.31	8.00	5.38	30.00
CBL 725 DA	19.15	6.31			7.50																N/A	N/A	N/A	N/A
CB 725 SR	27.81	5.88																			N/A	N/A	N/A	N/A
CB 725 SR-M-XX	See "Z" Dim.	5.88																			1.64	10.00	7.50	30.34

Figure 42. Pneumatic actuator drawing.

A lockout capability has been added to shutoff valves POV-4 and POV-5. The tube that connects the pneumatic actuator to the topworks of the valves was modified by drilling a 0.75-in-diameter hole perpendicular to the tube axis for insertion of a lockout pin. The CB 525 actuator is capable of producing 8,752 in-lb of torque when pressurized with 120 psi. The stress concentration K factor caused by the hole is 5.34. This leads to a shear stress level of 34.0 ksi under load. For the CB725 SR actuator, the maximum shear stress in the tube is 43.6 ksi, corresponding to a torque level of 11,225 in-lb. Hence, the lockout mechanism should fully resist the maximum load applied by the actuator without failing (as proven during full-load testing). Valve data are shown in table 22.

Table 22. Operating range and component materials for POV-4 and POV-5.

Component name: Shutoff valves POV-4 and POV-5	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <280 (GOX velocity at inlet and exit of valve)

Component name: Shutoff valves POV-4 and POV-5	TK Valve Dresser Inc.	OS228JBCCCCVP
	Material	Remarks
Valve body	(A351-CF8M or A182-F316	
Coil spring	Inconel X-750	
O-rings	Viton	
Seat material	PEEK	Soft seat for bubble tight shutoff
Ball, seat holder, stem,	17-4PH	

Bleed Valve HV-94

A bleed ring (2.25 in. thick) is located between shutoff valves POV-4 and POV-5. This bleed ring is made of 304 SS with RTJ joints and a 0.5-in. NPT (F) where a bleed valve is mounted (fig. 43). The purpose of this valve is to permit depressurization of the trapped volume of oxygen between the ball valves without requiring that the shutoff valves to be operated. The bleed valve is made of nickel alloy R-405 and is wrench-operated. It is a Whitey Model M-BVM8-SC11-5389 with an alloy 400 stem, alloy R405/B164 body, R-405 safety back screw, and alloy 400 safety vent tube. This valve has a 10,000 psi pressure rating. The inlet size is 0.5 MNPT. The bleed ring and valve are shown in figures 43 and 44. Bleed valve data are shown in table 23.

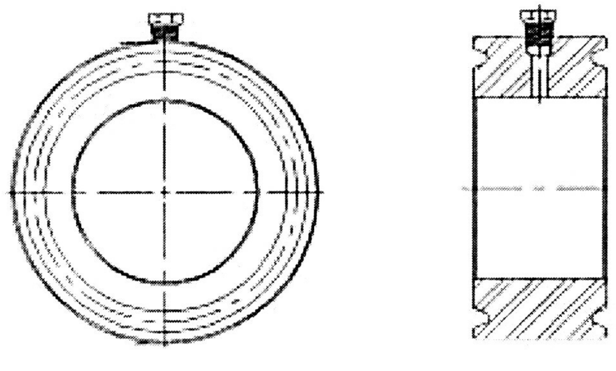


Figure 43. Bleed ring.

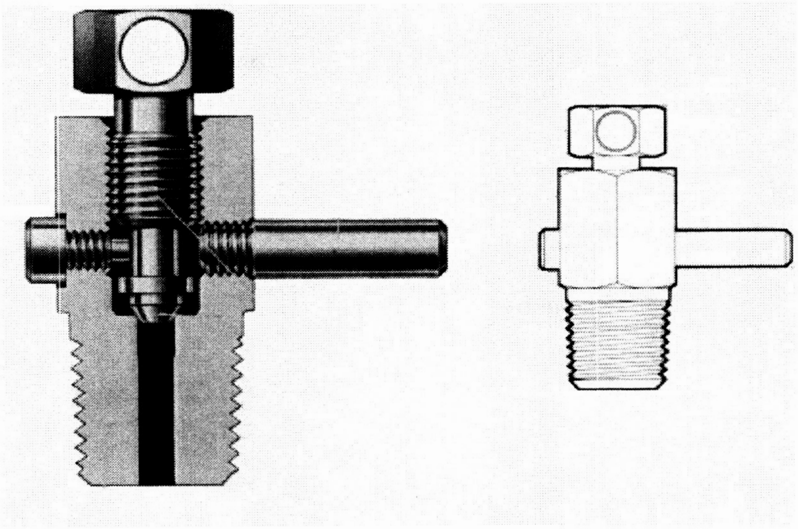


Figure 44. Cutaway view of bleed valve.

Table 23. Operating range and component materials for HV-94 and bleed ring.

Component name: Bleed ring bleed valve HV-94	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Bleed ring, bleed valves HV-94		Whitey and Crane Inc.
	Material	Remarks
Bleed rings	304SS	Crane
Bleed valve has alloy 400 stem, alloy R405/B164 body, R-405 Safety back screw and alloy 400 safety vent tube.	Alloy 400 and 405	Whitey Model M-BVM8-SC11-5389

Pressure Transmitter PIT-3

A pressure transmitter (a transducer with an integral digital readout) is installed on the 0.75-in. stainless steel line upstream of the GOX tank to measure the pressure in the GOX tank (fig. 45). A measurement of the GOX tank pressure is required as an input to the control system. A Rosemount Model 1151GP9E2AB2M7P2 pressure transducer with digital readout (on the side of the transducer) has been used. It is fabricated of 316 stainless steel (including the diaphragm) and is an inert liquid-filled transducer. It is packaged in a weather-tight environment, and has 0.25-in. NPT process connections. The range of this gauge is 0 to 3,000 psi and the accuracy is roughly ±0.25% of calibrated span. It was purchased with a "cleaning for special service" requirement. The transducer is pressure tested to 4,500 psi at the factory. Transducer data are shown in table 24.

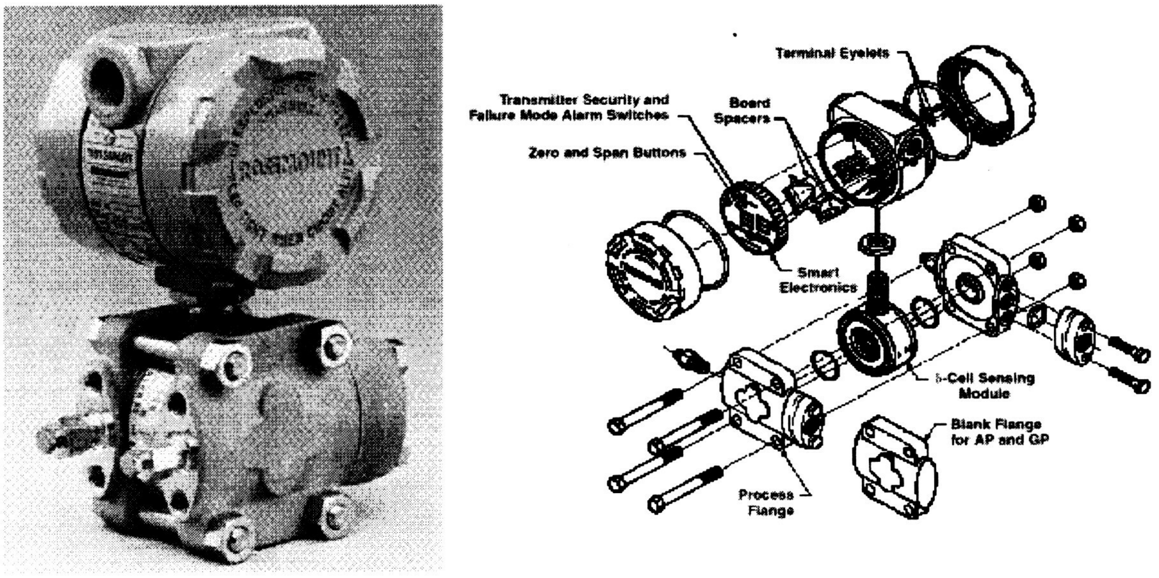


Figure 45. Pressure gauge (PIT-3).

Table 24. Operating range and component materials for PIT-3.

Component name: Pressure gauge PIT-3	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <5 (GOX velocity at inlet of gauge)

Component name: Pressure gauge PIT-3		Rosemount
	Material	Remarks
Material of construction (including diaphragm)	316 SS	
O-rings	Viton	
Fill fluid	Silicone	(Not in contact with oxygen)

Control Valve PCV-6

The oxygen system delivery pressure is controlled by control valve PCV-6 located downstream of shutoff valves POV-4 and POV-5 in the 3-in. line (figs. 46 and 47). This valve is a Norriseal Model 2-2700A-RJS36TGS-16NX W/2.0 CL316 SS trim, 2x2 control valve with 2-in. ASME 1500 class RTJ flanges, 316SS CF8M body and bonnet, 2.0-in. 316 SS linear style trim. The plug seal is made of Viton A. This valve was shipped cleaned for oxygen service. The valve was supplied with a 120-in^2 pneumatic actuator that was set up to fail closed. The face-to-face dimension of the valve is 14.88 in. The highest sound pressure level that this valve will generate is computed to be 109.7 dB under the run conditions described at the beginning of this section. This valve was designed, constructed, and tested in full compliance with ASME B16.34, B16.5 and ISA S75.03. Because of the cage-control trim, this valve was installed FLOW-DOWN.

An issue that arose during the WSTF oxygen system hazards analysis was the fire hazard posed by the compression heating that could occur in shutoff valves POV-4 and POV-5 if control valve PCV-6 is fully shut as shutoff valves POV-4 and POV-5 are opened. Fortunately, there is no requirement for full closure of the control valve PCV-6. Software limits are used to prevent the valve from fully closing (limit set at 10% open). The valve also has a Moore 760E positioner with 4-20 mA input. The valve data are shown in table 25.

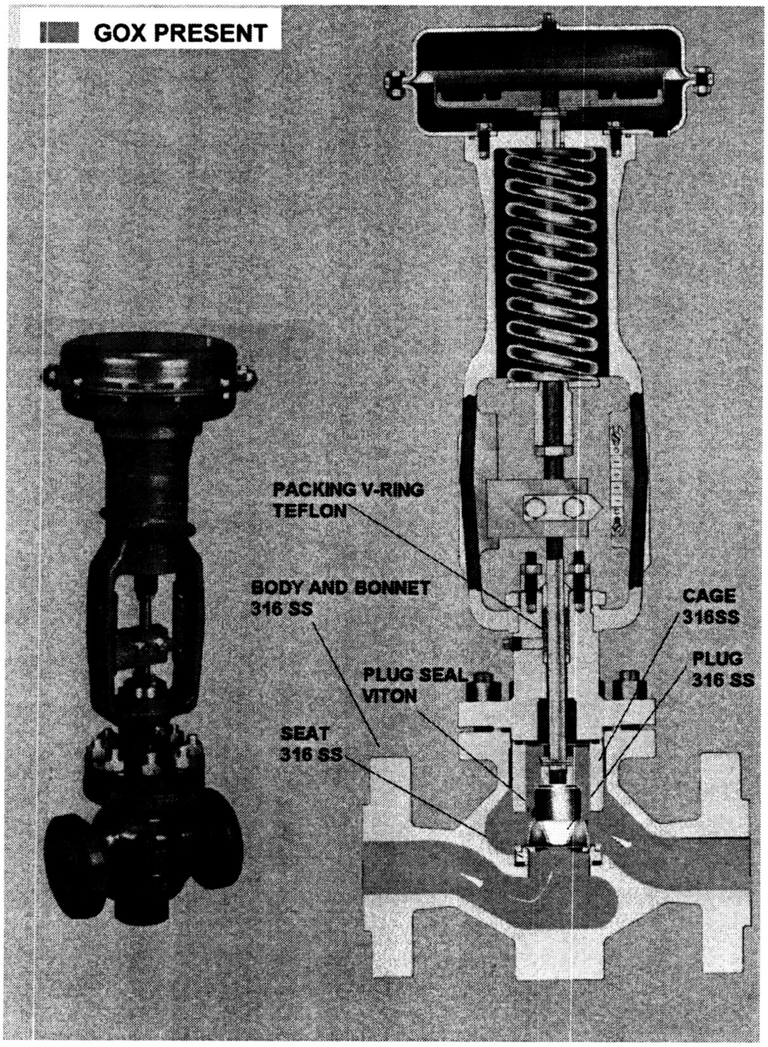


Figure 46. GOX control valve PCV-6.

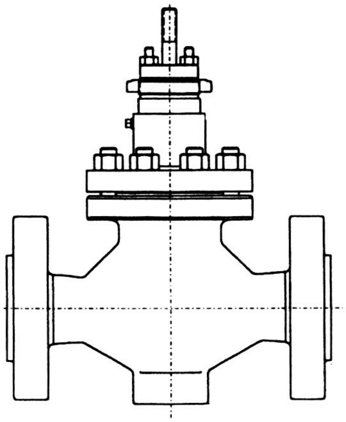


Figure 47. GOX control valve PCV-6 drawing.

Table 25. Operating range and component materials for PCV-6.

Component name: Control valve PCV-6	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to <480 (GOX velocity at inlet and exit of valve), 700 max interior velocity)

Component name: Control valve PCV-6	Norriseal	2700A
	Material	Remarks
Body and bonnet	316SS	
Bonnet gasket	Grafoil & SS	
Plug seal	Viton	
Valve stem	316 SS	
Packing spring	Iconel-X750	
Packing washer	304SS	
Compressor bar	316SS	
Packing retainer	316SS	
Plug	316SS	Monel is high cost option
Cage	316SS	
Seat ring	316SS	
Plug/stem pin	316SS	
Reduced trim adapter	316SS	
Packing V-ring	Teflon	
Trim gasket	Inconel/Grafoil	
Cage guide ring	Teflon/graphite	

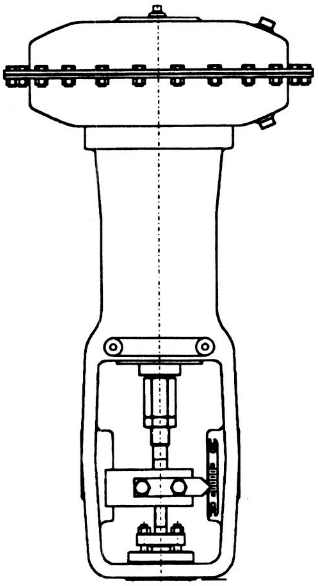


Figure 48. GOX control valve PCV-6 actuator.

The pneumatic actuator on the control valve is of the diaphragm type (fig. 48). The positioner controls the air flow to one side of the diaphragm. The chamber on the opposite side of the diaphragm is vented to atmosphere. A spring is used to return the actuator to its closed position.

The Moore 760E with the high-flow spool option is a cam-characterized, double-acting electronic valve positioner that uses a standard 4-20 mA electronic input signal (figs. 49 and 50). It then converts this signal to a pneumatic output to position a control valve PCV-6 rectilinear actuator. The Moore 760E uses a high-gain, piloted spool valve to load the actuator for positioning in response to electronic input signals. A characterized cam provides mechanical feedback. Cam profiles are available for linear, equal percentage, or quick opening position. Feedback input shafts are available for rectilinear or rotary action. Rectilinear action can range from 0.5 in. to 6 in. in length. The supply air fed to this positioner must be clean and dry. It consumes up to 18 SCFM of supply air when in operation.

All electronic components are securely sealed in an airtight, explosion-proof housing; however, zero and span adjustments are easily accessible for simple calibration and maintenance.

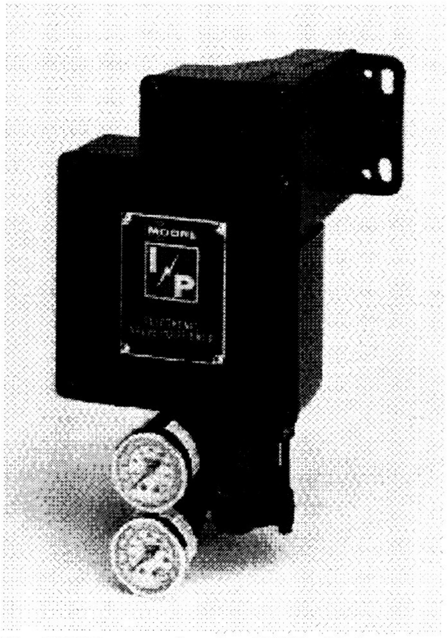


Figure 49. GOX control valve PCV-6 Moore positioner.

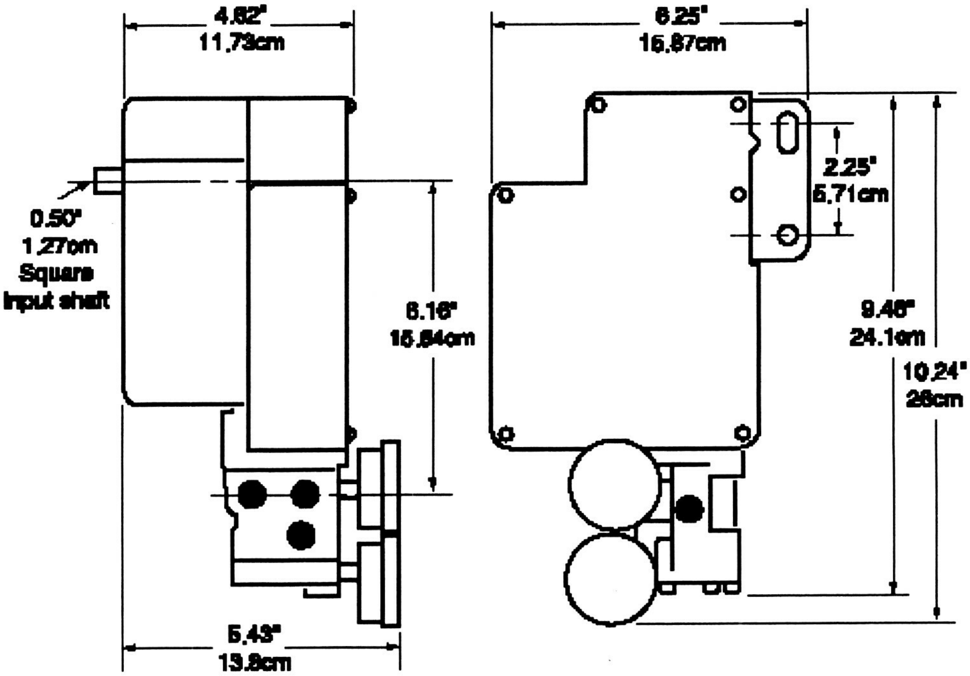


Figure 50. GOX control valve PCV-6 Moore positioner drawing.

ASME Venturi (FE-101)

A 316 stainless steel ASME venturi (FE-101) manufactured by Flowell Corporation is inserted in the main gaseous oxygen line. This device (figs. 51 and 52) has ASME class 1500 weld-neck flanges. The venturi is U-code stamped and supplied with a weld certification; overall length is 19.39 in. The purpose of this venturi is to measure the mass-flow rate of gaseous oxygen.

Flowell manufactures venturi tubes built in accordance with ASME Fluid Meters, ASME MFC-3M and R.W. Miller Flow Measurement Engineering Handbook. These meters provide a high degree of sustained accuracy with high-pressure recovery. Accuracy is ±1% uncalibrated and ±0.25% calibrated. The venturi was purchased uncalibrated because it meets our accuracy requirements. The venturi tube chosen for this application has a throat diameter of 1.967 in. ($\beta = 0.749$).

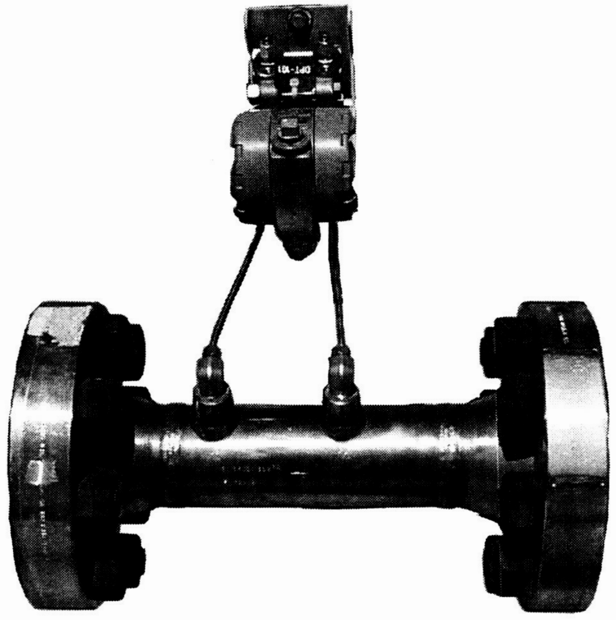


Figure 51. The ASME venturi (FE-101) and differential pressure transducer DP-101.

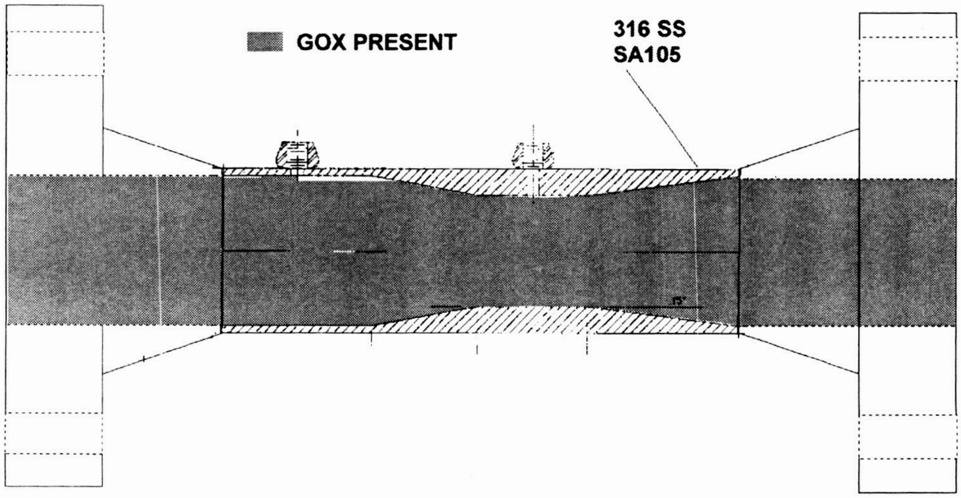


Figure 52. The ASME venturi (FE-101).

The expected differential pressure levels are shown in figure 53. This plot was computed using standard ASME Venturi (FE-101) analysis techniques (Mark's Handbook, ref. 6). It should be noted that these types of flow meters are most accurate for steady-state flows. In practice, it has been found that calculation of the oxygen mass-flow rate based on the pressure differential measured across the sonic nozzle is more accurate during the startup and shutdown transients. Venturi data are shown in table 26.

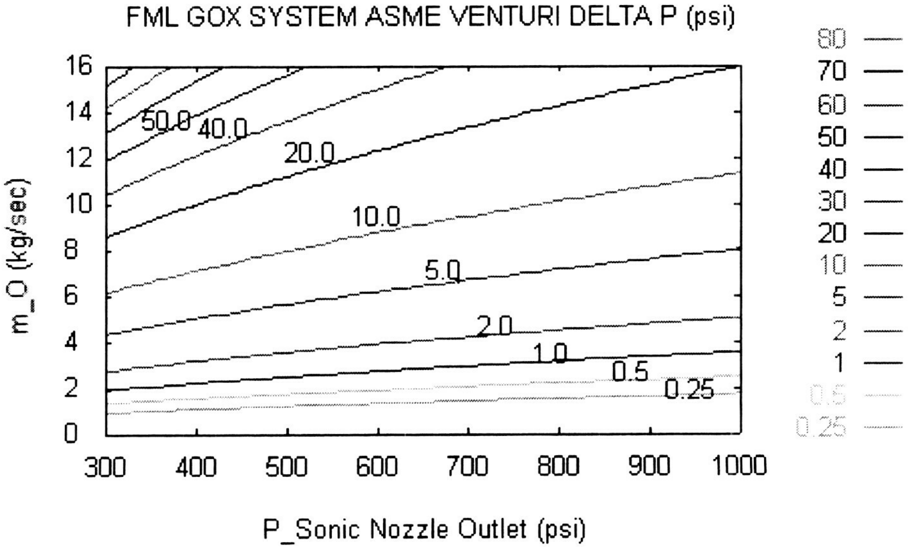


Figure 53. Expected ASME venturi (FE-101) differential pressure.

Table 26. Operating range and component materials for FE-101.

Component name: ASME venturi FE-101	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to 200 (GOX velocity at inlet and exit of valve) 550 in interior of venturi

Component name: ASME venturi (FE-101)		Flowell Inc.
	Material	Remarks
Venturi	316SS	
Venturi housing	316SS	

Sonic Nozzle

The purpose of the nozzle plate is to set the oxygen mass-flow rate to the combustion chamber and to isolate the oxygen feed system from pressure fluctuations in the combustion chamber (figs. 54 and 55). It is also used to determine the oxygen mass-flow rate. The nozzle plates are made out of 2-in.-thick brass bar. A cylindrical hole is bored into these plates of nozzle diameter in the range of 0.2 in. to 2.0 in. It is well known that to establish sonic velocity in a nozzle, the thickness of the nozzle plate should not be less than the nozzle diameter. The plate holder is made of A36 steel with the oxygen-whetted passages lined with brass. The covers are made of 304 stainless steel. The feed piping attaches to the nozzle holder by ASME 1500 RTJ-type 3-in. faces that have been machined in the two ends of the nozzle-plate holder. The flanged pipe is fastened to the nozzle holder by eight grade B7 1.125-in. studs with heavy hex nuts torqued to 355 ft-lb.

The sonic nozzle plate covers are held on by six grade B7, 0.75-in. bolts torqued to 150 ft-lb. If it is assumed that the pressure that acts on the sonic nozzle plate cover is a uniform 3,000 psi over the complete area of the portion of the cover that fits into the holder, (i.e., 8 in^2) and that the bolts that retain the plate cover are solely in tension, the stress in each bolt is

$$\begin{aligned}\sigma &= P / A \\ &= (4{,}000 \text{ lb})/0.44 \text{ in}^2 \\ &= 9{,}054 \text{ psi}\end{aligned}$$

where : P is the bolt axial force $P = (3000 \text{ psi} \times 8 \text{ in}^2.)/(6 \text{ bolts}) = 4{,}000 \text{ lb / bolt}$
A is the cross-sectional area of one bolt $= 3.14 \times (0.75 \text{ in.} / 2)^2 = 0.44 \text{ in}^2$

The proof strength for an SAE A354 grade 8 bolt is 120 ksi; hence the safety factor is 12.0/0.905 = 14. These bolts should be torqued to 150 ft-lb to develop the optimum degree of tightening and sealing force on the copper (C110 annealed 0.065-in. thick) gasket. Nozzle data are shown in table 27.

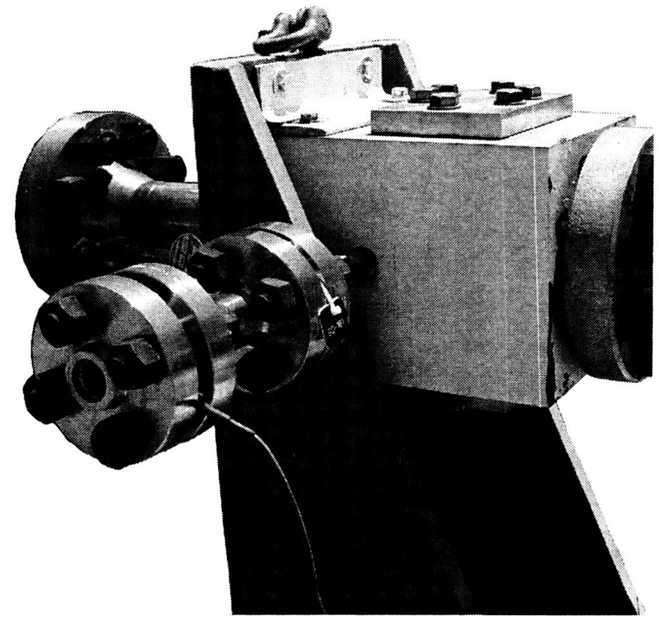


Figure 54. Sonic nozzle and BD-101.

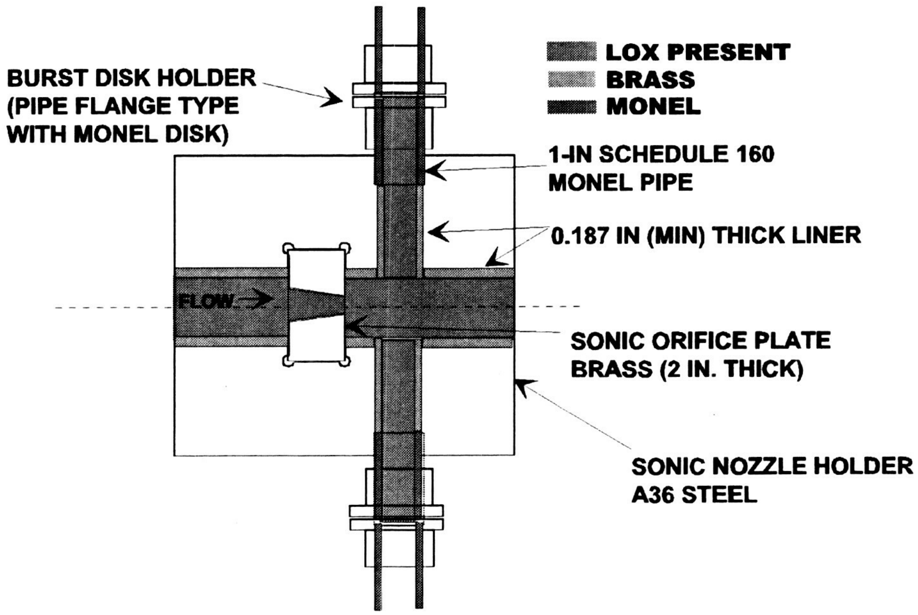


Figure 55. Sonic nozzle plate holder.

Table 27. Operating range and component materials for sonic nozzle.

Component name: Sonic nozzle	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 2,900
Velocity range, ft/sec	0 to 200 (GOX velocity at inlet and exit), sonic in the interior.

Component name: Sonic nozzle		
	Material	Remarks
Nozzle holder	316SS	Manufactured in house
Nozzle plate	Brass	Manufactured in house

Burst Disks BD-100 and BD-101

Burst disks BD-100 and BD-101 are located immediately downstream of the sonic nozzle plate. The purpose of these disks is to relieve pressure in the combustion chamber (or any component downstream of the sonic nozzle) in the very unlikely event of a blockage during a run of the combustion facility (when main GOX valves 2 and 3 are open). Two Oseco 1.0-in. FAS disks (2,200-psi rupture pressure) held by Oseco FRDH2 1500 No. 316 inlet/316 outlet bolted rupture disk holders have been mounted on Monel pipe studs. The holder is made of 316 stainless steel and the burst disks are made of Monel.

No discharge piping has been connected to the burst disk sensor holder that is placed a short distance downstream of the holders. Because oxygen is heavier than air, discharge piping would provide little benefit. It should be noted that these burst-disk holders are directed to the side and only see pressure when the combustion chamber is in operation; hence, nobody will be in the vicinity in the unlikely event that they burst. The holder is the same type as that depicted in the section that describes BD-99.

The Oseco 1-in. Monel disks have been chosen to burst at a pressure of 2,220 psi which is the maximum pressure rating of the class 900 flanges on the combustion chamber (weakest component downstream of the flow regulating sonic nozzle). Note: The manufacturer recommends that the actual pressure that the disk is exposed be no higher that 90% of the pressure rating stamped on the disk. Because these disks are mounted immediately downstream of a sonic nozzle, they should experience pressure levels in the range of a few hundred psi under normal operation. The Oseco model number of the holder is 1" RDH2 316/316 and the disks are 1-in. FAS series. Following ASME VIII procedures for critical flow, the flow capacity of the burst disk can be computed as

$$W = K_D\, C\, A\, P\, [(M/(Z \times T)]^{1/2}$$

where:

W = flow, lb/hr
K_D = discharge coefficient = 0.62 per ASME UG 127(a) (2) (a)
A = actual discharge area, (0.601 in^2)
C = constant based on specific heats (use 356 for gaseous oxygen)
P = (set pressure × 1.10) + 14.7, psia
M = molecular weight (use 32 for oxygen)
Z = compressibility factor (1.0 at P = 2,200 psia and T = 550°R)
T = absolute temperature, °F + 460

Therefore:

$$W = (0.62)\,(356)\,(2 \times 0.601 \text{ in.}^2)\,(2{,}220 \text{ psi})\,[(32/(1 \times 550)]^{1/2}$$
$$W = 1.42 \times 10^5 \text{ lb/hr}$$

and the mass flow is

$$\begin{aligned} \text{Mass flow} &= 1.42 \times 10^5 \text{ lb/hr} / (3{,}600 \text{ sec/hr} \times 32.2 \text{ ft/sec}^2) \\ &= 1.23 \text{ slugs/sec} \\ &= 1.23 \text{ slugs/sec} \times 14.5939 \text{ kg/slug} \\ &= 17.9 \text{ kg/sec} \end{aligned}$$

Hence, because this value is greater that the 16 kg/sec maximum oxygen mass-flow rate, these burst disks should be adequate for all but the most extreme situations (i.e., for all but those associated with failure modes that have very low probability of occurring).

The burst-disk holders are mounted on schedule 80 threaded stainless steel pipes segments that screw into the side of the sonic nozzle housing. For the 1-in. nominal, schedule 80, stainless steel pipe, P = 2,200 psi (burst disks BD-100 and BD-101 setting), D = 1.315 in., S = 20,000 psi, E = 0.8, y = 0.4, resulting in

$$t_m = P\,D / [2\,(S\,E + P\,y)]$$
$$t_m = (2{,}200 \text{ psi})(1.315 \text{ in.}) / [2\,(20{,}000 \text{ psi} \times 1.0 + 2{,}200 \text{ psi} \times 0.4)]$$
$$t_m = 0.069 \text{ in.}$$

Schedule 80 pipe (1 in.) has a wall thickness of 0.179; thus, 0.179(0.875 wall tolerance) = 0.157-in. and since 0.157-in. > 0.069-in, the wall thickness is satisfactory. Disk data are shown in table 28.

Table 28. Operating range and component materials for BD-100, BD-101, and holders.

Component name: Burst disks BD-100 and BD-101	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 1,000
Velocity range, ft/sec	0 to sonic (GOX velocity at exit of burst disk housing)

Component name: Burst disks BD-100 and BD-101	Oseco	1" RDH2
	Material	Remarks
Burst disk	Monel	
Holder	316 SS	Mounted on Monel pipe studs.

Check Valve CKV-7

The Model 315J-C8M4OX 3-in. check valve (figs. 56 and 57) is a swing-type, ASME class 1500, cast 316SS (A351, CF8M) valve made by Newmans/OIC (Newco) with RTJ flanges. Newco valves comply with ANSI B16.34, API 600, and API 598, and the installation dimensions comply with ANSI B16.10. The swing disk on this valve is Monel (an option that was retrofitted on the purchased valve to reduce the likelihood of particle-impingement ignition). The face-to-face dimension of the valve is 18.5 in. It is bolted back-to-back to the sonic nozzle plate holder by high-strength B7 threaded studs. The bonnet is held on by ten 0.875-in. B7 stainless steel studs torqued to 170 ft-lb.

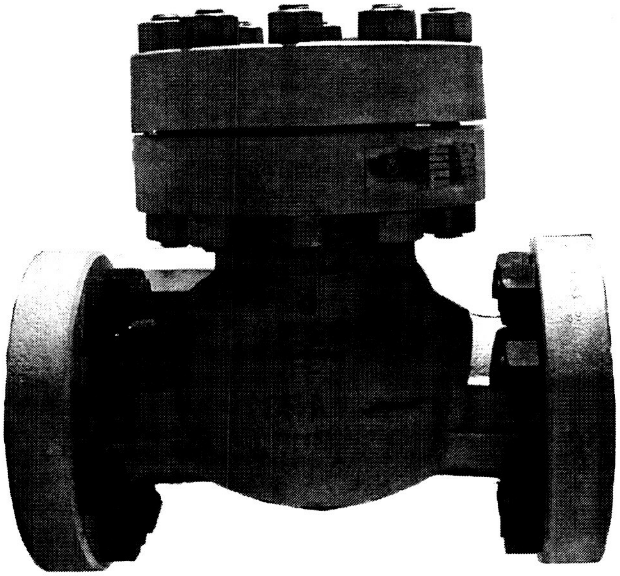


Figure 56. Check valve CKV-7.

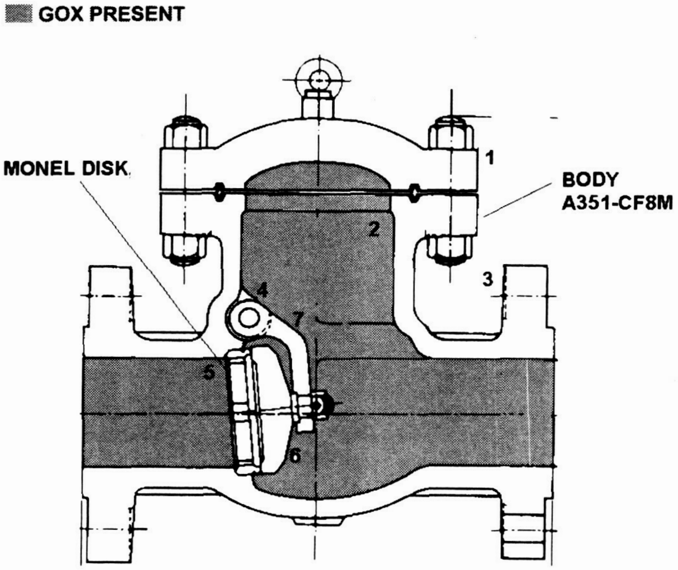


Figure 57. Check valve CKV-7.

The cover sealing surfaces are ring-type joint. Basic dimensions, that is, wall thickness, face-to-face, and flanges comply with the relevant API, ANSI, and BS standards. Bonnet bolting: studs and nuts are manufactured from alloy steel to the relevant ASTM standards. Finished surface seat rings provide seal with the disk, and the seating face is ground and lapped, for a perfectly tight seal. Valve data are shown in table 29.

Table 29. Operating range and component materials for CKV-7.

Component name: Check valve CKV-7	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 1,000
Velocity range, ft/sec	0 to 200 (GOX velocity at inlet and exit of valve)

Component name: Check valve CKV-7	Newmans/OIC	315J-C8M5F
	Material	Remarks
Body and bonnet	A351-CF8M	
Disk	Monel	

Regulator

Three Victor Model SR4J K-cylinder regulators, two for the igniter and one for the carbon dioxide purge system are used (fig. 58). This is a high capacity regulator that has a maximum inlet pressure of 3,000 psi, a delivery range of 200 to 3,000 psi and is constructed of brass. It also has a built-in. relief valve. One issue that came out of the WSTF oxygen hazards review is that the pressure gauges on these regulators are sometimes calibrated using oil that is difficult to clean from the Bourdon tubes. It was found, through verification with the manufacturer, that this is not the case for the regulators purchased. Regulators are listed in table 30 and regulator data are shown in table 31.

Table 30. K-cylinder regulators used.

Victor model and part No.	Quantity	Gas	Remarks
SR 4J-540 0781-1445	1	Oxygen	200 – 3,000 psi
SR 4J 350 0781-1444	1	Methane	200 – 3,000 psi
SR 4F-320 0781-1401	1	Carbon dioxide	50 – 750 psi

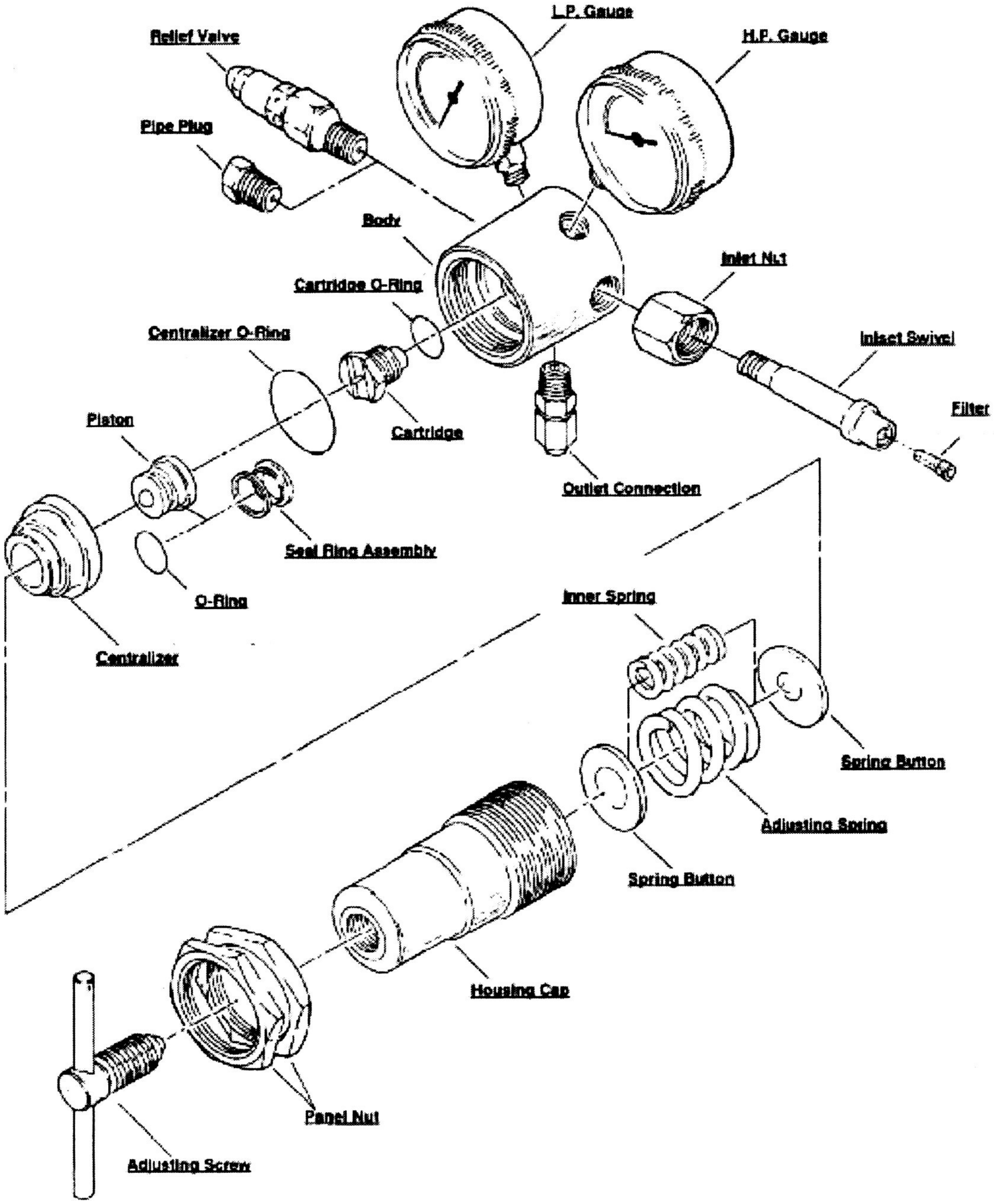


Figure 58. K-cylinder regulator.

Table 31. Operating range and component materials for regulators.

Component name: Regulator	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 3,000
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Regulator	Victor	SR4J
	Material	Remarks
Body	Brass	
Seats	Kel-F	

Check Valves CKV-13, CKV-23, CKV-33

Check valves CKV-13, CKV-23, and CKV-33 prevent reverse flow from the combustion chamber and igniter body from flowing into the igniter feed system. These valves are in-line type check valves that are mounted on pipe nipples attached to the igniter body. Their cracking pressure is 10 psi. They are manufactured by Checkall, Inc, Model UN-10-050-MO-M-10.0IX with female 0.5-in. NPT pipe threads on each end. They are constructed of Monel and contain no soft goods (fig. 59). The valve MAWP is 10,000 psi, and the leak rate of these metal-to-metal seated valves is 85 cm^3/min. During the igniter portion of the IST, it was determined that the auxiliary methane line to the precombustion chamber (line with CKV-33) was not necessary. As a result, this line was capped off and CKV-33 was not installed. Valve data are shown in table 32.

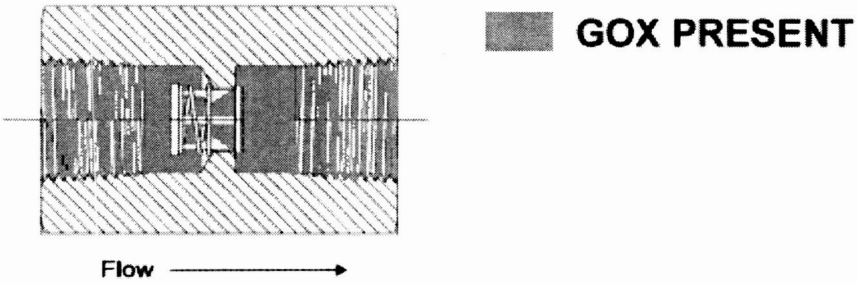


Figure 59. Check valves CKV-13, -23, -33.

Table 32. Operating range and component materials for CKV-13, -23, -33.

Component name: Check valve CKV-13, -23, -33	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 1,500
Velocity range, ft/sec	0 to <200 (GOX velocity at inlet and exit of valve)

Component name: Check valves CKV-23, -33, -44	Checkall, Inc	UN-10-050-MO-M-10.0IX
	Material	Remarks
Body	Monel	
Spring	Inconnel	

Check Valve CKV-43

Check valve CKV-43 prevents flow from the combustion chamber from entering the purge system. It is the same valve as check valve CKV-3.

Shutoff Valves POV-11, POV-21, and POV-41

The flow of oxygen and methane in the igniter system and the flow of carbon dioxide in the purge system are controlled by the Whitey Model M-45F8-SC11-33C, 2,500 psi, air-actuated ball valves (figs. 60 and 61). These valves are shown below. The valves were shipped cleaned for oxygen service from the factory. The pneumatic actuator has limit switches that are monitored by the control system.

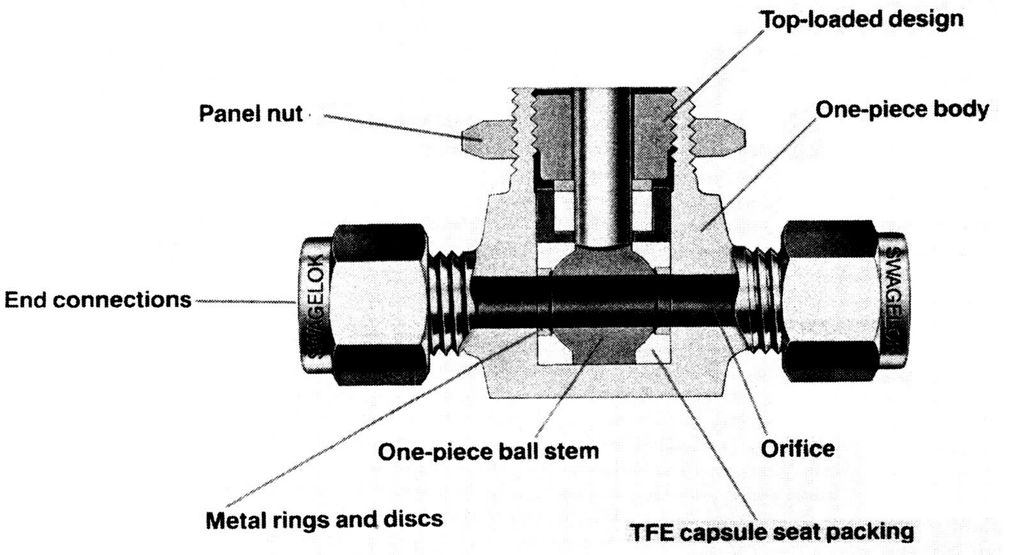


Figure 60. Ball valve.

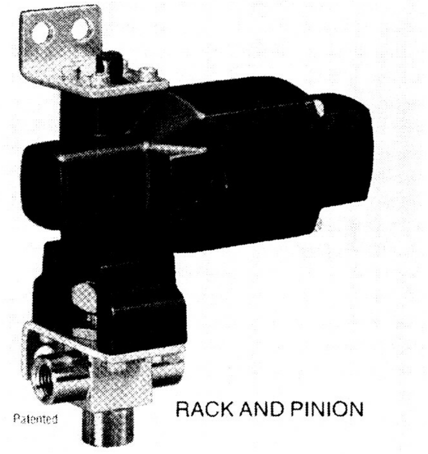


Figure 61. Pneumatic ball valve actuator.

This valve is made of alloy 400 and has a MAWP of 2,500 psi, $C_v = 6.3$, normally closed, 0.5-in. NPT (F) connections, seal material of Teflon, and seat material of alloy 400. The pneumatic actuators that control these valves are Whitey Model 133; the actuators are spring-return. The spring provides a closing torque of 123 in-lb at the start of closing and 74-in. lb at the end of the stroke. With 120 psi applied, the torque produced by the actuator is 182 in-lb (at start of stroke) and 139 in-lb (end). With 140 psi applied, the torque produced by the actuator is 232 in-lb (at start of stroke) and 183 in-lb (end). Valve data are shown in table 33.

Table 33. Operating range and component materials for POV-11, POV-21, POV-31, and POV-41.

Component name: Ox Shutoff Valves POV-11, POV-21, POV-31, and POV-41	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 3,000
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Shutoff valves POV-11, POV-21, POV-31, and POV-41	Whitey	M-45F8-SC11-33C
	Material	Remarks
Body	Alloy 400	
Seat	Alloy 400	
Soft goods	TFE/D1710	

Metering Valves HV-12, HV-22, and HV-32

HV-12, -22, and -32 are needle-type metering valves (fig. 62) with vernier that are used to set the flow rate of the igniter system. The valves chosen are made by Ideal-Aerosmith and are Model number V51-6-21. These valves have a maximum operating pressure of 3,000 psi and a C_v = 0.67 (orifice of D = 0.375 in.). They are made of brass, have metal-to-metal brass seats and bonnet, stainless steel needle, Teflon packing, 0.25-in. NPT (F) ports, 0.1875 orifice, and a black phenolic knob. They have 20+ turns from shutoff to full open. The operating temperature range is –65°F to 450°F. For safety reasons, these valves should not be adjusted while GOX is flowing through them. Valve data are shown in table 34.

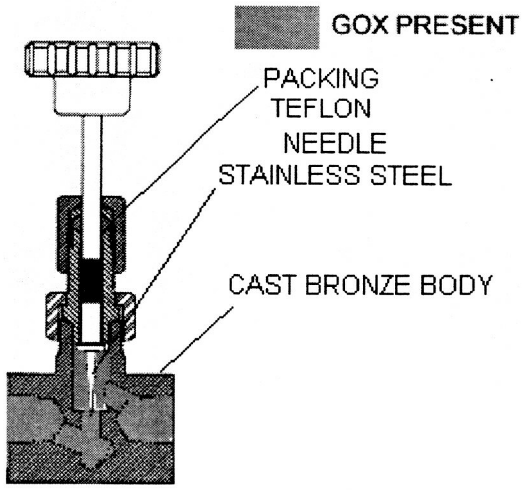


Figure 62. Metering valve.

Table 34. Operating range and component materials for HV-12, HV-22, and HV-32.

Component name: Metering valves HV-12, HV-22, and HV-32	
Temperature range, °F	0 to ambient
Pressure range, psi	Ambient to 3,000
Velocity range, ft/sec	0 to <100 (GOX velocity at inlet and exit of valve)

Component name: Metering valves HV-12, HV-22, and HV-32	Ideal-Aerosmith	V51-6-21
	Material	Remarks
Body	Bronze	
Needle	Stainless steel	
Packing	Teflon	

Miscellaneous Pneumatic Valve Components

Several valves are actuated pneumatically. These valves require 3- or 4-way solenoid valves to control the air supplied to the actuators from the pneumatic system. The main component of the pneumatic system is a 5-hp, 80-gal Champion air compressor. Table 35 lists the solenoid valves specified for pneumatic control:

Table 35. Solenoid valves.

Valve actuator	Part No.	Type	Connect	Max press., psi	Orifice size, in.	Remarks
CO_2 system	ASCO 8300G58F	3-way	0.25 NPT	250	0.1875	NC
Methane (igniter)	ASCO 8300G58F	3-way	0.25 NPT	250	0.1875	NC, 2 required.
Oxygen (igniter)	ASCO 8300G58F	3-way	0.25 NPT	250	0.1875	NC
Shutoff valve (POV-2)	ASCO 8262G1	2-way	0.125 NPT	750	0.0469	NC
Shutoff valve (POV-4)	ASCO 8344G72	4-way	0.375 NPT	150	0.375	Fast
Shutoff valve (POV-5)	ASCO 8342G3	4-way	0.375 NPT	125	0.1875	Slow
Bleed valve (POV-3)	ASCO 8342G1	4-way	0.25 NPT	125	0.1875	Slow

All of the above solenoids are 120 Vac and are weatherproof (type 4X solenoid enclosure) and come with 0.5 NPT conduit hubs. The opening time ranges from 5 to 100 msec.

The air supplying these valves is piped through a condensate separator and then filtered through a coalescing filter (Ingersoll-Rand Model IR150PC) designed to remove particulates 1 micron or greater in size. The flow capacity rating of this unit is 150 SCFM. The air piped to the Moore control valve controller is further dried by a desiccant dryer (Wilkerson Model X03-03-00) that has a maximum SCFM rating of 10 at 100 psi.

HYBRID COMBUSTION TEST SECTION

The 10-in. o.d. combustion chamber designed and built for the Hybrid Combustion Facility is composed of three major components: precombustion chamber, fuel casing, and postcombustion chamber. Each is explained in detail in the following paragraphs (fig. 63).

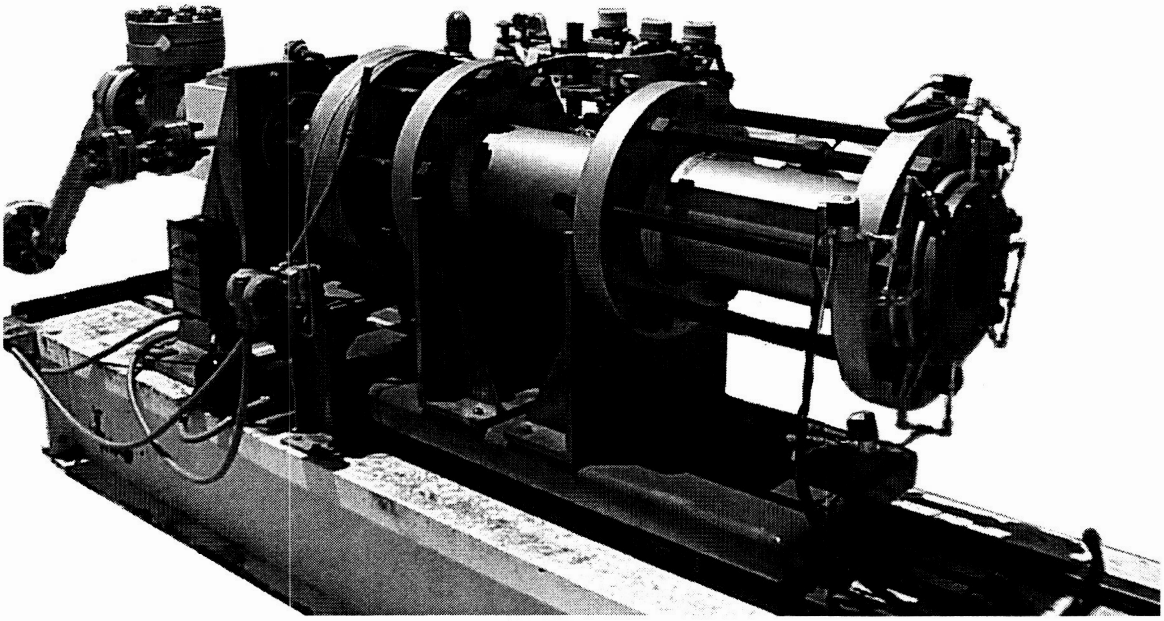


Figure 63. HCF combustion chamber.

Precombustion Chamber

The precombustion chamber is located at the forward end of the combustion chamber. The primary function of this chamber in a hybrid rocket is to supply the fuel port with a uniform oxidizer flow. Typically, in hybrid systems utilizing liquid oxidizer, the precombustion chamber walls are covered with fuel material. This significantly increases the precombustion chamber average gas temperature and accelerates the vaporization process. For the current design, which utilizes a gaseous oxidizer, this technique only complicates the combustion chamber design and the regression-rate data reduction. For that reason the steel walls of the precombustion chamber are insulated with ATJ graphite material.

The precombustion chamber is made of two steel components. The first is a 5-in-thick 21.5-in. o.d. carbon steel plate (injector plate) that connects the oxidizer feed system to the combustion chamber. This plate has a 3-in. RTJ joint machined on the oxygen-feed system end. The feed system end of the plate is fastened to the check valve flange with eight 1.5-in-diameter bolts, and the oxidizer flows into the chamber through a 2.8-in. brass-lined bore through the center of the plate. At the other end of the center hole an oxidizer injector is held in place by a retaining plate. This replaceable injector element will give us the flexibility to control the injection pattern, injection velocity, and the number of jets of the oxidizer into the combustion chamber. It is reported in the hybrid rocket literature that injection parameters influence the motor performance and stability. Common examples of injection configuration are axial injection and radial injection. The baseline configuration selected for the preliminary experiments is the axial injection through a single 2-in. o.d. circular injector. If unstable combustion is encountered, other configurations can be tried.

The second structural component of the precombustion chamber is the forward closure casing (precombustion chamber casing) which is a carbon steel tube with 10-in. o.d. and 1.244-in. wall thickness. An ATJ graphite inner sleeve (precombustion chamber insulator) is inserted into the forward closure casing to protect the exposed steel from hot combustion products.

The precombustion chamber houses the ignition-gas injection port, methane gas injection port, and two small ports for pressure transducers. Hot products from the ignition source are injected into the precombustion chamber radially through a hole drilled though the steel casing and graphite insulator. Since the duration of the ignition pulse is short (approximately 0.5 sec) and the injected mixture is fuel-rich (low oxidization rate), the hole through the steel casing will not be insulated. In order to obtain smooth and reliable ignition, it is a common practice to inject some gaseous fuel into the precombustion chamber along with the hot ignition jet during the ignition period. Accommodations were made to inject a radial methane stream into the precombustion chamber if necessary. The use of extra methane injection during ignition will be kept as an option, if reliable and smooth ignition is not achieved. The methane line will be connected to the combustion chamber casing with a 0.5-in. NPT thread and will be transmitted through a 0.4-in- diameter hole. The methane stream is injected 60 degs off of the ignition stream and 0.25 in. upstream of the igniter injection point.

It is often convenient to measure the combustion chamber pressure in the precombustion chamber because of the low temperatures in this portion of the combustion chamber compared with the temperatures at other locations in the chamber. Two 0.125-in. diameter NPT threaded holes are used in the precombustion chamber casing to accommodate a Kistler 600 series pressure transducer (KPT-1) and a Rosemont pressure transducer. In order to create a clean transmission line between the chamber pressure and the pressure transducer sensor, a 0.03125-in-diameter hole is drilled through the ATJ graphite insulator and precombustion chamber casing. The azimuthal location of the pressure transducer port is selected to be 90 degs from the ignition jet in order to protect the transducer from the hot ignition pulse. Four axial pins (from the injector plate through the injector plate insulator into the precombustion chamber insulator) are used to secure the position of the graphite insulator. Thus the radial holes in the forward casing and insulator are securely aligned.

The 2-in-long and 0.7-in-thick fore-end of the precombustion chamber casing is inserted into an annular 2-in. deep groove machined in the 5-in-thick end plate. The two elements are held together with eight 1-in. diameter studs that extend from the end plate to the combustion chamber casing forward flange. Sealing the connection is achieved by a 0.1875-in. wide O-ring (SAE No. -369). The deflection of the combustion chamber casing at the O-ring location is negligible, even under the maximum pressure loading conditions (1,000-psi chamber pressure). The other end of the forward casing is inserted into the combustion chamber casing. The sealing of that connection is achieved by another 0.1875-in. O-ring (SAE No. -372).

In the current design, the precombustion chamber internal volume is approximately 20 in^3. It is noted in the hybrid rocket literature that the free volume from the sonic nozzle all the way to the fuel port significantly influences the stability of the motor[*]. It is observed in the past that unstable motors can be stabilized by simply reducing the fore-end volume of the motor. Thus it may be necessary to iterate on the precombustion chamber volume (along with the injection pattern) to achieve stable combustion. With the current design this could be achieved relatively inexpensively since the forward casing is designed to be a simple tube with no flanges welded on.

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[*] The instabilities observed in hybrids are not catastrophic in nature. They typically appear as finite-amplitude pressure oscillations.

Combustion Chamber Casing

The second major component of the combustion chamber is the combustion chamber casing that covers most of the fuel grain length. The combustion chamber casing is composed of a very long seamless carbon steel tube with 10 in. o.d. and 1.224-in-wall thickness and ASME class 900 slip-on flanges (o.d. of 21.5 in.) attached at both ends. The combustion chamber casing is 28 in. long. The ASME Boiler and Pressure Vessel Design Code is applied to determine the stresses generated in the flanges under the maximum design pressure of 1,000 psi. It is calculated that the maximum stress occurs in the tangential direction with a numerical value of 4.32 kpsi. Use of a carbon steel material with 40-kpsi yield strength would give a satisfactory safety factor of 9.26.

The combustion chamber case internal surface is not significantly exposed to hot combustion gases since it is protected by the fuel and the paper phenolic insulator which has a 0.08-in. wall thickness. Any leakage of the hot gases to the combustion chamber casing is prevented by the overlapping design of the insulators and fuel and by the reasonably tight tolerances between the elements.

Postcombustion Chamber

The last major component of the combustion chamber is the postcombustion chamber. The purpose of this portion of the combustion chamber is to provide a relatively large cavity to enhance the mixing and combustion of the unburned fuel. The exhaust nozzle is also housed in this element. The tube-like structure was machined out of carbon steel with an integral ASME class 900 flange. The inner surface of the steel postcombustion chamber casing is protected by the ATJ graphite postcombustion chamber insulator.

Disturbances downstream of the nozzle under choked conditions do not affect the internal ballistic characteristics of the combustion chamber (the main focus of the research program on fuel burning properties). Therefore, we decided to use a simple convergent nozzle. This simplified the aft chamber design and significantly reduced the cost of fabrication and future operational costs associated with the fabrication of C-D nozzles of different sizes for different test conditions. ATJ graphite was chosen as the nozzle material in order to keep the costs low. As will be described in a later section, the postcombustion chamber was modified slightly to accommodate an insulator that is effectively a divergent nozzle with an expansion ratio of approximately 2. The purpose of this modification was to protect the postcombustion chamber end plate from excessive heat (melting experienced during some of the early runs).

Graphite is a nozzle material that is commonly used in solid rocket applications. This material is vulnerable to significant throat erosion caused by oxidizer attack during the high O/F (oxidizer to fuel ratio) operation (lean mixture) of hybrids (especially at high chamber pressures). In order to limit the nozzle erosion, the mixture ratios are sometimes held fuel-rich. Some other nozzle material alternatives are silica-phenolic (commonly used in hybrids) or carbon-carbon composites. The use of these nozzle materials requires a large initial investment and thus is not recommended for this program. At a nominal operating chamber pressure of 600 psi and an O/F of 2.1 the erosion rates for graphite nozzle throats is expected to be in the range of 0.008-0.012 in/sec. Finally we would like to note that the nozzle parameters (such as the discharge coefficient) are fairly insensitive to the details of the convergent nozzle contour as long as sharp corners are avoided. A reasonable nozzle contour is shown in drawing A9-0002-M17 in appendix A. The Nozzle is fabricated on a lathe by boring the throat, cutting a 55° taper, blending by eye, and then hand-finishing with sandpaper.

The total acceptable nozzle wear is set by the ability of the nozzle to establish the correct combustion chamber pressure. The run schedule started with runs of small nozzle area and progressed to runs with larger nozzle area to minimize the effect of nozzle erosion on the results and also to minimize nozzle fabrication costs. It is unlikely that the nozzle could fail structurally as a result of erosion.

The postcombustion chamber casing is connected to the combustion chamber casing with eight 1.5-in-diameter bolts that run from the fuel casing aft flange to the aft combustion chamber casing flange. Note that there is a coupling element between the major combustion chamber components. The function of this carbon steel coupler is to accommodate different fuel-grain lengths inexpensively. Coupler length variation can also be used to adjust the postcombustion chamber volume (aft chamber residence time), a critical parameter that sets the combustion efficiency.

Fuel Grains

Fuel-grain units are prepared at Stanford University. A fuel-grain unit is composed of a paper phenolic tube (of the required length) with a maximum o.d. of 7.675-in. and a minimum wall thickness of 0.125 in., two ATJ graphite insulators (fuel-grain end insulators) flush mounted on each side of the phenolic tube, and the fuel grain which is attached to the inner wall of the phenolic tubing and the inner lips of the graphite insulators. Graphite insulators are bonded to the ends of the phenolic tube and then the grains are centrifugally casted. The fuel units are weighed, measured, and then transported to Ames and cartridge-loaded into the combustion chamber casing. The grain-fuel units weight approximately 40 to 60 lb. The graphite insulators are reusable and the phenolic tubing is disposable. Note that combustion chamber inner diameter is sized to match the o.d. of the relatively inexpensive, readily available paper phenolic tubes. Two grain lengths have been tested to date (33.2 and 47.2 in. long).

Igniter

A two-stage ignition system is used to start the self-sustained hybrid combustion (figs. 64 and 65): ignition of a gas-gas igniter followed by ignition of the paraffin fuel grain.

A high-velocity gas burner is used to generate a high-temperature jet of combustion products (including free radicals) that will initiate the combustion reactions of the fuel in the combustion chamber. The igniter uses CH_4 and O_2 as the fuel and oxidizer, respectively. The partially mixed fuel-rich composition of gaseous fuel and oxidizer is injected into the igniter chamber at an O/F ratio of approximately 2. (Note that the stoichiometric O/F for a methane oxygen system is 4). The igniter ignition source is two spark plugs located in the igniter chamber.

Ignition of the paraffin fuel grain is achieved after mixing of the hot gas-gas igniter stream with the primary oxidizer flow in the precombustion chamber. The energy contained in the ignition stream vaporizes the solid fuel grain and the free radicals present initiate the combustion reaction between the vaporized hybrid fuel and the main oxidizer flow in the fuel port. After a certain period of igniter operation (approximately 0.5 sec), self-sustained combustion of the paraffin is achieved. Provisions have been made for a secondary injection of methane directly into the precombustion chamber, but reliable ignition has been achieved without this added boost so this line has been capped off.

The ignition system parameters that can be adjusted to obtain a reliable and smooth ignition of the fuel are igniter oxidizer mass-flow rate, igniter methane mass-flow rate, motor methane mass-flow rate, and the scheduling of igniter oxidizer/fuel mass flow, motor oxidizer/methane flow, and spark timing.

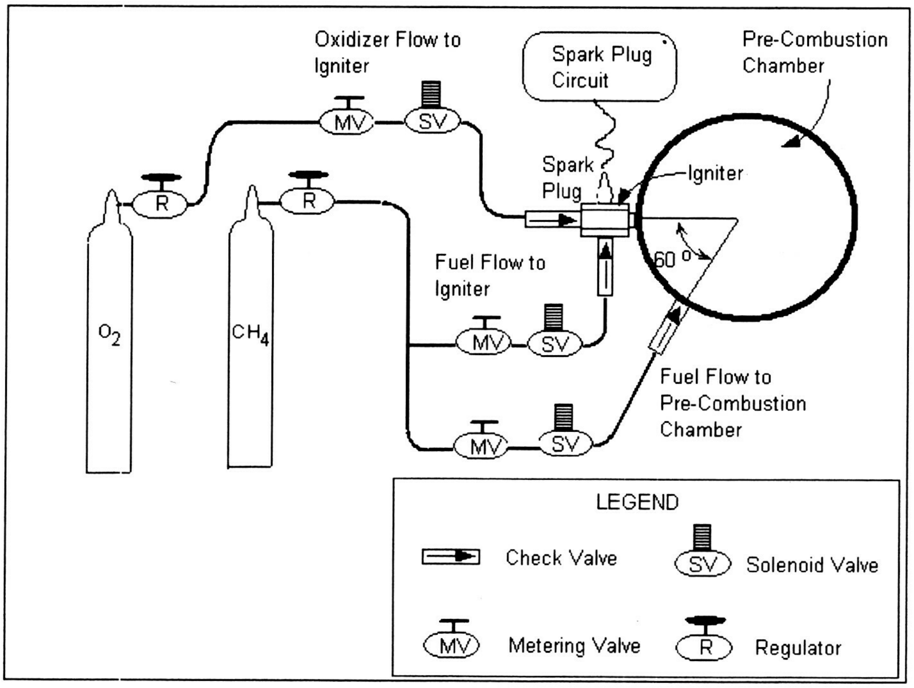


Figure 64. HCF igniter system schematic.

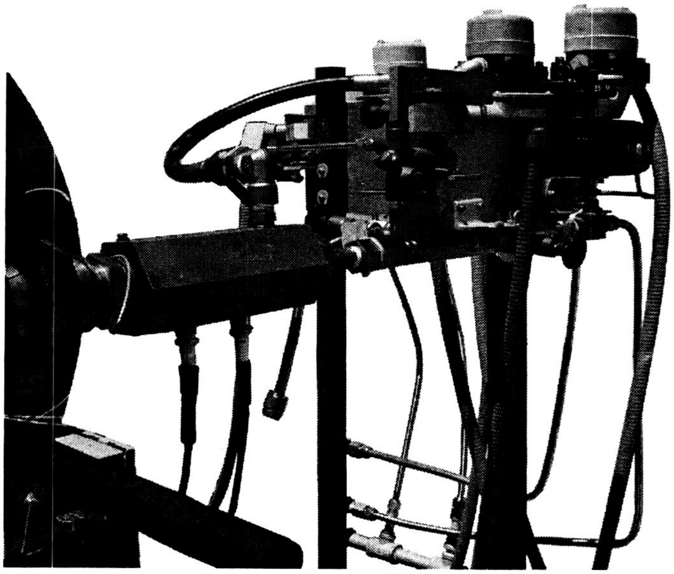


Figure 65. HCF igniter.

The igniter system spark generator consists of an Accel Model 8140 automotive coil and a simple solid-state circuit (fig. 66) that sends a pulse train to the coil primary. The spark generation frequency is approximately 100 Hz.

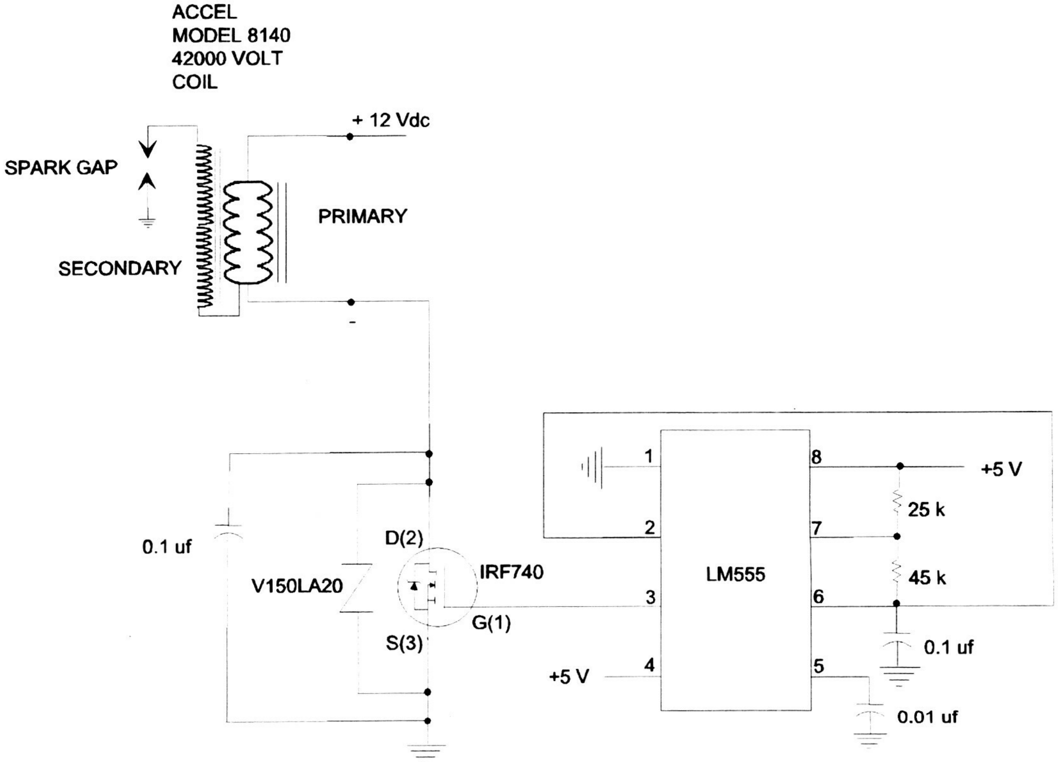


Figure 66. Igniter pulse generator circuit schematic.

Combustion Chamber Specifications

The combustion chamber is shown in figs. 67-70; specifications are shown in table 36.

Table 36. Combustion chamber specifications.

Maximum operational pressure	1,000 psi
Injector plate weight	442.8 lb
Precombustion chamber weight (casing and insulator)	77.0 lb
Combustion chamber casing weight (including fuel-grain unit)	795.3 lb
Postcombustion weight (including insulators and nozzle)	336.0 lb
Fuel-grain unit weight:	35.0-45.0 lb
Total weight:	1668.6 lb
Motor center of mass (from the injector plate outside face – for minimum combustion chamber length)	21.0 in.
Combustion chamber max flange diameter	21.5 in
Combustion chamber length	45.1-in. to 57.1 in.
Combustion chamber o.d.	10 in.
Fuel grain o.d.	7.675 in.

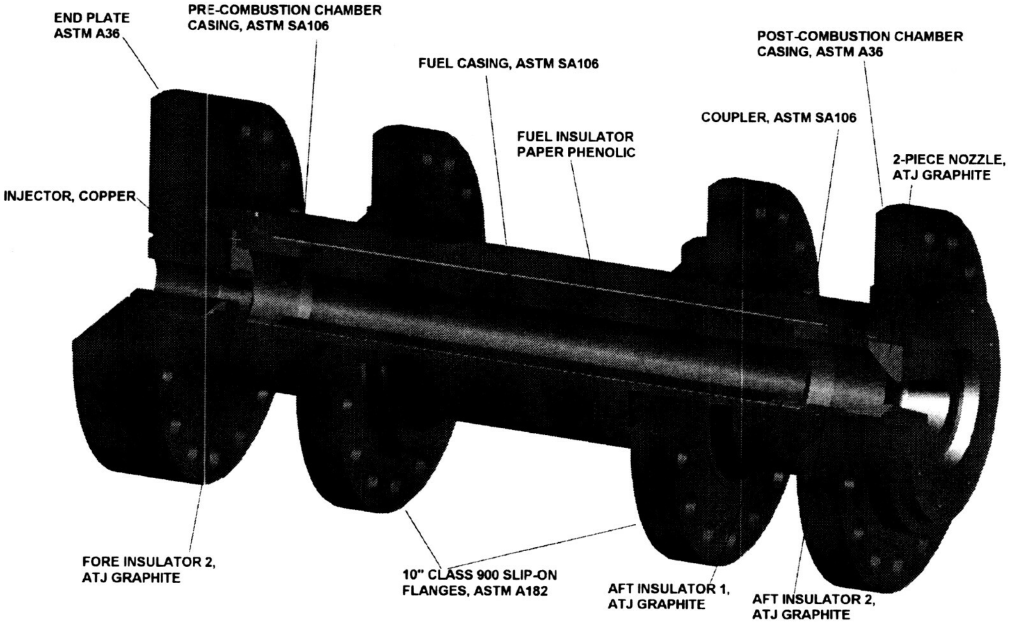


Figure 67. Perspective view of combustion chamber (with short coupler installed).

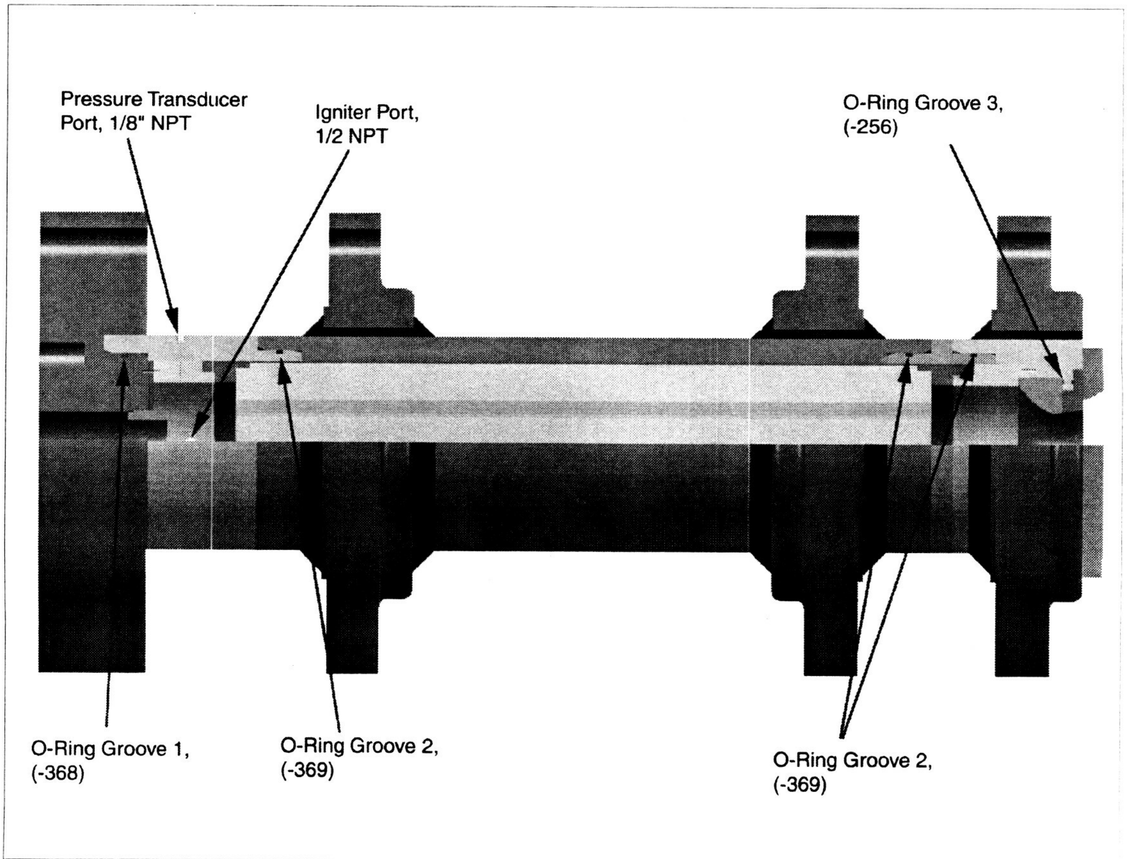


Figure 68. Side view of combustion chamber.

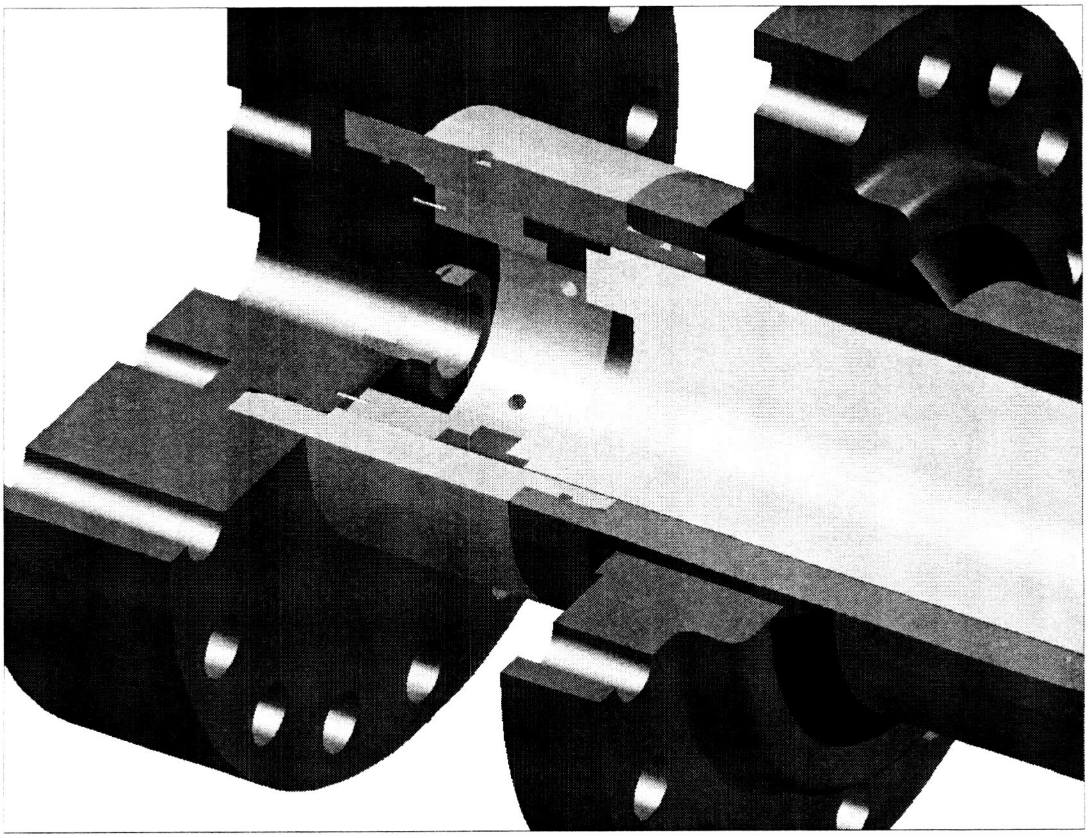


Figure 69. Close-up of precombustion chamber.

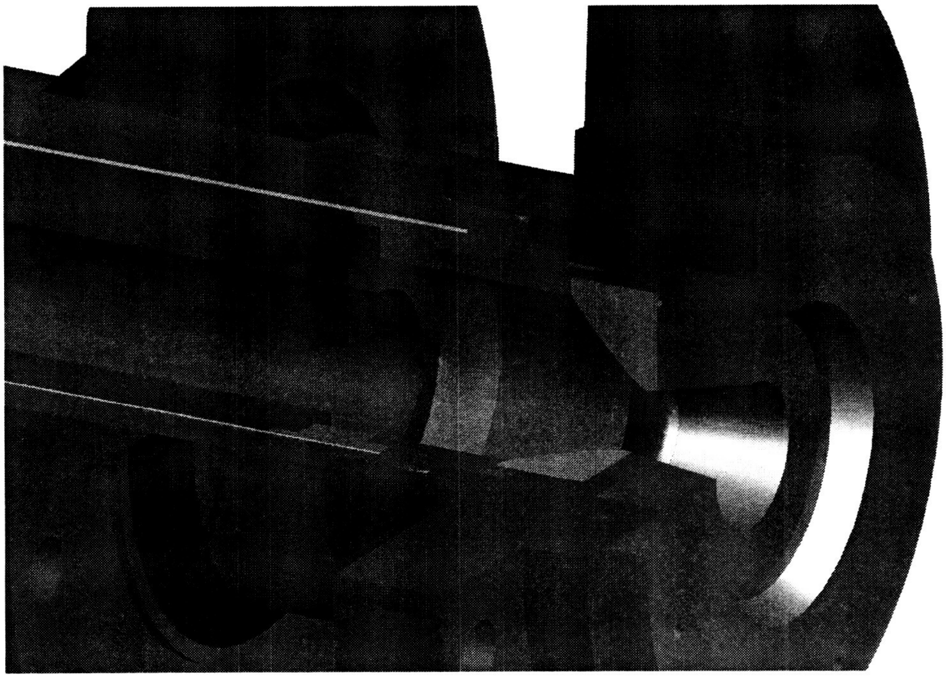


Figure 70. Close-up of the postcombustion chamber showing nozzle.

Combustion Chamber O-Rings

O-ring joints are utilized to achieve sealing between the combustion chamber components under internal pressure conditions. The combustion chamber O-ring joints are between the end plate/precombustion chamber casing, precombustion chamber casing/fuel casing, coupler/fuel casing, coupler/postcombustion chamber, and nozzle/postcombustion chamber casing. Viton was selected and used as the O-ring material because of its wide temperature range (-60°C-200°C) and good chemical compatibility characteristics. Some of the important properties of Viton are its hardness of 60-95 (Shore A scale) and its tensile strength which is in the range of 80-160 bar. The details of the three different kinds of O-ring joints used in the design are described in table 37.

Table 37. Combustion chamber O-rings.

	O-Ring groove 1	O-Ring groove 2	O-Ring groove 3
Connections	End plate/precombustion chamber casing	precombustion chamber casing/fuel casing, coupler/fuel casing, coupler/postcombustion chamber	nozzle/postcombustion chamber casing
O-ring kind	-368	-369	-256
O-ring i.d.	actual 7.725 in., nominal 7 0.75 in.	actual 7.975 in., nominal 8 in.	actual 5.734 in., nominal 5 0.75 in.
O-ring diameter	actual 0.210 in., nominal 0.1875 in.	actual 0.210 in., nominal 0.1875 in.	actual 0.139 in., nominal 0.125 in.
Configuration	radial	radial	face
Percent O-ring stretch	1.07%	3.2%	
Mean O-ring cross section	0.209 in.	0.207 in.	0.139 in.
Nominal percent cross-sectional squeeze	17.7%	16.9%	25.2%

There are several other design issues relevant to the use of O-rings in a high-temperature, high-pressure environment:

1. Structural deflections: One of the most common failures of O-ring joints occurs as a result of extreme deflections of the structure in the vicinity of the joint. This is especially critical for rocket applications during the transient operation. It is estimated that the deflection of the combustion chamber structure will be small, and no leakage caused by deflection is expected.

2. O-ring extrusion: For large pressure differences and large diametrical clearances, the elastomeric O-ring materials can be extruded in the groove (leakage and O-ring damage may result). The extrusion behavior of O-rings at various hardness values is shown in figure 71. Note that, the extrusion limits shown are very conservative since they are based on 100,000 load cycles. The worst-case scenario for the HCF is also shown in the figure (the diametrical clearance is selected to be 0.006 in.). As indicated by the figure, O-ring extrusion is not expected to be an issue.

3. Temperature: All joints and sealing are protected by thick ATJ graphite insulators. The temperature increase of the O-ring joints is predicted to be small for the typical short run times of the facility. The minimum operating temperature for the O-ring material selected is –60°C, well below the lowest expected temperature in the Bay Area.

4. Assembly: All joints are chamfered at 15° for safe and easy assembly.

5. All O-rings are inspected after every run and replaced if necessary.

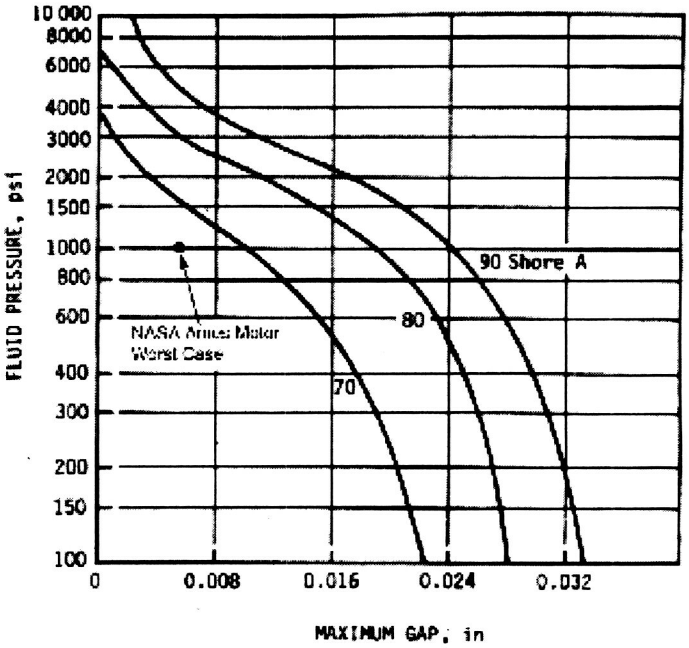


Figure 71. Extrusion limits for O-rings.

SUPPORT STRUCTURE

Combustion Chamber Support

In order to analyze the structural integrity of the combustion chamber support structure, an estimate of the maximum thrust load is required. The following calculation is based on the actual HCF configuration described in this document. Addition of a nozzle with a substantial divergent section will change this estimate. Note that the oxygen delivery system has a greater capability than can be used in the present design (a larger combustion chamber may be constructed in the future). This very conservative maximum thrust estimate neglects several factors that substantially reduce the actual thrust level. It is assumed that the maximum combustion chamber pressure is 900 psi, that the oxygen supply mass-flow rate = 6 kg/sec, that the oxygen-to-fuel ratio is 2.4, and that the adiabatic flame temperature of 6,357°R is equal to T_{throat}.

$$
\begin{aligned}
\dot{m} &= \dot{m}_{GOX}\,(1+1/OF) \\
&= (6\ \text{kg/sec})(2.204\ \text{lb}_m/\text{kg}) \times (1+1/2.4) \\
&= 18.73\ \text{lb}_m/\text{sec}
\end{aligned}
$$

$$
\begin{aligned}
v_{throat} &= M\,[\gamma R g_c T_{throat}]^{1/2} \\
&= (1.0)[1.164 \times 69.7 \times 32.2 \times 6357]^{1/2} \\
&= 4{,}075\ \text{ft/sec}
\end{aligned}
$$

$$
\begin{aligned}
F &= \dot{m}\; v_{throat} + (p_{th} - p_a)\,A_{throat} \\
&= \dot{m}\; v_{throat} + (0.528 p_r - p_a)\,A_{throat} \\
&= [(18.73 \times 4075)/\,32.2\,] + (0.528 \times 900 - 14.7) \times 144 \times 0.0115 \\
&= 2370 + 774.1
\end{aligned}
$$

$$=3{,}144.1 \text{ lb} \quad \text{(for converging nozzle only)}$$

where:

$\dot{m}_{GOX}$ = oxygen mass-flow rate, (lb_m/sec)
OF = oxygen-to-fuel mass-flow ratio (approximately = 2.4)
F = thrust force (lb)
M = Mach number = 1.0 at throat
γ =ratio of specific heats of combustion products (computed by a chemistry code) = 1.164
$\dot{m}$ = total mass-flow rate, (lb_m/sec)
R = gas law constant = R_u/MW = (1,544.0 ft-lb/mole °R)/(22.13) = 69.7 ft lb_f/lb_m °R
v_{throat} = exhaust nozzle throat flow velocity (ft/sec)
p_r = static pressure in the combustion chamber (psi)
p_{throat} = static pressure at exhaust nozzle throat (psi)
T_{throat} = assumed equal to adiabatic flame temperature computed by a chemistry code, (°R)
p_a = ambient pressure, $lb/ft^2 = 2{,}117\ lb/ft^2$
A_{throat} = exhaust nozzle throat area, (ft^2) = $\pi\ (1.45 \text{ in}/2)^2/144 = 0.0115\ ft^2$

The above thrust estimate is for a nozzle without a divergent section downstream of the nozzle throat (the original HCF configuration). Recent modifications to the HCF have involved the addition of a divergent section with an expansion ratio of approximately 2. For the same chamber pressure, oxygen mass-flow rate, and O/F ratio used above, the modified configuration will produce a maximum thrust approaching 4,500 lb. A convergent-divergent nozzle with a large expansion ratio may be used at some point. A nozzle of this type will increase the thrust level (depending on the area ratio) and, before installation, this analysis should be revisited. For stress analysis purposes, the "design load" thrust level was chosen to be 6,000 lb (25% higher than the highest thrust level expected).

Since the HCF is a distributed system that is bolted to the concrete pad at several points and since there is GOX flowing through the delivery pipe to the combustion chamber, it is difficult to determine the point of application of the thrust force and the precise load path through the system. In the analysis that follows, the thrust force generated by the combustion process is considered to be resisted primarily by the thrust plate. As will be shown in the thrust measurement section of this document, this is not strictly the case. The GOX mass-flow through the components, supported by the thrust plate, significantly reduces the actual load experienced by the thrust plate.

The combustion chamber is supported by two brackets that attach to a rectangular frame (fig. 72) constructed out of 4-in. by 6-in. rectangular structural steel (0.5-in. wall thickness). The combustion chamber assembly rides on linear bearings that are bolted to two structural steel I-beams of length 21 ft. 5.5 in. The purpose of the linear bearings is to make thrust measurement possible and also to promote easy fuel-grain insertion and removal. The main force path through the structure is such that the thrust force is resisted by the thrust plate that is bolted to the I-beam support that, in turn, is bolted to the OARF concrete pad.

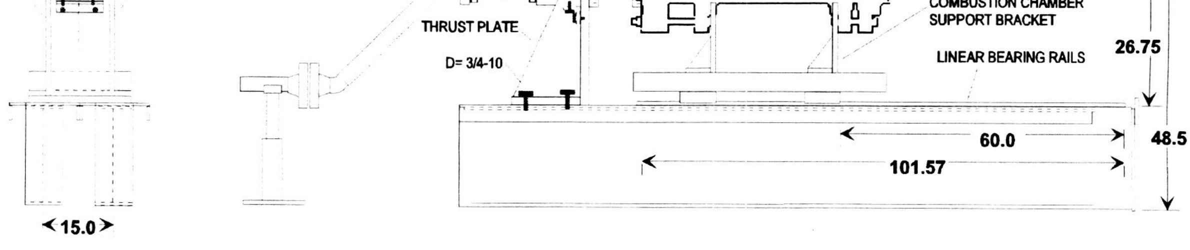


Figure 72. Combustion chamber structural support (dimensions in inches).

The primary applied loads experienced by the thrust-plate support structure are a portion of the weight of several components (conservatively assumed to be 1,323 lb) and the thrust force. The thrust plate is constructed of 1-in-thick A36 steel and held to the I-beams by four 0.75-in. bolts. As will be shown, the stress levels in the thrust plate and in the bolts are small. The components partially supported by the thrust plate are the check valve CK-7, the sonic nozzle holder, two pipe segments, and the precombustion chamber end plate. Note that the precombustion chamber end plate has a support bracket (not shown in fig. 72) that was installed to support the weight of this element during assembly and maintenance. This support has removable blocks that will be removed upon installation of a thrust-measurement capability. After the blocks are removed, the precombustion end plate support is no longer in contact with the combustion chamber.

Concerning the thermal expansion (or contraction) of the main 3-in. pipeline (including the in-line components) that runs between the GOX tank and check valve CKV-7 it was estimated in an earlier section of this document that substantial strain can develop in the pipeline caused by ambient temperature variations, if both ends of the pipeline are fixed. The SOP of the HCF requires that the four 0.75-in. bolts (in oversized holes) that attach the thrust plate to the I-beam support be left in a loosened state (except when running the facility) so that the pipeline can expand and contract freely. In the following analysis, it is assumed that this procedure has been followed; therefore, the effect of thermal stresses is assumed to be zero.

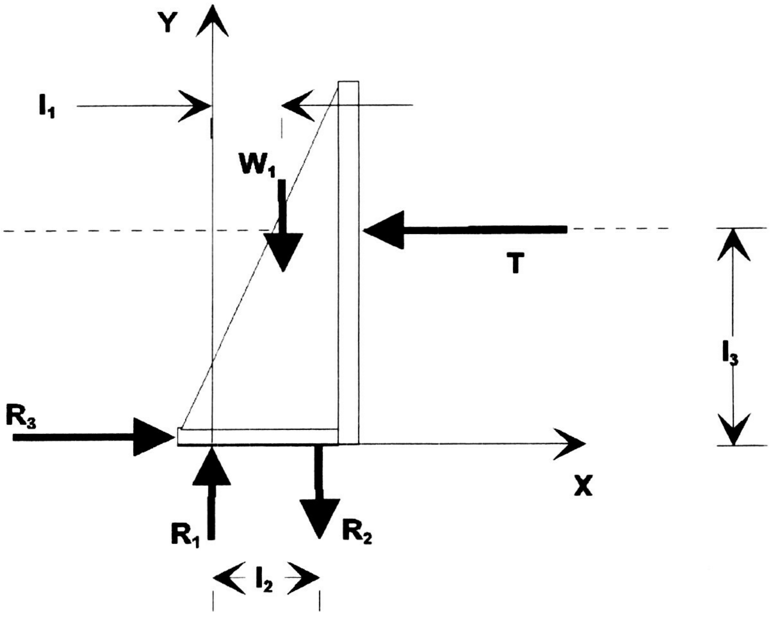


Figure 73. Free-body diagram of thrust plate.

Referring to figure 73 and assuming that the thermal stress in the 3-in. pipeline has been relieved and neglecting the reaction force of the 3-in. pipeline on the thrust plate, W_1 = 1,323 lb and T = 6,000 lb are the applied loads to the thrust plate support, l_1 =10 in, l_2 =12 in, l_3 =26.75 in, and by summing forces in the x-direction, R_3= 6,000 lb (2,721.7 kgf). Summing moments about the origin gives R_2 = 12,350 lb (5,625 kgf). By summing forces in the y-direction, R_1= 13,720 lb (6,226 kgf).

If the thrust plate is modeled as a tapered cantilevered beam with a point load of T = 6,000 lb, the stress at the extreme fibers of the flanges near the base of the vertical support plate is

Neutral axis: y = 2.79 in.
I = 604.5 in^4

$$\sigma = Mc/I = (6{,}000\text{ lb} \times 26.75\text{ in.})(12\text{-}2.79\text{ in.})/(604.5\text{ in}^4) = 2{,}445\text{ psi}$$

At the location of the lowest pipe-flange bolt hole, the bending stress is approximately the maximum:

$$\text{Neutral axis: } y = 1.12\text{ in.}$$
$$I = 14.5\text{ in}^4$$
$$\sigma_{max} = Mc/I = (6{,}000\text{ lb} \times 4.5\text{ in.})(4.0\text{-}1.12\text{ in.})/(14.5\text{ in}^4) = 5{,}364\text{ psi}$$

For A36 steel, the maximum allowable bending stress is 24,000 psi; hence, the safety factor is 24,000/5,364 = 4.47. Note that the safety factors shown in this document are defined based on allowable stress.

There are 12 critical fasteners (fig. 74) that resist the thrust load: four 0.75-i bolts are used to attach the thrust plate support to the main I beams and eight 0.5-in. bolts attach the sonic nozzle holder to the thrust plate support as shown below (in red). The critical fasteners are SAE grade 8 bolts. The bolts have an ultimate tensile strength of $F_u = 150{,}000$ psi. The allowable tensile stress is defined as $0.25 \times F_u$, the allowable shear stress is $0.15 \times F_u$, and the allowable bearing stress is $0.25 \times F_u$.

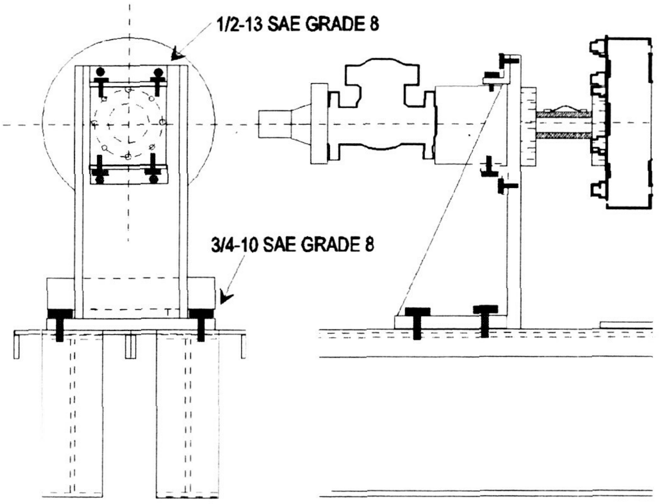


Figure 74. Critical support structure fasteners.

The support structure is attached to the structural I-beam by four 0.75 -in. bolts (in single-shear with threads in the shear plane). Considering failure in shear, the allowable shear stress in Grade 8 bolts with friction-type connections in oversized or short slotted holes is F_v =15.0 ksi. The allowable load P is then

$$P_{allow} = A_{one\ bolt}\, F_v = (\pi\ 0.75^2/4\text{ in}^2)(15{,}000\text{ psi}) = 6{,}623\text{ lb}$$

Since four bolts are used to resist the shear load of 6,000 lb (max), the safety factor is S.F. = (4)(6,623)/6,000 = 4.42.

These bolts bear on the 1.0-in-thick I-beam support structure (note that the I-beam is 0.5 in. thick with a 0.5-in-thick plate welded on top). The allowable bearing stress is F_p = 37,500; hence the allowable bearing load is

$$P_{allow} = A_{one\ bolt}\, F_p = (0.75\text{ in.} \times 1.0\text{ in.})(37{,}500\text{ psi}) = 28{,}125\text{ lb}$$

Since four bolts are used to resist the load of 6,000 lb (max), the bearing load safety factor is (4)(28,125)/6,000 = 18.8.

The allowable tension stress in Grade 8 bolts is F_t =37.5 ksi. The allowable tension load in one bolt is

$$P_{allow} = A_{one\ bolt}\, F_t = (\pi\ 0.75^2/4\ \text{in}^2)(37{,}500\ \text{psi}) = 16{,}600\ \text{lb}$$

Since two of the four bolts are used to resist the R_2 =12,350 lb reaction load, the safety factor is (2)(16,600)/12,350= 2.7. The four 0.75-in. grade 8 bolts that hold the thrust plate to the I-beam are torqued to 110 ft-lb.

The sonic nozzle is attached to the thrust plate by two 0.5-in-thick steel angle brackets and eight 0.5-in bolts (fig. 74). The line of action of the applied loads (i.e., weight and thrust) is approximately through the bolt centroid which, in turn, is located approximately at the center of gravity; hence the bolts experience combined tension and shear (moments are small and are neglected). The total weight transmitted through this attachment was estimated (above) to be 1,323 lb and the design thrust load is 6,000 lb. It is difficult to estimate precisely how the loads are distributed between the eight bolts but a reasonable worst-case loading is a combined $T/4$ in shear and $W_1/4$ in tension. The allowable shear stress in Grade 8 bolts is F_v =22.5 ksi, hence the allowable load P is then

$$P_{allow} = A_{one\ bolt}\, F_v = (\pi\ 0.5^2/4\ \text{in.}^2)(22{,}500\ \text{psi})=4{,}418\ \text{lb}$$

The shear safety factor is (4,418)/(1,323/4) = 13.4.

The allowable tension stress in Grade 8 bolts is F_t =37.5 ksi. The allowable tension load in one bolt is

$$P_{allow} = A_{one\ bolt}\, F_t = (\pi\ 0.5^2/4\ \text{in.}^2)(37{,}500\ \text{psi}) = 7{,}363\ \text{lb}$$

The tension safety factor is (7,363)/(6,000/4) = 4.9.

The combustion section rides on THK linear bearings Model HSR55HBSS-G (rails are Model HSR55-2580LG-RAIL). The purpose of these linear bearings is to permit the combustion chamber to slide in the thrust direction to allow for the measurement of thrust by an instrumented pipe spool attached between the combustion chamber and the thrust plate. These types of bearings are very good at resisting normal and side loading and moments about any axis (fig. 75). They have relatively low friction in the sliding direction.

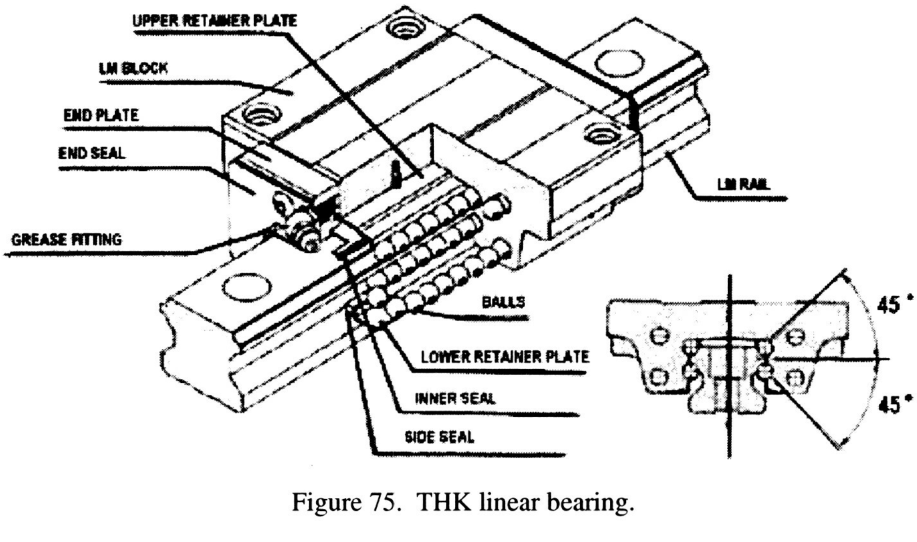


Figure 75. THK linear bearing.

The static permissible loads for the HSR55HBSS-G are shown in the following table:

Lateral moment	375 kgf-m
Torsional moment	375 kgf-m
Rolling moment	494.6 kgf-m
Static normal load	18700 kgf

Under certain failure scenarios, the thrust vector could become misaligned with the axis of the facility by up to 10° as shown in figure 76 (assume 20° to be absolutely certain). This lateral load would be opposed by all four of the HSR bearing pucks. Shown below is a free-body diagram of this situation.

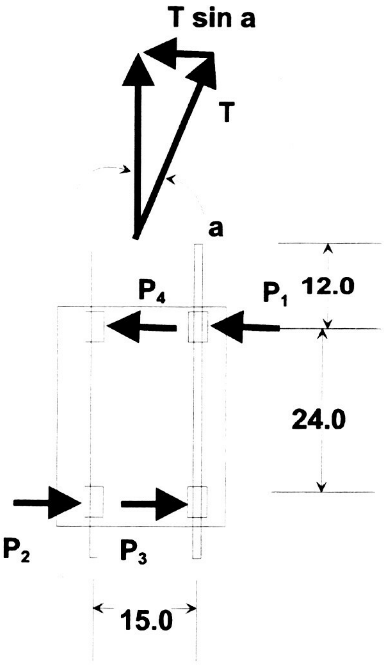


Figure 76. Worst-case linear bearing load.

Consider only the most aft and forward sets of bearings. If the maximum thrust $T = 6{,}000$ lb and $\alpha = 20°$, then the bearing side-loads are

$$P1 = P4 = (T \sin \alpha)/4 + [(24/2+12)/24](T \sin \alpha)/2 = 1{,}539 \text{ lb} = 698 \text{ kgf}$$
$$P2 = P3 = (T \sin \alpha)/4 - [(24/2+12)/24](T \sin \alpha)/2 = -513 \text{ lb} = -232 \text{ kgf}$$

These calculated side loads are a small percentage of the static load rating of the HSR55HB SS bearings (shown in the above table). The bearing normal loads are all approximately the same and are equal to

$$P = T/2\ (28/15) = 5{,}600 \text{ lb} = 2{,}539 \text{ kgf}$$

Hence the linear bearing puck safety factor is 18,700/2,539 = 7.4.

During the HCF IST, a hydraulic jack was used to apply a check load of 5,000 lb to test the structural integrity of the facility. This load simulated a load above the maximum actual thrust load that the facility will ever experience. During this load test, the x-deflection of the thrust plate was measured at the y-location of the thrust vector and found to be only 0.022 in.

Pipe and Valve Supports

The steel piping and valves are supported by using off-the-shelf pipe stanchions manufactured by Piping Technology Inc. The supports are adjustable stanchion supports, some with U-bolts to hold the pipe in place. The U-bolts are not tightened, thus permitting the 3-in. pipe to expand and contract the predicted 0.109 in (maximum longitudinal movement caused by ambient temperature variations) without imposing a significant level of stress. The 3-in. pipe is supported at five points (not including the GOX tank and thrust plate support points) with a separation distance no greater than 7 ft between the supports (substantially less than the maximum allowable of 12 ft for 3-in. steel pipe).

The 0.75-in. steel tube is supported by stands located every 6 ft. The 0.75-in. stainless steel tube, that carries the LOX is suspended by hangers (to permit expansion and contraction) and supported every 6 ft.

CONTROL SYSTEM

A Programmable Logic Controller-based (PLC-based) control system is implemented to control the operation of the LOX pumping process, the GOX delivery system, and the ignition of the fuel. The PLC and accompanying IO blocks are mounted in a rack adjacent to the combustion chamber. The PLC is connected via Ethernet to a PC computer located in the control room that has the HCF Graphical User Interface (GUI). The operating system for this PC is Windows 98. Figure 77 depicts the control system schematically.

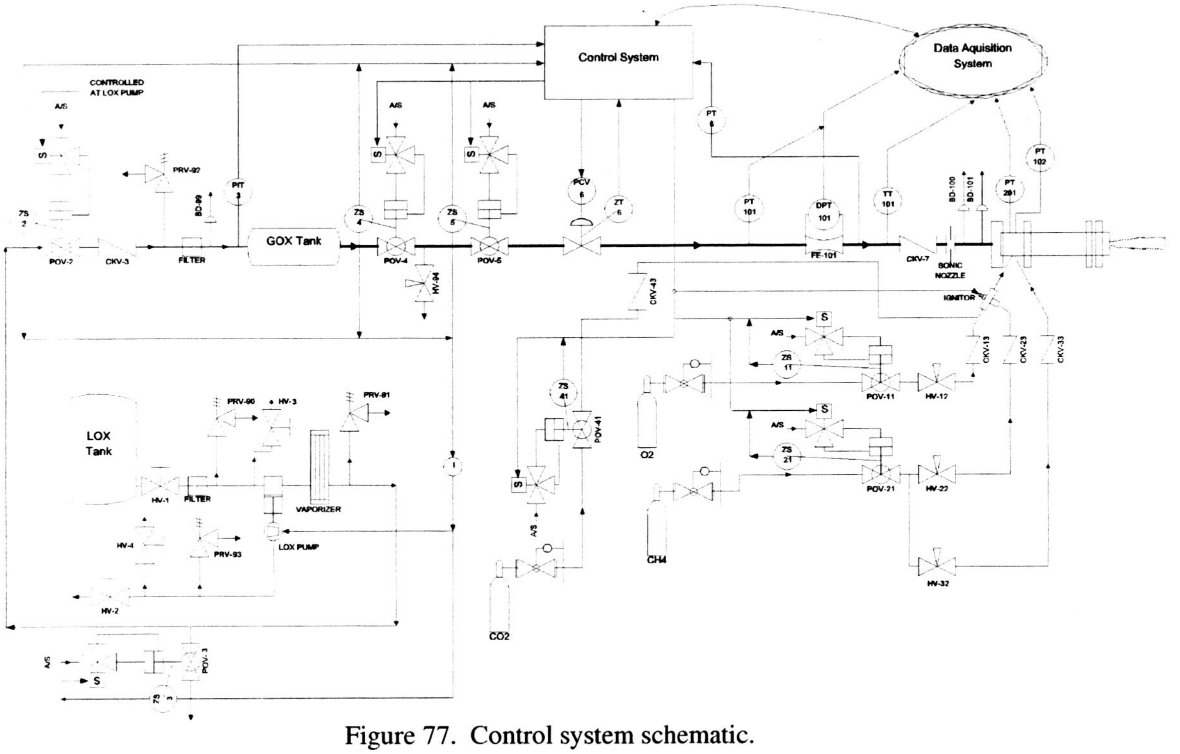


Figure 77. Control system schematic.

Continuous and sequential logic is used to control the combustion facility. Sequential logic follows startup and shutdown sequences, and continuous control strategies are used to maintain constant pressure in the oxygen delivery system.

Control System Hardware

The combustion facility is controlled by a standard industrial PLC General Electric Model 90-30. Operator control and monitoring is by means of a PC running an industrial GUI is a HMI (Human Machine Interface) SCADA software program called Intouch written by Wonderware Corp.

The GE 90-30 CPU was identified as the best fit to operate and control the HCF. This PLC has a relatively low I/O count, is fairly fast, and is capable of relative time stamping of the process variables. It is also Genius block capable and TCP/IP addressable. The main hardware components of the control system are listed in table 38, and figure 78 shows the installation of the control electronics.

Table 38. Control system components.

Name	Part No.	Function	Comments
GE 90-30 CPU	IC693CPU360	PLC	Fastest in series
CPU Baseplate	IC693CHS397		5 I/O slots
Genius Module	IC660BBD022	24 Vdc source in/out	Two of these units are used
Genius Module	IC660BBA020	Analog in/out	24/48 Vdc, 0.5 A max.
Genius Module	IC660BBD101	115 V 60 Hz	15 A max.
Ethernet TCP/IP Module	IC693CMM321		For programming and communication

Table 39 lists the components that the control system interfaces with and the required signals.

Table 39. Primary control system signals.

Component	Signal in	Signal out	Remarks
ASCO solenoid valves for ball shutoff valves POV-2, POV-3, POV-4, POV-5, POV-11, POV-21, and POV-41.	120 Vac	Supply pressure 120-psi max. control air to Bettis actuators	This is the signal required to open the main shutoff valves.
Bettiswitch snap switches enclosure 5R041 ABC WT00 (for POV-4 and POV-5) and Swagelok switch units for POV-2,POV-3, POV-11, POV-21, and POV-41		Provides Contact closures	Signals the valve state (open, closed, or in between).
Moore 760E I to P control valve (PCV-6) positioner	4-20 mA	0 to 150 psi air to control valve (PCV-6) bonnet	Use in PID loop to set GOX pressure in main line.
Rosemount pressure transducers (PT-6 and PIT-3)	Line pressure (0 to 3,000 psi),	4-20 mA	PT-6 is used as feedback in pressure regulation PID loop.
Spark igniter relay	24 Vdc	Contact closure	Used to complete the igniter spark circuit.
Burst-disk sensors BD-99, BD-100, and BD-101		Continuity if not burst	Normally closed switch. Opens when disk blows.

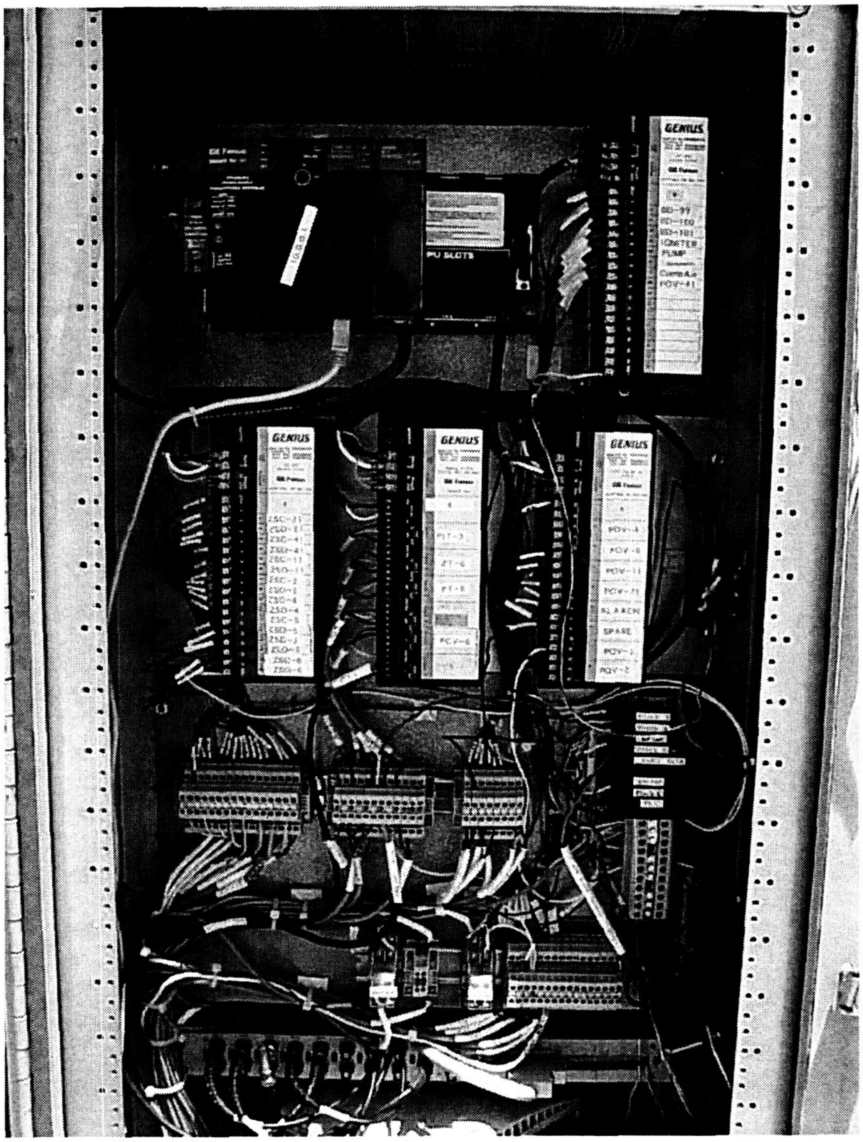


Figure 78. Control system electronics.

The instrumentation required by the control system is used solely for this purpose (no direct tie to the scientific data acquisition system).

A Rosemount Model 1151GP9E2AB2P2 absolute pressure transducer (PT-6) is used to measure the pressure in the 3-in. line upstream of check valve CKV-7. This transducer has a 3,000 MAWP rating and is calibrated to measure pressure levels between 0 and 3,000 psi. The time constant of this transducer is 0.5 sec and the accuracy is ±0.25% of calibrated range. The transducer is filled with an inert liquid, is made of 316 stainless steel, and was supplied cleaned for oxygen service. The 4-20 mA output signal of this transducer is used in a PID feedback loop by the PLC.

A Rosemount Model 1151GP9E2AB2M7P2 absolute pressure transducer (PIT-3) is used to measure the GOX tank pressure. This transducer is similar to PT-6 in all respects with the exception that it has a digital display that displays the GOX tank pressure.

Control System Configuration and Programming

A flowchart of the control system is shown in figure 79.

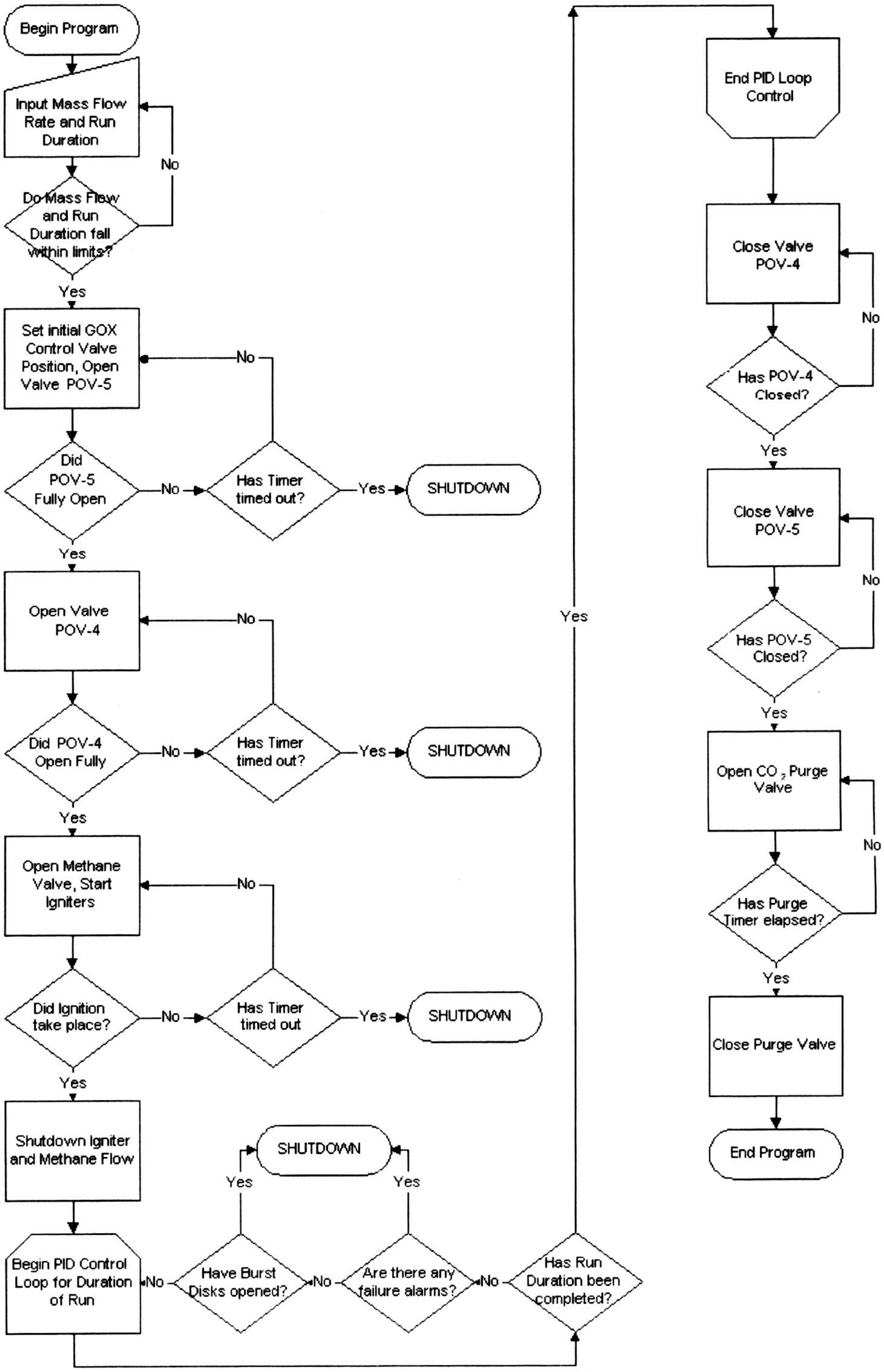
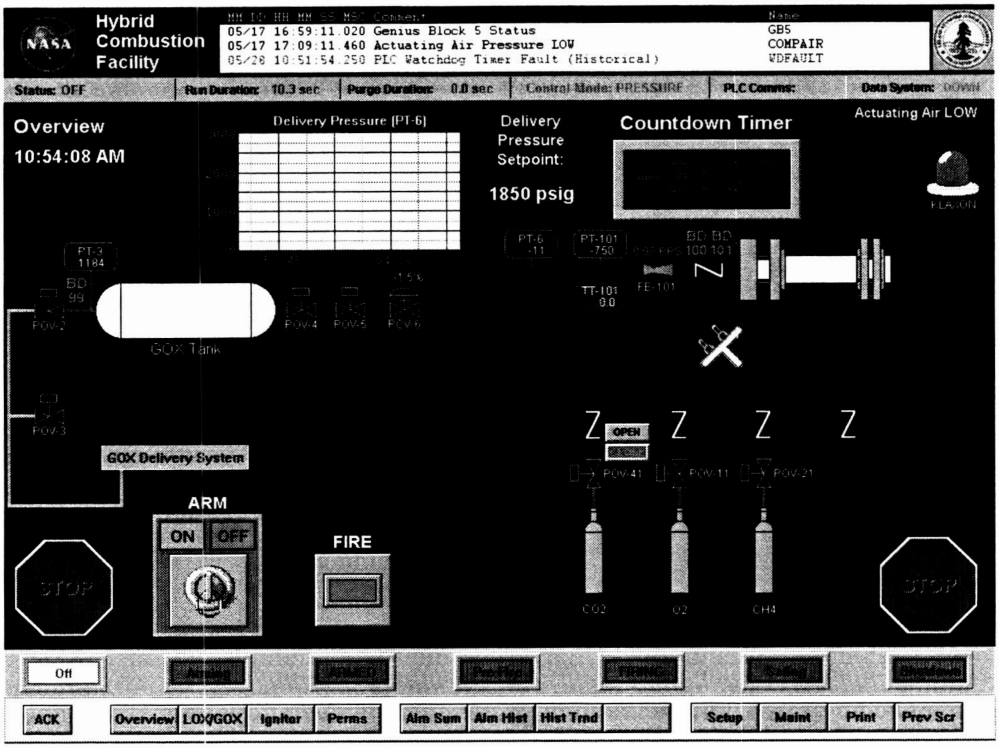


Figure 79. Control system flowchart.

The primary function of the control system is to maintain a constant oxygen delivery pressure while the combustion chamber is in operation. As the GOX tank is depleted during a run, the pressure in this tank drops. Control valve PCV-6 opens to compensate for the GOX tank pressure drop, thereby maintaining a constant oxygen delivery pressure.

The control system GUI has nine screens; the most significant of which are the Set-Up screen and System Overview screen (from which all other screens are accessible). The system overview screen is shown in figure 80.



```
MM DD HH MM SS MSC Comment                                  Name
05/17 16:59:11.020 Genius Block 5 Status                    GB5
05/17 17:09:11.460 Actuating Air Pressure LOW               COMPAIR
05/28 10:51:54.250 PLC Watchdog Timer Fault (Historical)    WDFAULT
```

Status: OFF

Run Duration: 10.3 sec

Purge Duration: 0.0 sec

Control Mode: PRESSURE

PLC Comms:

Data System: DOWN

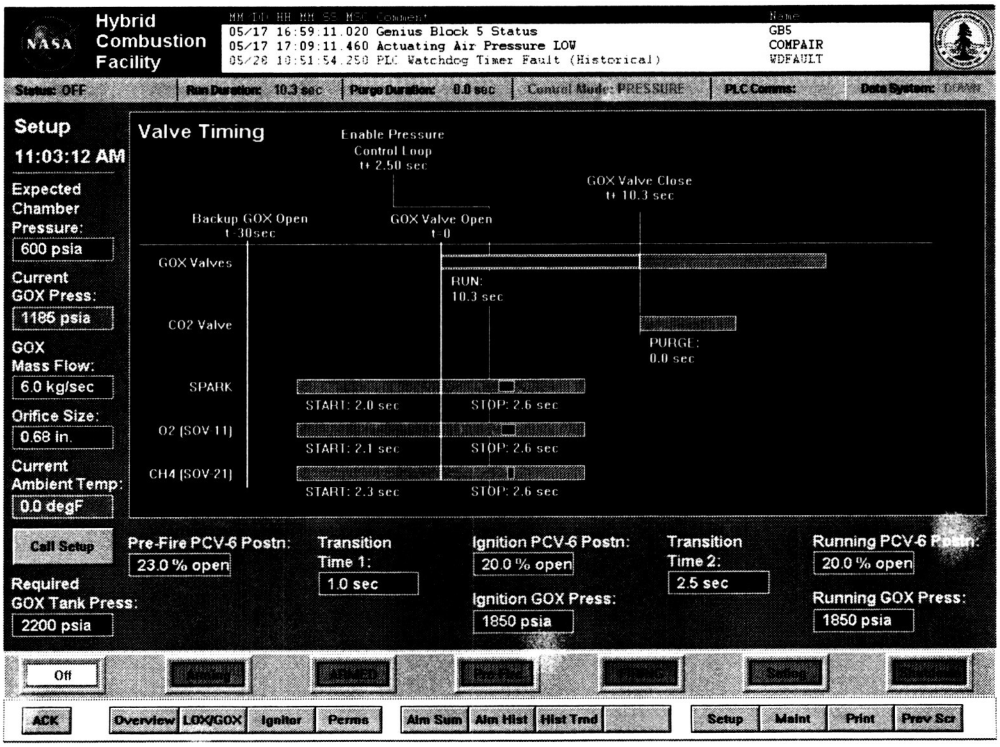
Delivery Pressure Setpoint: 1850 psig

Figure 80. Control system overview screen.

The overview screen loads automatically when the control computer is activated. Using the Overview screen, test-specific variables are set and monitored. Pressure and mass-flow control and operational mode are set on this screen, and valve states, alarms (including burst disks), and the oxygen delivery are monitored. All automated HCF valves can also be operated from this screen when the system is placed in maintenance mode and certain safety conditions are met (e.g., GOX tank not pressurized when attempting to open both POV-4 and POV-5). Open-valve icons are colored red, closed valves are blue, and valves in transition are yellow.

To perform a firing of the facility, (after completion of several preparatory procedures and data entry on the "Setup" screen) the user simply clicks on the key icon and the countdown is initiated starting at 3 min. At 30 sec, there is a built-in. hold that requires the user to click on the "Fire" button to continue the countdown.

Figure 81 shows the Set-Up screen, within which test parameters are specified. Other screens of the control software will reflect the configurations established in this screen.



```
MM/DD HH MM SS MSC Comment                              Name
05/17 16:59:11.020 Genius Block 5 Status                GB5
05/17 17:09:11.460 Actuating Air Pressure LOW           COMPAIR
05/20 10:51:54.250 PLC Watchdog Timer Fault (Historical) WDFAULT
```

Status: OFF | Run Duration: 10.3 sec | Purge Duration: 0.0 sec | Control Mode: PRESSURE | PLC Comms: | Data System: DOWN

Setup 11:03:12 AM

Expected Chamber Pressure: 600 psia

Current GOX Press: 1185 psia

GOX Mass Flow: 6.0 kg/sec

Orifice Size: 0.68 in.

Current Ambient Temp: 0.0 degF

Required GOX Tank Press: 2200 psia

Pre-Fire PCV-6 Postn: 23.0 % open

Transition Time 1: 1.0 sec

Ignition PCV-6 Postn: 20.0 % open

Ignition GOX Press: 1850 psia

Transition Time 2: 2.5 sec

Running PCV-6 Postn: 20.0 % open

Running GOX Press: 1850 psia

Figure 81. Control system set-up screen.

The GOX tank is pressurized by pumping LOX, stored in a large cryogenic tank, through a vaporizer by using a pump especially designed for cryogenic liquids. The pump has the capability to pump 2.2 gal/min with pressures up to 2,900 psi on the discharge side. After a typical run of the combustion facility, the pressure level in the GOX tank will be approximately 85% of the pressure present prior to the run (up to 2,900 psi). High pressure should not be held on the downstream side of the pump for extended periods of time (of the order of days) because the pump has seals that will lose their bubble-tight sealing capability. A remotely operated bleed valve (POV-3) is installed on the pipe downstream of the pump for the purpose of bleeding off the high-pressure GOX. This valve is automatically actuated by the control system upon completion of pumping or by using a button on the control-system GUI.

The control valve range is from 10% to 100% open and is controlled through a PID loop by the PLC. The nozzle-orifice diameter, desired mass-flow, chamber pressure run duration, and ignition parameters are manually entered. The control valve is positioned to the appropriate initial position based on information obtained from an independent modeling computer program that is activated by depressing the "Call Setup" button on the overview screen. .

The HCF can be brought to an immediate shutdown in the event of a system fault or malfunction. An E-STOP can be initiated automatically by the HCF computer, or by the operator, by pushing various E-STOP buttons located in the control room and on the control system rack out on the pad. Specifically, the E_STOP can be activated by depressing a mushroom switch mounted on the side of the control system rack adjacent to the combustion chamber, or by depressing a mushroom switch on a box located on the table next to the control system monitor, or by disconnecting the orange isolation cord that runs between the control room and the control system rack. When an E-STOP is initiated, shutoff valves POV-4 and POV-5 are closed and, if the E-STOP is issued during a firing of the facility, an automatic carbon dioxide purge is initiated. Emergency Response and Evacuation procedures are described in a document entitled "Hybrid Combustion Facility Emergency Response and Evacuation Procedures."

During the IST, approximately 30 control system tuning and test runs were performed using liquid nitrogen. For each run, the GOX tank was pumped up to the desired level (if necessary) and the delivery system was operated. At the end of these trials, a steady oxygen-system delivery pressure (corresponding to that required for a chamber pressure in the range of 300 to 1,000 psi) was achieved across the operation envelope (mass-flow range of 0.5 to 16 kg/sec). Note that these test runs were also used for other purposes such as verifying that relief valves and check valves do not chatter.

INSTRUMENTATION AND DATA ACQUISITION

The instrumentation system used to acquire scientific data during a run of the facility consists of a PC with a high-speed A/D (analog to digital) converter (National Instruments 16-channel, 16-bit, 100-K samples/sec aggregate sampling rate Model PCI-MIO-16XE-10) interfaced with several instruments and controlled by National Instruments Labview software. The PC is located adjacent to the combustion chamber and the monitor and keyboard for this PC are in the control room (connected by an Aten Model CE220L KVM switch). The operating system used by the data acquisition system is Windows NT Workstation 4.0. The baseline measurements, which are logged every run, include a low- and a high-frequency response measurement of chamber pressure, the delivery pressure and temperature, and two independent measurements of the oxygen mass-flow rate (one using the differential pressure measured across a venturi and the second based on the pressure difference measured across the sonic nozzle).

Thermocouple

A thermocouple (fig. 82) designed for high-pressure applications was used. Omega Corporation's pipe-plug probe Model TC-K-NPT-G-72, shown below, is mounted in a Thredolet (Bonny Forge Inc.) on the (3-in. nominal) main gaseous oxygen delivery pipe upstream of the sonic throat for the purpose of measuring the temperature of the oxygen flowing into the combustion chamber. This thermocouple has a maximum temperature rating of 900°F and a pressure rating of 2,500 psi. The thread on the thermocouple probe is 0.25-in. NPT (M). Because of the short length of this probe and the Thredolet (Bonny Forge Inc.) mounting, it will not be exposed directly to the main stream of the oxygen flow (advantageous from an oxygen safety point of view). The thermocouple is grounded and connected to an Omega Model TX91A-K6 temperature transmitter that produces a 0 to 10 Vdc output signal proportional to the temperature.

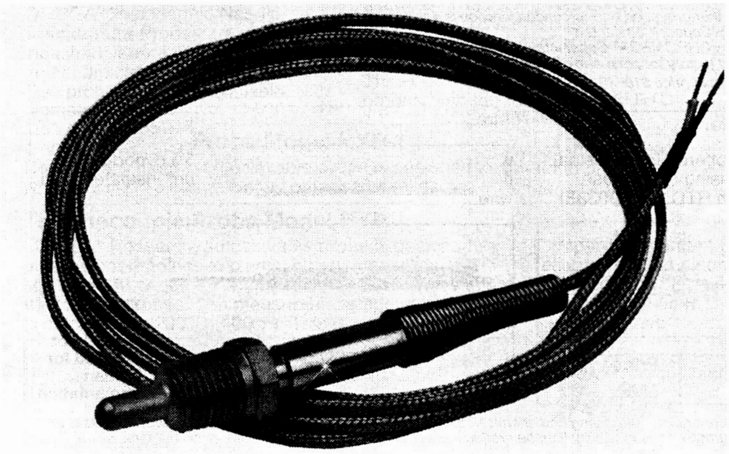


Figure 82. Omega thermocouple.

Differential Pressure Transducer DP-1

The differential pressure generated by the ASME Venturi (FE-101) is measured by a differential pressure transducer DPT-1 that is plumbed between the pressure tap at the throat and the tap upstream of the throat. This transducer has a 2,000 MAWP rating. The Rosemount Model 1151DP5M2AB2P2P4P8 is an inert-fluid-filled differential pressure transducer that is capable of withstanding high static pressure (up to 2,000 psi) and responding to differential pressure within a range of 750 in. H_2O (30 psi). The time constant of this transducer is 0.5 sec and the accuracy is ±0.2% of calibrated range. The transducer is made of 316 stainless steel filled with an inert liquid and it was supplied cleaned for oxygen service. The output is 1 to 5 Vdc and the pressure line connections are NPT (F).

Kistler Pressure Transducer

An absolute Kistler pressure transducer (fig. 83) is used to measure the combustion chamber pressure through a pressure tap in the wall of the precombustion chamber. The chosen transducer is a Kistler Model 601B1 gauge with a range of 0 to 15,000 psi, a maximum pressure of 18,000 psi, and maximum temperature rating of 500°F.

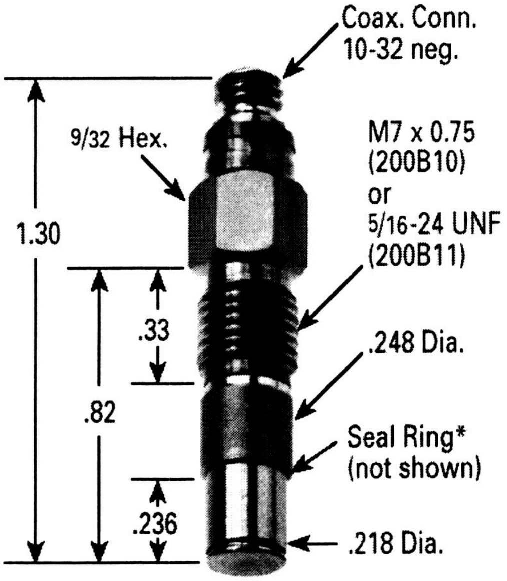


Figure 83. Kistler dynamic pressure transducer (KPT 1).

Pressure Transducer PT-102

A Rosemount Model 1151GP9M2AB2P2 (1 to 5 Vdc, output) is hooked up to a pressure tap in the precombustion chamber. This transducer has a range of 3,000 psi and is similar to PIT-3 (except for the digital display).

Thrust Measurement

At some point in the future, it may become desirable to measure the thrust force created by the combustion process. In general, for any air-breathing or rocket propulsion system, accurate thrust-force measurements are difficult to achieve. In the original design of the HCF, provisions were made to obtain thrust-force measurements. The combustion chamber was mounted on linear bearings and a pipe spool, specifically designed with thrust-force measurements in mind, was included. The original plan was that the thrust force produced by the combustion chamber would be measured using a strain-gauged pipe spool (3-in. schedule 160 stainless steel pipe) mounted between the sonic nozzle holder and the precombustion chamber (fig. 84). As will be seen in the following paragraphs, the force experienced by the pipe spool in not solely the thrust force, and additional measurements (i.e., the pressure inside the pipe spool) must be made in order to obtain the thrust.

The resolution requirements for the thrust measurement are fairly demanding. During the course of the current measurement program, the thrust level has varied between 1,000 and 4,000 lb. Typical chamber pressure fluctuations are between 2% and 8% rms of the mean. To properly resolve the expected thrust fluctuations for low-thrust cases, the resolution of the system should be at least one-fifth of the minimum thrust fluctuation or (0.02)(1,000 lb)/5 = 4 lb.

In order to explore the design of a thrust measurement system, it is useful to choose a baseline case. A good baseline case is one that produces $F = 4{,}000$ lb of thrust. Considering a segment of 3-in. schedule 160 pipe clamped at one end with the thrust force of 4,000 lb acting axially on the other end, a crossectional area of A, and a modulus of elasticity E (with no internal pressure for the time being), the axial stress σ and the increment in axial strain ε are

$$\begin{aligned}\sigma &= F / A \\ &= 4{,}000 \text{ lb} / [\pi\ (3.5^2 - 2.626^2)/4.0 \text{ in}^2] \\ &= 951 \text{ psi}\end{aligned}$$

$$\begin{aligned}\varepsilon &= \sigma / E = F / (A\ E\ ) \\ &= 4{,}000 \text{ lb} / \{[\pi\ (3.5^2 - 2.626^2)/4.0 \text{ in}^2]\ (29.0 \times 10^6 \text{psi})]\} \\ &= 33 \times 10^{-6} \text{ in/in}\end{aligned}$$

Typically, traditional foil strain gauges in conjunction with accurate Wheatstone bridge instrumentation can resolve down to 1 x 10^{-6} in/in of strain (in a full-bridge setup). The claim by Vishay Inc. is that their Model 3800 can resolve down to 0.1 x 10^{-6} in/in (corresponding thrust load resolution is 12 lb). So even using the best traditional strain gauge instrumentation, the resolution is insufficient.

The sensitivity of the measurement can be increased by using a pipe spool that has a thinner wall. This is possible because the MAWP of this portion of the facility is 2,200 psi and the pipe spool is made of schedule 160 pipe that can withstand a much higher pressure level. If the pipe spool had an o.d. of 3.1 in. and an i.d. of 2.626, following ASME B31.3, the minimum wall thickness required for the 3-in. nominal A312 F304 pipe spool can be determined from

$$\begin{aligned}t_m &= P\ D / [2\ (S\ E + P\ y)] \\ t_m &= (2{,}200 \text{ psi})(3.1 \text{ in.}) / [2\ (20{,}000 \text{ psi} \times 1.0 + 2{,}200 \text{ psi } \times 0.4)] \\ t_m &= 0.163 \text{ in.}\end{aligned}$$

In the above equation, $P = 2{,}200$ psi (the MAWP), $D = 3.1$ in., $S = 20{,}000$ psi, $E = 1.0$ (for seamless pipe), and $y = 0.4$ resulting in a $t_m = 0.163$ in. Inclusion of a 0.875 wall tolerance leads to a minimum wall thickness of 0.187. So a wall thickness of 0.237 in. is satisfactory. The axial stress that would develop in the pipe from a 4,000 lb thrust load would be $\sigma = 4{,}000 \text{ lb}/[\pi\ (3.1^2 - 2.626^2)/4.0 \text{ in}^2] = 1{,}876$ psi and the strain is $\varepsilon = P / (A\ E\ ) = 4{,}000 \text{ lb} / \{[\pi\ (3.1^2 - 2.626^2)/4.0 \text{ in}^2]\ (29.0 \times 10^6 \text{psi})]\} = 65 \times 10^{-6}$ in/in. The 6-lb resolution of this system is marginal and not a significant gain over that of the o.d. = 3.5-in. pipe and so use of a thinner-walled pipe will not be pursued.

Semiconductor strain gauges have sensitivities that are 100 times greater than foil gauges, but their sensitivity to temperature is greater than foil gauges and also their response is more nonlinear. The nonlinearity can be handled by a multipoint calibration and application of a higher-order data reduction scheme. The temperature effects can be corrected by measuring the temperature using a thermocouple or an RTD temperature sensor.

Regardless of the strain measurement technique chosen, the oxygen that flows through the pipe spool has momentum that must be accounted for in order to obtain an accurate total thrust measurement. Considering the baseline case, if the oxygen mass-flow rate through the pipe spool is 8 kg/sec, the combustion chamber pressure is 1,000 psi, the oxygen-to-fuel ratio is 2.4, the throat diameter is 1.45 in. (convergent nozzle only), and the adiabatic flame temperature of 6,357°R is equal to T_{throat}, the total thrust F produced by the facility is

$$\begin{aligned} \dot{m}_{out} &= \dot{m}_{GOX}(1+1/OF) \\ &= (8\ \text{kg/sec})(2.204\ \text{lb}_m/\text{kg}) \times (1+1/2.4) \\ &= 24.98\ \text{lb}_m/\text{sec} \end{aligned}$$

$$\begin{aligned} v_{throat} &= M\,[\gamma R g_c T_{throat}]^{1/2} \\ &= (1.0)[1.164 \times 69.7 \times 32.2 \times 6{,}357]^{1/2} \\ &= 4{,}075\ \text{ft/sec} \end{aligned}$$

$$\begin{aligned} F &= \dot{m}_{out}\, v_{throat} + (p_{throat} - p_a)\, A_{throat} \\ &= \dot{m}_{out}\, v_{throat} + (0.528 p_r - p_a)\, A_{throat} \\ &= [(24.98 \times 4{,}075)/32.2] + (0.528 \times 1{,}000 - 14.7) \times 144 \times 0.0115 \\ &= 3{,}161.3 + 850.0 \\ &= 4{,}000\ \text{lb (for converging nozzle only)} \end{aligned}$$

where:

$\dot{m}_{GOX}$ = oxygen mass-flow rate, (lb_m/sec)
$\dot{m}_{out}$ = total mass-flow rate, (lb_m/sec)
OF = oxygen-to-fuel mass-flow ratio (approximately = 2.4)
F = thrust force (lb)
M = Mach number = 1.0 at throat
γ = ratio of specific heats of combustion products (computed by a chemistry code) = 1.164
$\dot{m}$ = total mass-flow rate, (lb_m/sec)
R = gas law constant = R_u/MW = (1,544.0 ft-lb/mole °R)/(22.13) = 69.7 ft lb_f/lb_m °R
v_{throat} = exhaust nozzle throat flow velocity (ft/sec)
p_r = static pressure in the combustion chamber (psi)
p_{throat} = static pressure at exhaust nozzle throat (psi)
T_{throat} = assumed equal to adiabatic flame temperature computed by a chemistry code (°R)
p_a = ambient pressure, (lb/ft^2) = 2,117 lb/ft^2
A_{throat} = exhaust nozzle throat area, (ft^2) = $\pi\,(1.45\ \text{in}/2)^2/144 = 0.0115\ \text{ft}^2$

The force T transmitted to the thrust plate by the pipe spool can be determined through consideration the free-body diagram shown in figure 84.

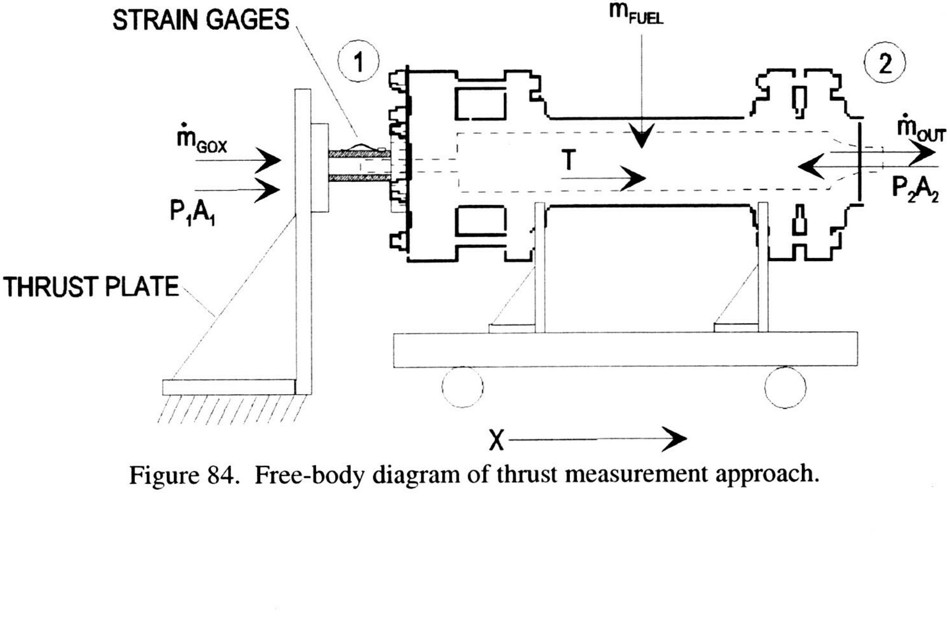


Figure 84. Free-body diagram of thrust measurement approach.

Considering stations 1 and 2 and if p is pressure, A is corsectional area, $\dot{m}$ is mass-flow rate, and v is velocity, application of conservation of momentum results in

$$p_1A_1 - (p_2 - p_a)A_2 + T = (\dot{m}_{GOX} + \dot{m}_{fuel})\, v_2 - (\dot{m}_{GOX})\, v_1$$

For a purely convergent nozzle, conditions at station 2 are throat conditions and noting that the total mass-flow out $\dot{m}_{out} = \dot{m}_{GOX} + \dot{m}_{fuel}$ therefore,

$$p_1A_1 + T = \dot{m}_{out}\, v_{throat} - (\dot{m}_{GOX})\, v_1 + (p_{throat} - p_a)A_{throat}$$

From the above, the total thrust produced is

$$F = \dot{m}\; v_{throat} + (p_{throat} - p_a)\, A_{throat}$$

After substituting in, the force measured in the pipe spool (T), the total thrust force F can be determined as a function of the force in the pipe spool, and the velocity, mass flow, and pressure in the pipe:

$$p_1A_1 + T = F - (\dot{m}_{GOX})v_1$$
$$F = T + (\dot{m}_{GOX})\, v_1 + p_1A_1$$
$$4{,}000 \text{ lb} = \text{T} + [(8 \text{ kg/sec})(2.204 \text{ lb}_m/\text{kg}) / 32.2]\, v_1 + (1{,}000 \text{ psi})\, (\pi\, 2.626^2/4 \text{ in}^2)$$
$$4{,}000 \text{ lb} = T + 0.548\, v_1 + 5{,}416 \text{ lb}$$

This is an interesting result, because it demonstrates that the pipe spool is in tension (T must be negative) when GOX is flowing through the pipe spool. In addition, this relation demonstrates that in addition to the strain in the pipe spool (caused by T) the pressure in the pipe, the GOX mass-flow rate and velocity must be measured to determine the total thrust F. Alternatively, since we have an accurate measurement of $\dot{m}_{GOX}$ (as measured using the sonic orifice), using continuity and the equation of state, the above equation can be written (note T_1 is temperature):

$$F = T + (\dot{m}_{GOX})\, v_1 + p_1A_1$$
$$F = T + (\dot{m}_{GOX})^2 R\, T_1 / p_1A_1 + p_1A_1$$

So to measure the total instantaneous thrust, the static pressure, the temperature of the GOX in the pipe spool, and the GOX mass-flow rate must be measured in addition to the pipe spool strain. These are quantities that can be measured to ± 0.5%, so the total measurement uncertainty will be 0.72% of the thrust force for the $F = 4{,}000$ lb baseline case.

Additional concerns are that the pipe spool will experience stress caused by the internal oxygen pressure and also (possibly) stress caused by temperature variations in addition to the stress caused by the thrust force. The solutions of two well-known linear problems in elasticity, namely that of a thick-walled cylinder under pressure and that of an axially-loaded cylinder, can be superimposed to obtain the strain in the pipe spool (fig. 85).

Since this spool is between the sonic nozzle and the GOX injector, the maximum internal pressure expected during a run is slightly higher than the chamber pressure (maximum of 1,200 psi). The stress in a pipe wall has three components (note that compressive stress is negative, tensile stress is positive) and for a thick-walled, axially unconstrained pipe and at the exterior surface ($r=b$), they are given by the following:

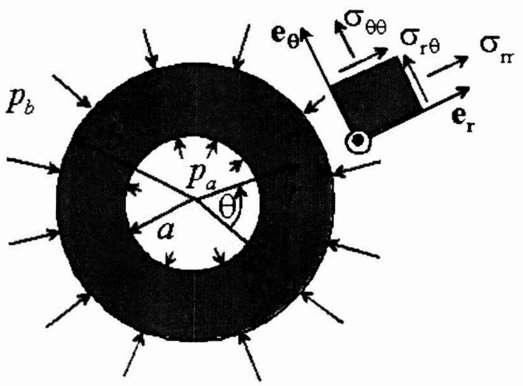


Figure 85. Pipe under internal and external pressure.

$$\sigma_{rr} = (p_a a2\text{-}p_b b^2)/(b^2 - a^2) - a^2b^2(p_a - p_b)/[(b^2 - a^2)r^2]$$
$$=[(1{,}000\text{ psi})(1.313\text{ in})^2 - (14.7\text{ psi})(1.75\text{ in})^2]/ (1.75^2\text{-}1.313^2) - (1.313^2)(1.75^2)(1{,}000\text{-}14.7)/[(1.75^2\text{-}1.313^2)(1.750^2)]$$
$$= -14.7\text{ psi (compressive)}$$

$$\sigma_{\theta\theta} = (p_a a2\text{-}p_b b^2)/(b^2 - a^2) + a^2b^2(p_a - p_b)/[(b^2\text{-}a^2)r^2]$$
$$=[(1{,}000\text{ psi})(1.313\text{ in})^2 - (14.7\text{ psi})(1.75\text{ in})^2]/ (1.75^2\text{-}1.313^2) + (1.313^2)(1.75^2) (1{,}000\text{-}14.7)/[(1.75^2\text{-}1.313^2)(1.750^2)]$$
$$= 2{,}523.4\text{ psi (tensile)}$$

$$\sigma_{zz} = 2\nu\ (p_a a2\text{-}p_b b^2)/(b^2 - a^2)$$
$$= (2)(0.29)\ [(1{,}000\text{ psi})(1.313\text{ in})^2 - (14.7\text{ psi})(1.75\text{ in})^2]/ (1.75^2\text{-}1.313^2)$$
$$=727.5\text{ psi (tensile)}$$

The corresponding strain field is

$$\varepsilon_{rr} = (1+ \nu)a^2b^2/[E(b^2 - a^2)]\{-(p_a \text{-}p_b)/r^2 + (1 - 2\nu)\ (p_a a^2 - p_b b^2)/(a^2b^2)\}$$
$$=\{(1 + 0.29)\ (1.313^2)(1.75^2)/[(29\times 10^6\text{ psi})\ (1.75^2\text{-}1.313^2)]\}\{-(1{,}000\text{-}14.7)/1.750^2 + [1 - (2)(0.29)]\ [(1{,}000)(1.313)^2 - (14.7)(1.75)^2]/ [(1.75^2)(1.313^2)]\}$$
$$=-33.0 \times 10^{-6}\text{ in/in}$$

$$\varepsilon_{\theta\theta}= (1+ \nu)a^2b^2/[E(b^2 - a^2)]\{(p_a \text{-}p_b)/r^2 + (1 - 2\nu)\ (p_a a^2 - p_b b^2)/(a^2b^2)\}$$
$$=\{(1 + 0.29)\ (1.313^2)(1.75^2)/[(29\times 10^6\text{ psi})\ (1.75^2\text{-}1.313^2)]\}\{(1{,}000\text{-}14.7)/1.750^2 + [1 - (2)(0.29)]\ [(1{,}000)(1.313)^2 - (14.7)(1.75)^2]/ [(1.75^2)(1.313^2)]\}$$
$$= 79.9 \times 10^{-6}\text{ in/in}$$

$$\varepsilon_{zz} = -[2\nu/E]\ (p_a a2\text{-}p_b b^2)/ (b^2 - a^2)$$
$$=-[(2)(0.29)/ (29\times 10^6\text{ psi})]\ [(1{,}000\text{ psi})(1.313\text{ in})^2 - (14.7\text{ psi})(1.75\text{ in})^2]/ (1.75^2\text{-}1.313^2)$$
$$=-25.1 \times 10^{-6}\text{ in/in}$$

for a 3-in. schedule 160 pipe at P_a=internal pressure = 1,000 psi, where E = 29×10^6 psi, ν =0.29 for F304 stainless steel, a = 1.313 in., b = 1.750 in. b/a = 1.333, and P_b = external pressure = 14.7 psi.

A cylinder axially loaded in compression by a force of $T = 4{,}000$ lb has the following Cartesian strain components (note that $\sigma_{xx} = \sigma_{yy} = 0$):

$$\varepsilon_{zz} = \sigma_{zz}/E$$
$$\varepsilon_{xx} = -\nu\sigma_{zz}/E$$
$$\varepsilon_{yy} = -\nu\sigma_{zz}/E$$

In a polar-cylindrical basis, the stress components are

$$\begin{aligned} \varepsilon_{rr} &= \nu\sigma_{zz}/E \\ &= \nu\{T/[\pi(b^2 - a^2)/4]\}/E \\ &= (0.29)\{4{,}000 \text{ lb}/[\pi(1.75^2 - 1.313^2)]\}/(29\times 10^6 \text{ psi}) \\ &= 9.5 \times 10^{-6} \text{ in/in} \end{aligned}$$

$$\begin{aligned} \varepsilon_{\theta\theta} &= \nu\sigma_{zz}/E \\ &= \nu\{T/[\pi(b^2 - a^2)/4]\}/E \\ &= (0.29)\{4{,}000 \text{ lb}/[\pi(1.75^2 - 1.313^2)]\}/(29\times 10^6 \text{ psi}) \\ &= 9.5 \times 10^{-6} \text{ in/in} \end{aligned}$$

$$\begin{aligned} \varepsilon_{zz} &= \sigma_{zz}/E \\ &= -T/[\pi(b^2 - a^2)/4]/E \\ &= \{-4{,}000 \text{ lb}/[\pi(1.75^2 - 1.313^2)]\}/(29\times 10^6 \text{ psi}) \\ &= -32.8 \times 10^{-6} \text{ in/in} \end{aligned}$$

Hence for this case, the axial strain ε_{zz} arising from the internal pressure is approximately 80% of the axial stress caused by the thrust load, but fortunately it is of the same sign. The effect of this on the thrust measurement approach is that the axial strain caused by the internal pressure will be subtracted from the total measured strain and then the thrust will be computed. The procedure is as follows:

1. Measure ε_{rr} and $\varepsilon_{\theta\theta}$ using a strain gauge rosette mounted at the midpoint exterior surface of the pipe spool (fig. 86).
2. Measure p_1 and T_1 in the pipe spool.
3. Determine T from the strain measurements using p_1 (same as p_a above).
4. Knowing $\dot{m}_{GOX}$ from the pressure differential across a sonic orifice measurements, compute the thrust force F using $F = T + (\dot{m}_{GOX})^2 R\, T_1/p_1A_1 + p_1A_1$

A further complication is that the oxygen flow may cool the pipe spool, which is located just downstream of the sonic nozzle. This effect can be measured and compensated for.

The result of this analysis is that a direct measurement of thrust is problematic and will probably not be undertaken in the future.

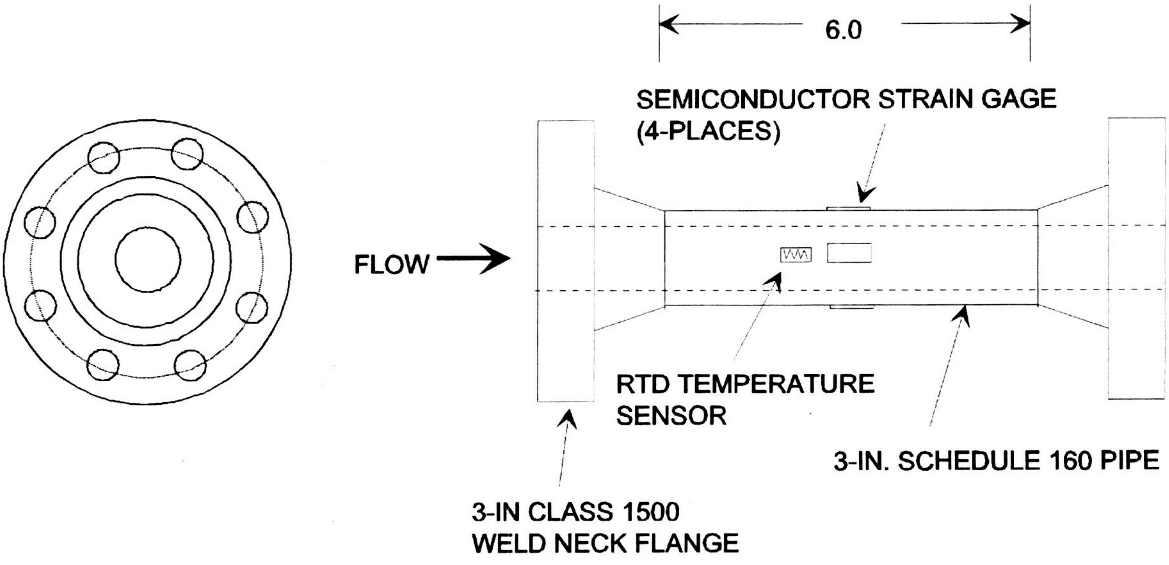
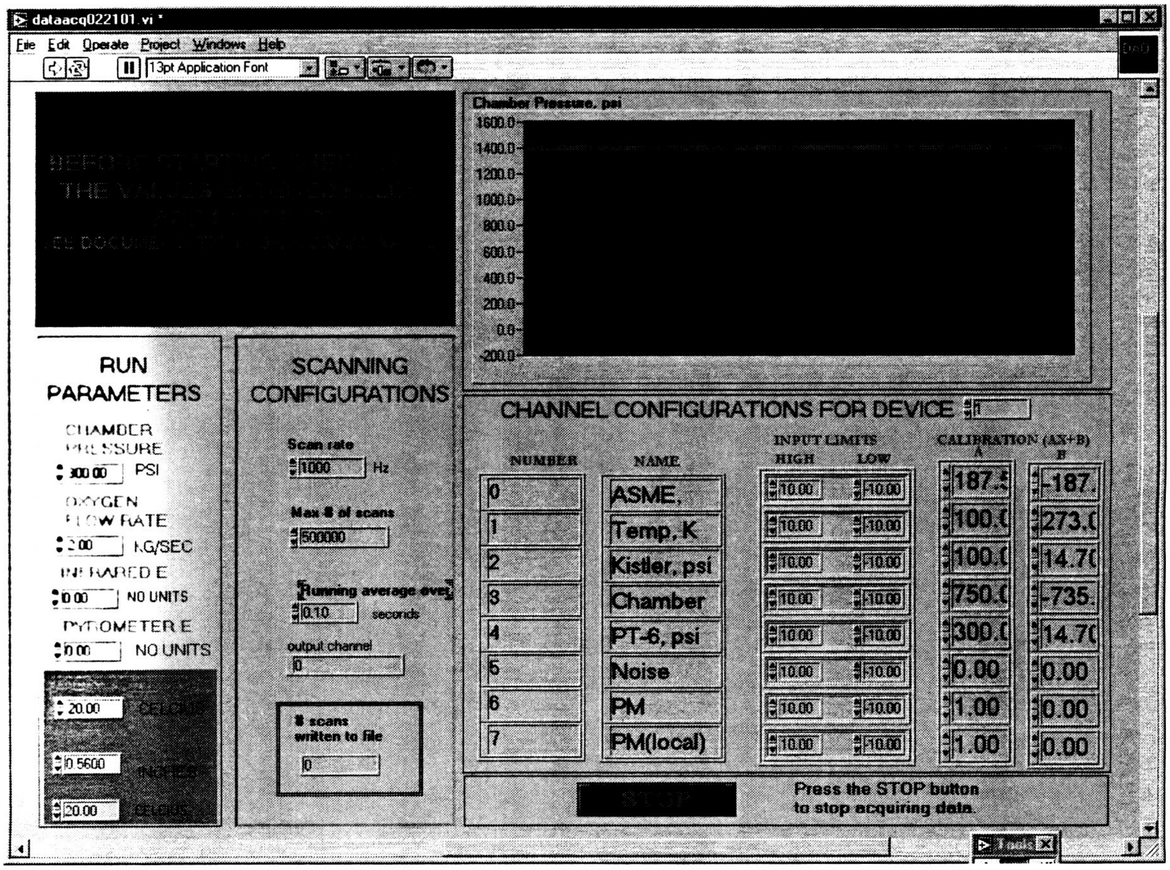


Figure 86. Thrust measurement approach.

Data Acquisition Software

The main screen of the Labview-based data acquisition is shown in figure 87.



RUN PARAMETERS

CHAMBER PRESSURE: 300.00 PSI
OXYGEN FLOW RATE: 2.00 KG/SEC
INFRARED E: 0.00 NO UNITS
PYROMETER E: 0.00 NO UNITS
20.00 CELCIUS
0.5600 INCHES
20.00 CELCIUS

SCANNING CONFIGURATIONS

Scan rate: 1000 Hz
Max # of scans: 500000
Running average over: 0.10 seconds
output channel: 0
scans written to file: 0

CHANNEL CONFIGURATIONS FOR DEVICE 1

NUMBER	NAME	INPUT LIMITS HIGH	INPUT LIMITS LOW	CALIBRATION (AX+B) A	CALIBRATION (AX+B) B
0	ASME,	10.00	-10.00	187.	-187.
1	Temp, K	10.00	-10.00	100.	273.
2	Kistler, psi	10.00	-10.00	100.	14.7
3	Chamber	10.00	-10.00	750.	-735.
4	PT-6, psi	10.00	-10.00	300.	14.7
5	Noise	10.00	-10.00	0.00	0.00
6	PM	10.00	-10.00	1.00	0.00
7	PM(local)	10.00	-10.00	1.00	0.00

Press the STOP button to stop acquiring data.

Figure 87. Data acquisition graphical user interface.

ELECTRICAL

All electrical connections comply with the following codes as specified in the AHB 1700.1 (ref. 7):

1. Occupational Safety and Health Act: The Act covers conditions, practices, and operations to ensure safe and healthful work places.

2. National Electrical Code published by the National Fire Protection Association (NFPA-70): This standard covers the requirements of a safe design, installation, repair, and maintenance of electrical systems in residential and industrial facilities.

3. National Electrical Manufacturers Association (NEMA): These standards cover electrical power equipment including standard ratings, performance, testing, manufacturing, and marking.

4. Electronics Industries Association (EIA): These standards cover electronic-type electrical equipment and components.

Bulk oxygen installations are not hazardous (not so classified) locations as defined and covered in Article 500 of NFPA 70 (1993). Therefore, general purpose or weatherproof types of electrical wiring and equipment are acceptable. Such equipment has been installed in accordance with the applicable provisions of NFPA 70 (1993). The specific electrical connections to the facility include the following:

1. Moore 760E control valve (PCV-6) positioner
2. Bettis shutoff-valve actuators (pressure switches)
3. Valve limit switches for the GOX, methane, and carbon dioxide K-bottle lines.
4. Rosemount pressure transducers
5. Solenoid valves that control the pneumatic valves
6. GOX system thermocouple
7. Kistler pressure transducer
8. LOX pump (230 Vac, 3-phase)
9. Burst disk sensors

All conduit is rigid, galvanized, threaded conduit with the exception of some short flexible runs to components. Only weatherproof conduit connections have been made. The layout of the electrical lines and the conduit routes are shown in figures 88 and 89.

The Moore positioner is housed in a NEMA 4 enclosure. It requires a 4-20 mA signal that is routed from the NEMA 4 instrument cabinet that houses the PLC through a conduit. The main GOX shutoff valves POV-4 and POV-5 require 120 Vac for the ASCO solenoid valves that control the Bettis actuators. Likewise, these cables are routed from the NEMA 4 instrument cabinet that houses the PLC through a conduit. The solenoid shutoff valves POV-3, POV-4, POV-5, POV-11, POV-12, POV-31, and POV-41 require 120 Vac that is carried to these valves through a conduit.

The Rosemount pressure transducers requires an excitation voltage of 24 to 32 Vdc and produce an output in the range of 1 to 5 Vdc. The conduit connection is 0.75 in. The output from the pressure transducer is carried in a weatherproof conduit to the control cabinet. The thermocouple has a requirement for a Wheatstone bridge signal-conditioner box (requires 110 Vac). This unit is located in a weatherproof enclosure approximately 5 m away from the 3-in. GOX pipeline. The output from the signal conditioner is carried in a weatherproof conduit to the control cabinet.

The Kistler pressure transducer requires a charge amplifier. This amplifier is mounted in a weatherproof enclosure (same as that for the thermocouple) that is located within 5 m (cable length) of the

Kistler transducer. The coaxial cable carries a very low-voltage, low-current signal from the transducer and amplifies it to ±10 mV, ±5mA. The cable has a special thread-on connector on the transducer end and a BNC connector on the charge amplifier end. The output signal from the charge amplifier is carried in a weatherproof conduit to the control cabinet.

The LOX pump control panel is remotely mounted in a NEMA 3R enclosure. It has a combination motor starter and low-voltage control transformer, a high-pressure switch/gauge combination, local control, and running time meters. The motor power lines run from the control panel, which is located approximately 30 ft from the LOX pump. The motor that drives the LOX pump is a 3-phase 10 hp motor; the current requirements are approximately 25 A. The pressure gauge switch leads runs in a separate weatherproof conduit. A wiring list is provided in table 40.

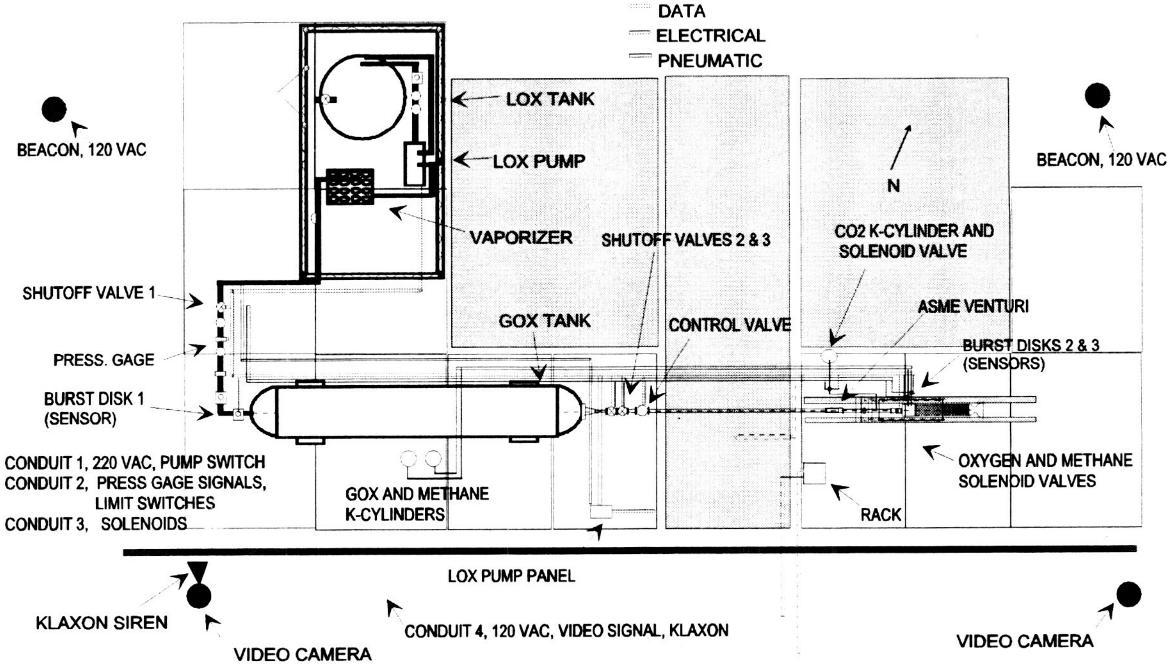


Figure 88. Data, electrical, and pneumatic lines.

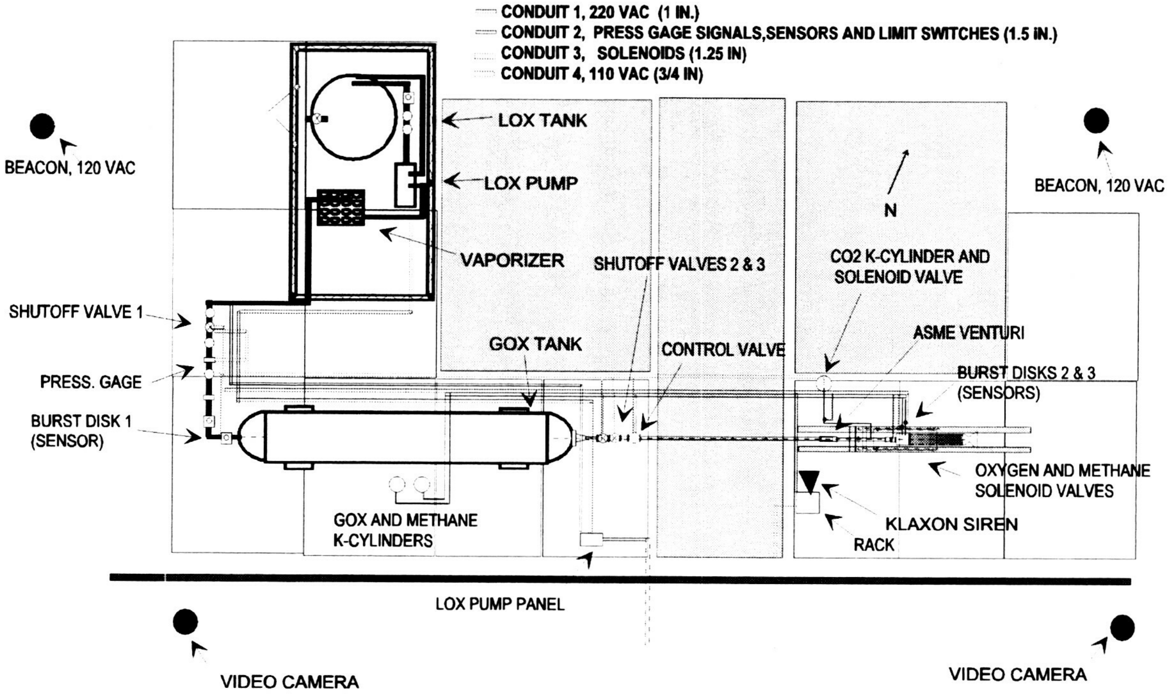


Figure 89. Conduit routes.

Table 40. Wiring list.

Component Designation	Control System Designation	Function	Manufacturer Part No.	Volts	Max Current, A	WireType	No. of Conductors	Wire Gauge	Conduit No.	Conduit Connect Type
CO_2 system solenoid valve	SV-14		ASCO 8300G58F	120 Vac	2		3	16	3	½
Methane (igniter) solenoid valve	SV-10		ASCO 8300G58F	120 Vac	2		3	16	3	½
Methane (igniter) solenoid valve	SV-12		ASCO 8300G58F	120 Vac	2		3	16	3	½
Oxygen (igniter) solenoid valve	SV-8		ASCO 8300G58F	120 Vac	2		3	16	3	½
Shutoff Valve POV-2 solenoid valve	POV-2		ASCO 8262G1	120 Vac	0.6		3	16	3	½
Shutoff Valve POV-4 solenoid valve	POV-4		ASCO 8344G72	120 Vac	0.6		3	16	3	½
Shutoff Valve POV-5 solenoid valve	POV-5		ASCO 8342G3	120 Vac	1.2		3	16	3	½

Component Designation	Control System Designation	Function	Manufacturer Part No.	Volts	Max Current, A	WireType	No. of Conductors	Wire Gauge	Conduit No.	Conduit Connect Type
CO_2 system limit switch	SV-14		Honeywell	24 Vdc			4	20	2	¾
Methane (igniter) limit switch	SV-10		Honeywell	24 Vdc			4	20	2	¾
Methane (igniter) limit switch	SV-12		Honeywell	24 Vdc			4	20	2	¾
Oxygen (igniter) limit switch	SV-8		Honeywell	24 Vdc			4	20	2	¾
Shutoff Valve POV-2 limit switch	POV-2		Honeywell	24 Vdc			4	20	2	¾
Shutoff Valve POV-4 limit switch	POV-4		Bettis	24 Vdc			8	20	2	¾
Shutoff Valve POV-5 limit switch	POV-5		Bettis	24 Vdc			8	20	2	¾
Control Valve PCV-6	PCV-6		Moore 760E		4-20 mA		3		2	
			Moore 760E Limit Switches	24 Vdc			4	20	2	
	ZT-6	control Valve (PCV-6) position feedback	Moore 760E		4-20 mA	Shielded twisted pair	2	20	2	
Data Acq. Diff. Pressure Transducers	DPT-101	For ASME Venturi (FE-101)	Rosemount 1151DP5M2AB 2P2P4P8	1 to 5 V			2		2	½
Control System. Pressure Transducers	PT-6	Static pressure upstream of venturi	Rosemount 1151GP9E2AB 2P2		4-20 mA	Shielded Twisted Pair	2		2	½
Data Acq. Pressure Transducers	PT-101	Static pressure upstream of venturi	Rosemount 1151GP9M2AB 2P2	1 to 5 V			2		2	½

Component Designation	Control System Designation	Function	Manufacturer Part No.	Volts	Max Current, A	WireType	No. of Conductors	Wire Gauge	Conduit No.	Conduit Connect Type
Control System Pressure Transducers	PT-3 and PI	Measures and displays GOX tank pressure	Rosemount 1151GP9E2AB 2M7P2		4-20 mA	Shielded Twisted Pair	2		2	½
LOX Pump			ACD WDPD	230 3Ø	25	Power	3 + gnd	8	1	3/4
Video Camera		Survelliance	Panasonic	120 Vac	25 mA			20		3/4
						BNC				
Klaxon Siren		Warning	Edwards	120 Vac	0.6					1/2
Beacon		Warning	Edwards	120 Vac	0.35				NA	1/2
BD 99 Sensor			Oseco	24 Vdc					2	
BD 100 & 101 Sensors			Oseco	24 Vdc					2	
Chiller		Cool the rack	Technology Inc.	24 Vdc	7				NA	NA

FACILITY MODIFICATIONS

Since the beginning of the HCF integrated system tests (ISTs) that started in earnest in August 2001, several changes have been made to the facility to make it safer and more efficient to use. Most of the design changes were initiated by anomalies encountered during testing or by some aspect of the original design that was not functioning correctly. The following list details the modifications in chronological order.

1. The coupler that connected the gas-gas igniter chamber to the precombustion chamber had to be redesigned twice during the IST. In the original design, the 0.5-in. pipe nipple that attached the igniter body to the precombustion chamber (which also served as the throat for the igniter system) showed signs of melting after a few igniter system test firings. This was also true of the 0.4-in. opening in the side of the precombustion chamber. A coupler was then designed that had an ATJ insulated throat. This design was found to be unsatisfactory because of stress concentrations in the ATJ insulator (the stem of the insulator failed during an ignition test). In addition, there was evidence of excessive erosion of the ATJ insulator. This component was then changed in the subsequent redesign (the third generation). It was decided to use a consumable G-10 thermoplastic nozzle contained within a coupler, and the redesign worked very well. This new coupler can be easily disassembled for inspection and installation of a new nozzle. The G-10 nozzles are changed after every firing.

2. It was found that preventing all leaks in the NPT joints located in the original 0.5-in. pipeline between the LOX pump and the GOX tank was not possible. This line was replaced with 0.75-in. tube with Swagelok fittings and subsequently hydro-tested to 4,350 psi. The added benefit of this modification is that the total number of NPT connection points was greatly reduced (from 49 to10 NPT joints). The new line has remained leak free.

3. During the second run, a 0.25-in-thick insulator plate that insulated the fore end of the combustion chamber failed and the parts impacted the exhaust nozzle causing it to partially fail. The result was that the combustion chamber pressure dropped from 600 psi to approximately 150 psi and the run terminated normally. On inspection, two problems were identified. The insulator plate was not thick enough to withstand the pressure differential that could develop across it (particularly after being heated) and secondarily, it was decided that the ATJ graphite exhaust nozzle design was deficient in that stress concentrations probably contributed to the nozzle failure after being struck by debris from the failed precombustion chamber fore-end insulator. The fix was to simply not use a fore-end insulator, because this portion of the combustion chamber is not exposed to extreme heat. The exhaust nozzle design was changed to remove the step that existed in the original design.

4. The combustion chamber end plate that houses the exhaust nozzle showed some signs of excessive heating when running 4 kg/sec oxygen mass-flow cases. Typically, toward the end of a run, the metal directly exposed to the plume would begin to surface melt. It was decided to modify the postcombustion chamber end plate by placing an ATJ insulator downstream of the nozzle. Effectively, this insulator became the divergent portion of an exhaust nozzle, as shown in appendix A drawing number A9—0002-M20.

5. A minor problem with overheating of the oxygen injector became apparent very early on in the research program. The plume had a slight greenish tinge to it, a sign that something with copper in it was burning. This problem was quickly tracked down to the brass GOX injector which was being overheated by the ignition pulse and slightly burning on its outside surface. It was thought the burning could be prevented by changing to a stainless steel injector. Stainless has a higher melting temperature but its resistance to burning in an oxygen environment is not quite as good as brass. We installed a stainless steel injector and on the next run (5 Nov. 2001), something hot was thrown into the grass just downstream of the motor and started a small grass fire that was immediately extinguished. The combustion chamber was opened and it was found that the new stainless steel injector was completely melted. There was also some damage to the precombustion chamber end plate. Apparently, a few very small bits of hot metal from the injector were expelled and started the grass fire. It was decided to manufacture the new injector out of pure copper because, although the melting temperature of copper is lower than that of stainless steel, it has approximately 25 times the heat conductivity (see appendix A, drawing number A9—0002-M21). The new copper injector has performed flawlessly since.

6. During an inspection after approximately 40 igniter firings, the oxygen and methane check valves on the igniter were tested and found to be leaking. These valves have Teflon seals in them that were getting too hot. The valves were replaced with metal-seated Monel valves and no significant leakage problems have occurred since.

OXYGEN CLEANING

The use of oxygen within NASA is governed by a safety standard entitled "Safety Standard for Oxygen and Oxygen Systems," NSS 1740.15, that became effective in January 1996. This standard requires that oxygen system components be cleaned in accordance with established NASA and industry procedures including CGA G4.1 (ref. 8).

The first step in oxygen cleaning was to order parts as "cleaned for oxygen service" when manufacturers offered that option. It is recognized that quality control issues exist in industry concerning oxygen cleaning, so parts were disassembled and inspected after they were received and cleaned as necessary before being put into service. Precautions were used during handling and assembly to preclude contamination of component parts (e.g., lint-free gloves were worn).

Cleaning consisted of the typical cleaning, rinsing, and drying procedures used throughout industry (see ref. 8). The specific procedure that was followed depended on the initial state of the component and the materials that it was made of. Components were disassembled and cleaned using detergents, solvents, (primarily Ensolv), brushes, and lint-free rags (a procedure that is much more thorough than a simple solvent-flushing procedure). The components were either air-dried or blown dry with filtered gaseous nitrogen. Inspection of assembled cleaned components was done visually in bright sunlight or in illumination by a powerful light source.

If the component was not immediately installed, it was packed with the appropriate blind flanges, plugs, or caps, or securely taped to prevent contamination, making sure the tape did not touch any cleaned surface. Care was exercised in packaging to prevent shredded or abraded polyethylene material from becoming a contaminant. Finished components were affixed with a tag, label, or stamp showing that they met the requirements specified herein for oxygen services.

Cleaning of the GOX tank for oxygen service was particularly challenging because of the limited access to the interior of the tank and because of the tank's weight. This tank was cleaned for oxygen service following a multistep process including rust and scale removal by means of abrasive blasting and a nitric acid wash, detergent cleaning, alkaline cleaning, solvent cleaning, and drying according to CGA G4.1. The tank was inspected numerous times during and after the cleaning process using a bright lamp and a video camera mounted on a long pole that was inserted into the openings at the ends of the tank. After the GOX tank was cleaned, the tank was pressurized with nitrogen up to 2,000 psi and then rapidly purged in order to ensure that no particulate remained in the tank.

SAFETY ANALYSIS AND REVIEWS

During the design and fabrication phases of the HCF project many reviews (see table 41) were held to ensure that a safe reliable, and functional facility was built.

Table 41. Reviews and certifications.

Review	Date held or completed
Preliminary design review	2/24/00
Environmental review	4/7/00
Critical design review	5/15/00
Oxygen hazards review	6/26/00
Electrical review	11/00
Pressure system certification	9/01
Control system review	1/11/01
Independent review by ARC chief engineer	9/17/01
Operational hazards review (part of ISSR)	9/17/01
SOP, EOP, and IST plan review (part of ISSR)	9/17/01
Fire marshal briefing and review	3/29/01
Onsite oxygen system walk-through (WSTF)	8/30/01
Operational Readiness Review	9/17/01

Integrated Failure Modes and Effects Analysis

The approach taken to the Integrated Failure Modes and Effects Analysis (FMEA) was that each hardware item would be analyzed for possible single-point failure mode and for the worst-case effects on the entire system. This analysis is a companion analysis to the Oxygen Systems Hazards Analysis performed by WSTF and uses the same criticality classifications. The primary difference between the FMEA and the Oxygen Systems Hazards Analysis is that the FMEA does not consider the specific origin of the failure mode in detail but rather focuses on the effect of the failure mode on personnel, equipment, downtime, and the environment.

The followings are key requirements for the HCF FMEA:

1. No single failure will prevent the successful LOX and GOX flow shutoff.

2. No single point of failure of any component will create a hazard that endangers personnel (after engineering controls are in place).

3. No single point of failure of any component will result in other than minor damage to the HCF or the OARF.

The FMEA is a bottom-up method and is initiated by defining the hardware at the lowest level of interest which, in the case of the HCF, is the component level. The various failure modes that can occur for each item at that level are tabulated. The corresponding failure effect, in turn, is interpreted as a failure mode at the next higher functional level. Successive iterations result ultimately in identification of the failure effects up to the top functional level of the HCF.

FMEA Failure Criticality Classifications

The HFC FMEA failure mode criticality classifications are defined and assigned a number as follows:

<u>Severity code definitions:</u>

Catastrophic (I): Death or permanent disabling injury or extensive damage resulting in loss of mission.

Critical (II): Severe injury/illness or lost time injury (>6 months) or serious damage resulting insignificant delay of mission.

Marginal (III): Minor injury/illness or lost time injury (>1 day <6 months) or minor damage resulting in limited delay of mission.

Negligible (IV): No lost-time injury/illness or negligible system damage.

The probability of each failure mode has been analyzed, rated, and included in the FMEA chart below. The following scale was used:

<u>Probability code definitions:</u>

Probable (A): likely to occur several times in the life of the system.

Remote (B): likely to occur once in the life of the system.

Improbable (C): not likely to occur in the life of the system.

Highly improbable (D): occurrence is considered to be extremely unlikely in the life of the system.

The oxygen hazards analysis performed by White Sands Test Facility employs a five-level probability scale that includes a "highly probable" level. Although the Oxygen Hazards Analysis is not the same thing as a FMEA, it was deemed desirable to use a similar rating system. To be consistent with the current practice at Ames, a four-level system was used in the FMEA. In addition, it was felt that there is little difference between "probable" and "highly probable" in terms of the effect that these probabilities would have on design and operation of the facility (both are unacceptable). It should be noted that no component received a "highly probable" rating in the Oxygen Hazards Analysis so, in effect, the scales used in the two analyses are comparable (although the number assigned to the probability ratings used in the oxygen hazards analysis is in reverse order compared to that used in the FMEA).

FMEA Ground Rules and Assumptions

The HCF FMEA was conducted based on the following ground rules and assumptions:

1. Only the critical systems and components of the HCF were analyzed.
2. Only one failure mode exists at a time.
3. Failure modes that occur within a system or component, be it electrical or mechanical, are manifested at the interface by one of the following failure conditions:

   Premature operation
   Failure to operate at a prescribed time
   Failure to cease operations when required
   Failure during operation

4. Failures resulting from human error in the operation of the facility (e.g., procedural or induced errors) were not considered. Such items (which constitute a safety concern) are considered in other portions of this document.
5. All control system inputs are present and at nominal values.
6. Connector failures are limited to disconnect.

It should be noted that two different criticality ratings are reported in table 42 for the catastrophic and critical severity levels. The first rating is with no procedural controls in place. The second is with procedural controls considered (procedural controls referenced by a symbol and explained at the bottom of the table). Concerning procedural controls, it is desirable to have few or no such controls because of the possibility that the controls will be ignored or circumvented. During the design of the HCF, it was found that avoidance of all procedural controls was not possible so the goal was to have as few as possible. These controls are discussed in the following sections.

Hybrid Combustion Facility FMEA Table

Table 42. Hybrid Combustion Facility FMEA.

P: Personnel, E:Equipment, T:Significant Downtime V:Environment
I:Catastrophic, II:Critical, III:Marginal, IV:Negligible
A Probable:, B Remote:, C: Improbable, D: Highly Improbable

Ident no	Item/ functional ident.	Failure mode	Failure cause	Failure effect	Target	Hazard sev.	Probability	Action required/remarks
1	LOX tank	Small leak	Seal failure	LOX spilled but contained	E	IV	B	Replace defective or worn seal
2	LOX shutoff Valve (HV-1)	Defective, Doesn't open	Stuck	Can't pump LOX	E	IV	C	Drain LOX tank and replace valve
3	LOX shutoff	Defective;	Worn or	LOX pump	E	IV	B	Drain LOX tank.

	valve HV-1	Doesn't shut	stuck	(turned off) should effectively stop LOX flow				Replace valve seal. Relief valve will prevent over-pressurization
4	Return vent valve HV-4	Defective, Doesn't open	Stuck	Can't manually vent return line	E	IV	C	Replace valve
5	Return vent valve HV-4	Defective, Doesn't close	Worn or stuck	LOX spilled but contained	E	IV	B	Close HV-1 and replace valve
6	Return shutoff valve HV-2	Defective, Doesn't open	Stuck	No LOX circulation, can't pump	E	IV	C	Replace valve
7	Return shutoff valve HV-2	Defective, Doesn't close	Worn or stuck	LOX circulates until HV-1 closed	E	IV	B	Close HV-1 and replace valve
8	Return relief valve PRV-93	Defective, Doesn't close	Stuck	LOX leak	E	IV	B	LOX is contained, close LOX Shutoff Valve (HV-1)
9	Return relief valve PRV-93	Defective, Doesn't open	Stuck	No effect because of redundancy	E	IV	B	LOX feed line has a second relief valve. Replace valve
10	LOX strainer	Mesh fails	Wear	GOX strainer should trap debris	E	IV	B	Replace strainer
11	LOX strainer	Clogged	Particulate	LOX pump loss of prime	E	I IV	A	An audible noise will result. LOX Pump should be turned off
12	Relief valve PRV-90	Defective, Doesn't close	Stuck	LOX leak	E	IV	B	LOX is contained, close LOX Shutoff Valve (HV-1)
13	Relief valve PRV-90	Defective, Doesn't open	Stuck	No effect because of redundancy	E	IV	B	LOX tank has a second relief valve, Replace valve
14	LOX pump	Loss of Prime	Inlet blockage	Pumping ceases	P E	IV	A	Pump should be turned off immediately
15	LOX pipe	Leak	Improper installation	Contained LOX spill	E	IV	B	Fix leak.
16	Vaporizer	Excessive ice on fins	Humidity	GOX temperature too low	T	IV	A	Stop pump and wait for ice to melt.
17	½-in. SS pipe	Leak	Many causes	GOX vented	E	IV	A	Fix leak
18	Relief valve PRV-91	Defective, Fails closed	Stuck	Minor GOX pressure build-up	E	IV	B	GOX pressure will not exceed proof pressure of components Replace valve
19	Relief valve	Defective,	Stuck	GOX vented	E	IV	A	Replace valve

	PRV-91	Fails open						
20	Shutoff valve POV-2	Defective, Fails closed	Stuck	Can't pump GOX tank	E	IV	B	Replace valve
21	Shutoff valve POV-2	Defective, Fails open	Stuck	Run prevented	E	IV	B	Replace valve
22	Check valve CKV-3	Defective, Fails open	Stuck	Possible contamination of upstream components	E	IV	B	Replace valve, Inspect upstream components
23	Check valve CKV-3	Defective, Fails closed	Stuck	Can't pump GOX tank, possible LOX pump loss of prime	E	IV	C	Stop LOX pump and replace valve
24	Burst disk BD-99	Burst unexpectedly during run	Defect	GOX vented (sonic)	P E	I IV[a]	A	Stop run. Replace disk and pump up GOX tank
25	Burst disk BD-99	Defective, Doesn't Bursts at rated pressure during run	Defect	GOX not vented	P E	I IV[a]	C	Burst disks on sonic throat should burst. Replace disk
26	Burst disk BD-99	Defective, Bursts at low pressure	Defect	GOX vented. (sonic)	P E	I IV[b]	B	Replace disk and pump up GOX tank
27	GOX strainer	Clog	Debris	GOX pumping would cease. Mesh could fail	E	IV	A	Mode recognized by reduced GOX tank pressure. Replace strainer mesh
28	GOX tank	Metal particulate or contamination in tank	Strainer failure	If undetected, could result in fire downstream	P E	I III[a]	B	Mitigated by bayonet on GOX tank. OX clean tank before further use
29	Shutoff valve POV-4	Fails to open	Loss of power or pneumatics or defect	Can't run combustion chamber	E	IV	B	Fix valve
30	Shutoff valve POV-4	Fails to close	Loss of power, pneumatics or defect	Run terminated by redundant valve	E	IV	B	This valve fails closed; also shutoff valves 2&3 are redundant
31	Shutoff valve POV-5	Fails to open	Loss of power or pneumatics or defect	Can't run combustion chamber	E	IV	B	Fix valve
32	Shutoff valve POV-5	Fails to close	Loss of power, pneumatics or defect	Run terminated by redundant valve	E	IV	B	This valve fails closed; also shutoff valves POV-4 and POV-5 are redundant
33	Control valve PCV-6	Fails to move	Defect, jam.etc.	Downstream GOX pressure will decrease	E	IV	B	Fix valve and repeat test

34	CO2 purge system	Fails to turn on	Several are remotely possible	Data from test might be less accurate	E	IV	B	Fix CO2 system prior to next run
35	ASME venturi FE-101	Pressure transducer fails	Several possible causes	No mass-flow measurement	E	IV	B	Fix pressure x-ducer and repeat run
36	Sonic nozzle	Contaminated by paraffin	Combustion instability	Paraffin may burn	E	IV	A	Inspect and clean nozzle prior to next run
37	Check valve CKV-7	Fails to close	Stuck	Upstream components may get contaminated	E	IV	B	Fix valve, inspect upstream components and repeat run
38	Check valve CKV-7	Fails to open	Stuck	Cannot ignite paraffin fuel	E	IV	C	Fix valve and repeat run
39	Pressure transducer 1	Fails	Several remotely possible causes	Oxygen system pressure not properly established	E	III	B	Control system designed to detect this mode. Fix x-ducer and repeat run
40	Kistler pressure transducer 1	Fails	Several remotely possible causes	Chamber pressure not properly recorded	E	IV	B	Control system designed to detect this mode. Fix x-ducer and repeat run
41	Burst disks BD-100 and BD-101	Bursts	Extreme combustion instability	GOX will be vented until shutoff valves POV-4 and POV-5 are closed	P E	I III[a]	B	Control system designed to detect this mode. Replace disks and repeat run
42	Pneumatic air supply	Pressure loss	Several	Valves POV-4 and POV-5 and control valve (PCV-6) will not function properly	E	IV	B	Shutoff Valves POV-4 and POV-5 are designed to fail closed. Pneumatic system should be repaired
43	Power	Power loss	Several	Cannot run facility or shutoff valves POV-4 and POV-5 will close	E	IV	B	PLC Control system and valves are wired to handle this failure mode
44	PLC	PLC crashes	Several	Cannot run facility or shutoff valves POV-4 and POV-5 will close	E	IV	B	PLC Control system and valves are wired to handle this failure mode
45	Ignition system	Ignition failure	No spark	Cannot perform test	E	IV	B	Control system will detect and CO2 system will automatically

								purge the combustion chamber of methane and oxygen
46	Ignition system	Rough Ignition	Improper methane-oxygen ratio	Combustion chamber pressure spike	E	IV	A	Control system will detect
47	Combustion chamber	Combustion instability	Several	>5% Combustion chamber pressure variation	E	III	A	Control system will detect. If persistent, may require redesign of combustion chamber
48	Combustion chamber	Combustion chamber leak	Improper o-ring installation	Internal combustion chamber scoring	E	I III[a]	A	Replace damaged component
49	Combustion chamber	Combustion chamber leak	Pressure spike	Internal combustion chamber scoring	E	I III[a]	A	Replace damaged component
50	Combustion chamber	Fuel-grain burn to completion	Unexpectedly high burn rate	Internal combustion chamber scoring or burning	E	III	B	Replace damaged component
51	Combustion chamber	Exhaust Nozzle failure	Excessive erosion or extremely rough ignition	ATJ graphite could be expelled	E	IV	A	Pieces will strike blast deflector
52	Combustion chamber	Fuel-grain structural failure	Unknown	Hot paraffin could be expelled	E	IV	A	Pieces will strike blast deflector

Procedural controls:
[a] All personnel must be either in the control room or at least 250 ft away (outside OARF fence) during combustion chamber operation. [b] During LOX pump operation, all personnel must be at least 15 ft away from the pump, as recommended by CGA G 4.7.

The third procedural control is that the oxygen K-cylinder regulator (on the igniter system) is fully closed prior to opening the K-cylinder valve (on the top of the cylinder). This procedure is almost universally followed in the welding industry in which this type of regulator has been used for decades.

Summary of the FMEA Results

Based on results of the FMEA, a total of 28 unique components were analyzed in the HCF at the IST time frame. A total of 52 failure modes were identified. With three procedural controls in place, the catastrophic and critical modes become marginal and negligible. This means that with procedural controls, none of the identified failures of the HCF will result in a loss of system capability that would significantly affect the HCF hardware; they may, however, require that the run be repeated or that a component be replaced prior to continued facility operation.

It should be noted that during the FMEA, several failure modes were identified that had unacceptable criticality levels; the facility design was modified accordingly.

The analysis reveals no single point of failure in the HCF that would prevent the successful shutoff of the GOX or LOX flow. The analysis also reveals no single point of failure in the HCF that would result in injury to personnel when two procedural controls are followed.

At this point, it should be emphasized that FMEA does not include operator error or willful disregard of safety controls, barriers, and procedures. A best effort has been made toward designing safety into the facility, but as with almost any other piece of hardware, the best intentions of the designers can be defeated.

Oxygen System Hazards Analysis

As described in reference 2, oxygen is a strong oxidizer that vigorously supports combustion. Oxygen is reactive at ambient conditions, and its reactivity increases with increasing pressure, temperature, and concentration. Most materials, both metals and nonmetals, are flammable in high-pressure oxygen; therefore, systems must be designed to reduce or eliminate ignition hazards.

Cleanliness in oxygen systems is of paramount importance. Contamination by organic compounds can easily ignite and provide a kindling chain to ignite surrounding materials (including most metals). Likewise, metal particles can ignite and result in a kindling chain reaction when they impact other metallic parts of the system.

Some of the most important oxygen system safety precautions are leak prevention, minimization of the severity of ignition sources, proper material selection, cleanliness, proper design of system components, and proper system operation.

An independent Oxygen Hazards Analysis was performed by personnel from the NASA White Sands Test Facility. The following text describes the oxygen hazards that were considered during the HCF design process.

Associated with this test facility are several hazards including high and low temperatures, high pressures, various forces and those hazards associated with liquid and gaseous oxygen. These are formidable hazards, but many hours have been devoted to their consideration, and good design practices minimize the risks they pose.

Discussed below are the major hazards, the steps taken to minimize them, and the applicable codes. For the HCF, the greatest hazard is the possibility of an oxygen fire. Good design practice requires that ignition mechanisms be analyzed.

The GOX tank is constructed of carbon steel. The tank configuration is such that carbon steel is an acceptable material because of the following:

1. It was cleaned for oxygen service to the degree that no credible ignition mechanisms exist.
2. The GOX tank wall is so thick (6-in) that any heat generated from particle impact will be conducted away.

3. The flow velocity is very low in the tank with the exception of the areas immediately surrounding the pipe-flange attachment points.

The 2-in. nominal GOX shutoff valves POV-4 and POV-5, control valve PCV-6, ASME nozzle and sonic nozzle holder are fabricated of stainless steel.

Table 43 lists some potential ignition sources of fuel-oxygen mixtures and their applicability to the HCF.

Table 43. Hybrid Combustion Facility potential oxygen ignition sources.

Adiabatic compression	Unlikely because the response time of the valve actuators is too slow
Thermal ignition	There are no thermal sources outside of the igniter in the combustion chamber
Personnel smoking	Not permitted within 50 ft of an oxygen system
Open flames	The exhaust of the combustion chamber
Shock waves from tank rupture	Protected through use of burst disks and relief and check valves
Fragments from bursting vessels	No other vessels are located in the vicinity (aside from the GOX tank, LOX tank, and igniter K-cylinders that are part of the HCF)
Heating of high-velocity jets	The combustion facility itself creates a hot, high-velocity jet. This jet is directed away from the GOX and LOX tank
Welding	Not permitted within 100 ft while oxygen is present
Explosive charges	None present
Friction and galling	Those that arise from valve opening and closing; the speed of the actuators is relatively slow and so this should not be an issue
Resonance ignition	Outside of the combustion chamber exhaust nozzle, the only shocks in the system occur where the flow goes sonic (in the GOX control valve (PCV-6), and sonic nozzle); these shock systems should be stable
Mechanical impact	Mechanical impacts may occur on valve opening and closing (including the swing plate check valve in the main GOX line); these impacts should not be at a high enough rate to pose a hazard
Tensile rupture	All pipes are mounted on supports that allow for expansion and contraction
Mechanical vibration	All components are properly supported and secured; the tests will last at most 20 sec so vibration should not be an issue
Exhaust from thermal combustion engine	A LOX truck (with proper safeguards) will deliver LOX
Particle impact	The main sources for particles are those due to LOX impurities and those that remain in the GOX tank after the cleaning; the specification for the GOX tank cleaning is that the cleaning should remove all particulate greater than 300 micrometers
Electrical ignition	No electrical wires run through an oxygen-enriched environment; all components will be properly shielded and grounded; all wires will run in weatherproof conduits
Electrical short circuits, sparks, and arcs	See above

Metal fracture	Not likely to occur with good design practices
Static electricity (two-phase flow)	No two-phase flow present
Static electricity (solid particles)	No source present
Lightning	Highly unlikely because a 100-ft-tall crane is located nearby
Electrical charge generation	The LOX pump has a motor; this is the only component that could generate an electrical charge and this is very unlikely with proper grounding and shielding

Concerning the Oxygen Hazards Analysis performed by personnel at the White Sands Test Facility, table 44 summarizes the critical and catastrophic levels that are rated as either probable or highly probable hazards in the Oxygen Hazards report. As a result of the recommendations of this hazard report, several changes were made to the initial design including substitution of a Monel valve for HV-3, pneumatically actuated Monel valves for POV-2, POV-3, and POV-11, and a Monel bleed valve for HV-94.

Table 44. Hybrid Combustion Facility oxygen hazards analysis summary.[a]

Ames HCF	Frictional heating	Adiabatic compression	Mechanical impact	Particle impact	Mechanical stress	Static discharge	Extrusion	Chemical reaction	Contaminant promotion	Flow friction	Kindling chain	Mitigation
LOX shutoff valve (HV-1) - circle seal Model # ES2-084-OWPG1									3[1]			Valve was Ox cleaned prior to installation
Vent valve (HV-3), shutoff valve (POV-2), GOX purge valve - circle seal Model ES60T1-08				3[2]							3[3]	These three valves were replaced with Monel valves; GOX Purge valve deleted
LOX pump – ACD Model WDPD	3[4]										3[5]	Strict hour-meter-based maintenance shield installed
Check valves 1 & 3 – circle seal Model 220T1-4PP-8											3[6]	Filter placed upstream to capture particles
Burst disks – Oseco Model 1 & 2" UT-2 316/316							3[7]				3[8]	Brass and Monel used on BD 99, 100, and 101 supply pipe. Non-fragmenting disks purchased
Purge valves (HV-94) – Richardson Ind. Model HG481U4131412-M				3[9]								A Monel valve has been used
Control valve (PCV-6) 1 – Norriseal Model 2-2700A-RJS36TGS-16NX				3[10]							3[11]	Both valves are soft seated; several nitrogen purges are planned during IST

Pressure Regulator – Victor Model SR4J		3[12]									3[13]	Gauges have been Ox cleaned and verified; regulator will be fully reduced
Solenoid Valve (POV-2, POV-3 and POV-11) – Atkomatic Model HPSS8204-WP				3[14]							3[15]	Monel valves used

[a] The superscripted numbers refer to items in the list (items 1-15) that follows.

Ignition Hazards

0 = Almost impossible
1 = Remotely possible
2 = Possible
3 = Probable
4 = Highly probable

Reaction Effect

A = Negligible
B = Marginal
C = Critical
D = Catastrophic

The superscripted numbers in table 44 refer to the following list that was excerpted from the WSTF oxygen hazards report.

1. A similar valve burned when contaminant on the seat was ignited when the valve was closed. It is recommended to ensure the valve is initially clean and maintained clean to prevent contamination of the seat and that the LOX tank be periodically purged to avoid the buildup of light hydrocarbon contaminants.

2. Sonic velocities occur across the seats of these valves and the flow will accelerate particles across the seats as well. Stainless steel is susceptible to ignition by particle impact. It is recommended that Monel valves with Monel trim be used in this application.

3. If the body of the valve is ignited by particle impact, it is likely that a burn-through of the valve body will occur. If the particle ignition hazard is reduced, this hazard is reduced as well.

4. Frictional heating occurs as this pump operates. A similar CCI pump experienced a catastrophic fire. The probable cause of the fire was frictional heating when the stainless steel parts rubbed during operation. If the Teflon rings wear out, the stainless steel parts will rub together. It is recommended that the health of the Teflon rings be monitored on a regular basis. It is also recommended that the pump be monitored during operation for signs of excessive friction, such as noise, loading of the motor, or excessive current draw and an external LOX leak.

5. Frictional ignition resulting in a burn-through of the pump body is probable.

6. If the body of the valve is ignited by particle impact, it is likely that a burn-through of the valve body will occur. If the particle ignition hazard is reduced, this hazard is reduced as well.

7. When the burst disk ruptures, the likelihood of particles being extruded through the component igniting the housing is probable. It is recommended that the housing material and connecting fittings be changed to brass or Monel and that the vent lines, if any, be made of copper or brass for a distance of at least 10 pipe diameters downstream of the housing.

8. The component housing is flammable in these conditions. Therefore, a likelihood of kindling chain ignition resulting in a burn-through of the housing is probable.

9. Sonic velocities will exist, and particles will be accelerated across the seat of the valve when it opens. It is recommended that the materials of the valve body and trim be changed to brass or Monel or that a 5- to 10-micron nickel screen or sintered bronze filter immediately installed upstream of the valves.

10. The inlet and outlet velocities through this valve have been calculated to be 480 ft/sec, with a maximum velocity across the seat of 700 ft/sec. These velocities are greater than the velocities needed for particle impact in stainless steel. Particles will be accelerated within the valve and will impact the flammable stainless steel body and trim within the valve. It is recommended that it be ensured that particles within control valve PCV-6 are controlled by initial blowdowns of the system with dry, filtered, inert gas and by replacing the upstream metal-to-metal seat ball valve with another soft-seated valve. Or, it is recommended that changing the body and trim material be considered, perhaps from stainless steel to a material that is more resistant to ignition by particle impact, such as brass or Monel.

11. Ignition propagation resulting in a burn-through of the component is probable. If the Viton plug seal is ignited or a particle-impact ignition occurs within the valve, the resulting fire will probably burn through the body of the valve.

12. When the bottle valve is opened, the regulator is rapidly pressurized from ambient pressure to bottle pressure. The maximum theoretical temperature when pressurizing from ambient to 3,000 psi is 1,966°F (ASTM G-4 Math) and the AIT of Buna-N is 343°F (ASTM Manual 36). However, these components have a relatively good use of history and if the regulator is fully reduced, the seals are relatively well protected. It is recommended that these regulators be fully reduced after each use and that they be fully reduced before opening the bottle valve. Adiabatic compression ignition is also a hazard for the high-pressure gauge if it is contaminated. These gauges are often calibrated with oil and, if not cleaned properly, the oil can be ignited by adiabatic compression and burn through the thin Bourdon tube. It is recommended that the gauges be properly cleaned and verified clean prior to use with oxygen.

13. Ignition propagation resulting in a burn-through of the regulator body is possible but the possibility is mitigated by the situational nonflammable brass body. However, if the gauge is contaminated with oil and the oil is ignited by adiabatic compression, then burn-through of the Bourdon tube is probable.

14. Particles will be accelerated across the seat of the valve when it opens and impact the flammable stainless steel downstream. It is recommended that this valve be replaced with a brass or Monel-bodied valve with brass or Monel trim.

15. Ignition propagation resulting in a burn-through of the component is probable because of the probable risk of particle impact ignition and the flammability of the stainless steel body.

Regardless of the ignition hazard probability rating that a given component receives in an Oxygen Hazards Analysis, steps should be taken to avoid all possible ignition sources. In some situations, this is not possible. Ratings of "highly probable" or "probable" (A or B) coupled with reaction effect ratings of "catastrophic" or "critical" (I or II) have the potential to cause serious injury or death and are considered probable enough to be of great concern.

In summary, the design changes (shown in the mitigation column of table 44) negate all of the probable ignition hazards. One procedural control required is the reduction of the GOX K-cylinder regulator after each use. This is standard practice by welders who use these types of regulators daily.

Hazards Summary

All of the hazards identified in the OHA, FMEA, and Oxygen Hazard Analyses are summarized in tables 45 through 48. The numbers in these tables are either the FMEA identification number or the OHA hazard report number. It should be noted that the hazards identified in the Oxygen Hazards Analysis were either mitigated or have been included in the FMEA.

Table 45. HCF hazards summary (without procedural controls).

Without controls	**Hazard severity**			
	I	**II**	**III**	**IV**
Probability A	11, 24, 48, 49 (4)	**(0)**	47 **(1)**	14, 16, 17, 19, 27, 36, 44, 46, 51, 52 **(10)**
B	26, 28, 41 (3)	**(0)**	50, 004 **(2)**	1, 3, 5, 7, 8, 9, 10, 12, 13, 15, 18, 20, 21, 22, 29, 30, 31, 32, 33, 34, 35, 37, 40, 42, 43, 45 **(26)**
C	25 (1)	011 **(1)**	006, 014, 015, 39 **(4)**	2, 4, 6, 23, 38, **(5)**
D	001, 002, 012, 013, 014 **(5)**	005, 010, 016 **(3)**	003, 007 **(2)**	**(0)**

Table 46. HCF hazards summary (with procedural controls).

With controls	**Hazard severity**			
	I	**II**	**III**	**IV**
Probability A	<11, 24 to IV-A> <48, 49 to III-A> **(0)**	**(0)**	47, 48, 49 **(3)**	11, 14, 16, 17, 19, 24, 27, 36, 44, 46, 51, 52 **(12)**
B	<26 to IV-B> <28, 41 to III-B> **(0)**	**(0)**	28, 41, 50 **(3)**	1, 3, 5, 7, 8, 9, 10, 12, 13, 15, 18, 20, 21, 22, 26, 29, 30, 31, 32, 33, 34, 35, 37, 40, 42, 43, 45 **(27)**
C	<25 to IV-C> (0)	<011 to III-D> **(0)**	006, 014, 015, 39 **(4)**	2, 4, 6, 23, 25, 38, 004 **(7)**
D	001, 002, 012, 013, 014, **(5)**	005, 016 <010 to III-D> **(2)**	003, 007, 010, 011 **(4)**	**(0)**

Table 47. HCF hazards and controls from OHA.

Hazard report number	HRA (initial/final)	Hazard description	Control[a] (see notes)
001	3/3	High-pressure gasses injury	1
002	3/3	Injury due to burns (unintended ignition)	2
003	4/4	Injury to personnel in surrounding areas	3
004	2/4	Fire damage to surrounding areas	3
005	3/3	Cold surface related injury	4
006	3/3	Heat related injury following a test	6
007	4/4	Fire from inadvertent release of methane	7
010	3/4	Fire hazard in test area from venting	1
011	2/4	Fire hazard near blockhouse after venting	1
012	3/3	Injury caused by test article fragmentation	1
013	3/3	Loss of emergency access to control building	8
014	3/3	Fire from flow upstream of gas from cylinders	1
015	3/3	Mechanical assembly injury	7
016	3/3	Hearing damage from inadvertent gas release	7

Table 48. HCF hazards and controls from FMEA.

FMEA number	HRA initial/final	Hazard description	Control (see notes)
11	1/3	Clogged LOX strainer fire	7
24	1/3	GOX tank burst disk bursts during run (fire)	1
48	1/2	Combustion chamber O-ring leak during run	1
49	1/2	Combustion chamber pressure spike leak	1
26	1/3	GOX tank burst disk burst at low p. During run	1
28	1/2	Metal particulate contamination in GOX tank	1
41	1/2	Cchamber burst disks burst during run	1
25	2/4	GOX tank burst disk doesn't burst during run	1
47	2/2	Extreme combustion chamber instabilities	1
50	2/2	Burn of fuel to completion	1

[a]Control notes: (1) Primary control is a procedure for limiting access during testing (everybody in blockhouse or outside fence). (2) Control is control system. (3) Control is blast deflector and watch person. (4) Control is personal protection equipment. (6) Control is 30-min wait time after run. (7) Primary control is SOP procedures. (8) Control for is EOP requirement of notification of oxygen enriched environment.

ENVIRONMENTAL IMPACT

As one might imagine, there are several environmental concerns with this project that have been addressed by members of the environmental oversight groups at Ames and by groups within other agencies. These concerns include air pollution, endangered species, and noise. A National Environmental Policy Act (NEPA) Environmental Checklist was completed and submitted to the senior environmental compliance specialist at Ames.

On 7 April 2000 a Record of Environmental Consideration was signed. The record summarized the efforts of the environmental specialists that have worked on this project. The primary areas considered were air pollution, noise, and endangered species. It also stated that the project qualifies for a Categorical Exclusion and has no special circumstances that would suggest a need for an Environmental Assessment.

Included in the record is a letter from the U.S. Fish and Wildlife Service stating that the project will not adversely affect the California clapper rail (an endangered species present in the vicinity of the OARF).

Emissions

An air pollution expert at Ames determined that since the HCF primary products of combustion are water and carbon dioxide when paraffin is burned in an oxygen environment, (no nitrogen-based compounds of significance) air pollution is not a concern.

Endangered Species

There are two endangered species in the vicinity of the OARF. These are burrowing owls and also clapper rails. Contact was made with California Fish and Game concerning mitigation efforts and U.S. Fish and Wildlife Service approved the project. Prior to the initiation of the project, active burrowing owl nests existed within approximately 50 ft of the proposed location for the facility. As part of a mitigation plan, 20 one-way doors were fabricated and placed at the entrance to the remaining satellite burrows to ensure that owls are not present within the OARF during testing.

Noise

The community noise impact will be small because the combustion chamber is pointed toward the bay and the proposed tests have very short run times. Most tests will be 10 sec or less with a few runs lasting up to 20 sec at a maximum rate of one test per day. The Jet Noise 7-computer code was used to perform noise predictions. The predicted yearly day-night noise levels (L_{AE}) at a bicycle trail and trailer park (two nearby sites of public activity) will be less than 51 dB, which is well within the allowable limits for operation during the noisy afternoon hours. At the location of the fence surrounding the OARF, the L_{AE} level is 75 dB. Given the short duration of the tests, it is unlikely that Ames personnel will be significantly impacted (not more than the current venting of the Ames high-pressure air system that generates comparable noise levels but of longer duration).

The noise levels were predicted using the Jet Noise 7 empirical code, which was designed for turbojets. The following assumed conditions were used:

d_n = 2-in. throat diameter
A_e/A_n = exit-to-throat area ratio = 9
T_j = 2,500° K combustion temperature
P_o = 1,000 psi combustion pressure
h_j = 3-ft jet height above ground
d_e = 6-in. calculated exit diameter

Figure 90 shows the predicted 90 dBA (A-weighted) sound level contour around the rocket superimposed on a map of the OARF area. The peak noise is 110° from flight direction. The decay rate information shown in figure 91 can be used to extrapolate to other distances along a radial line. The third-octave spectra are illustrated in figure 92.

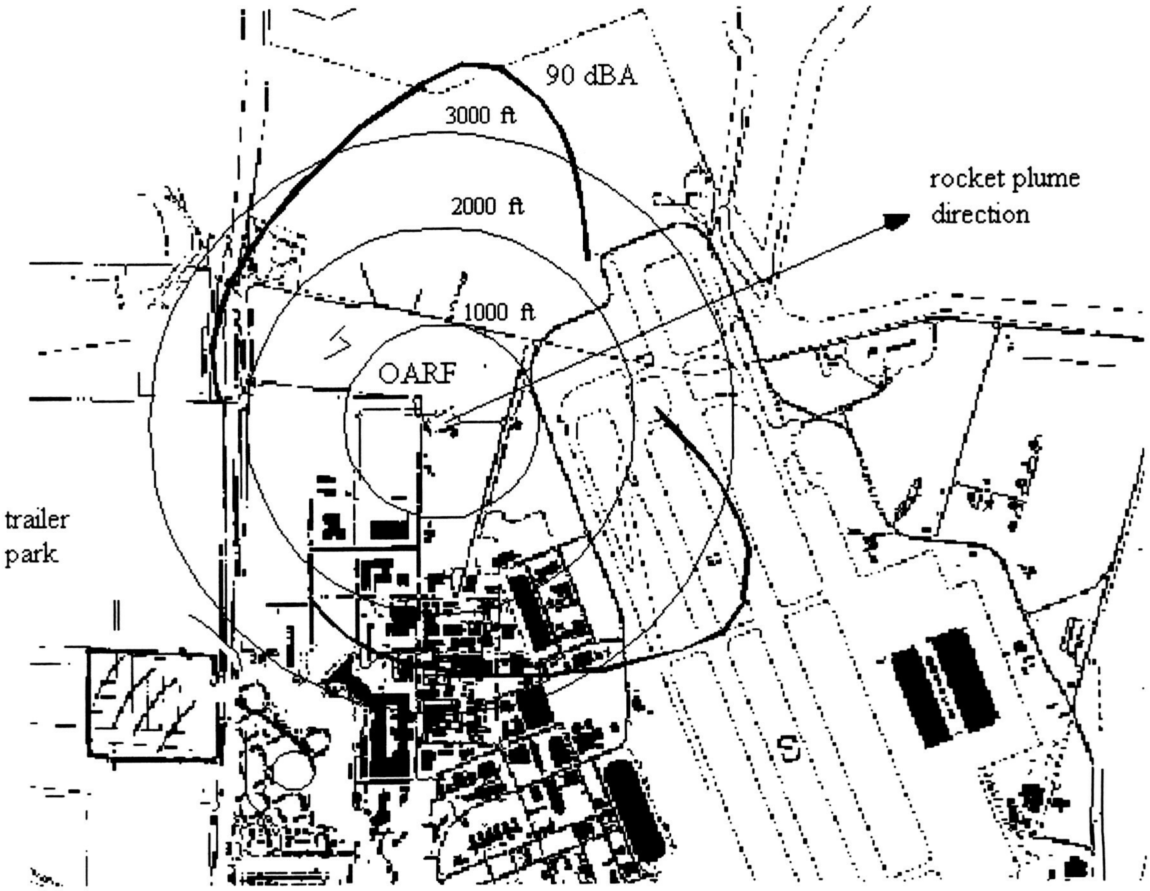


Figure 90. Predicted A-weighted noise level contours at OARF.

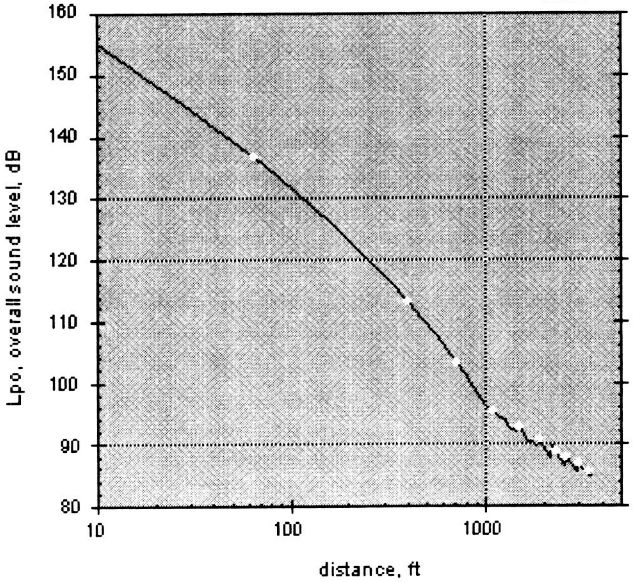


Figure 91. Noise attenuation with distance.

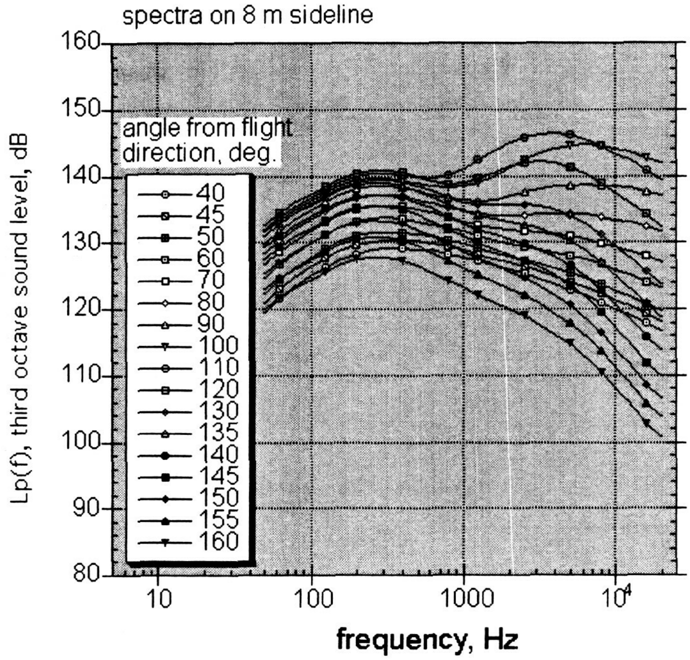


Figure 92. Predicted noise spectra.

It was found that the predicted noise level is higher than the actual measured noise level by roughly 10 dB to 20 dB, depending on the frequency and angle. The reason for this difference is that the noise code used is based on a ~V_{jet}^8 relationship for jet noise and, as Mach number increases to rocket levels, the noise variation with jet speed drops to ~V_{jet}^3 (ref. 9), hence the noise predictions are very conservative.

RESULTS FROM A TYPICAL HCF FIRING

To date, approximately 41 tests have been carried out in the HCF on the SP-1a fuel formulation. Shown in figure 93 is an image of the plume of a 1,000-psi chamber pressure, 4-kg/sec oxidizer mass-flow rate case from the 18th run of the facility (26 March 2002). Presented in figure 94 are the corresponding time histories.

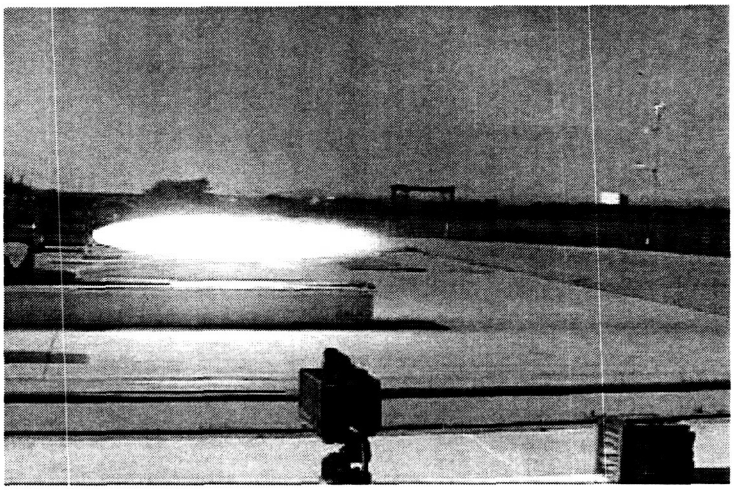


Figure 93. Plume image from a 1,000-psi chamber pressure run.

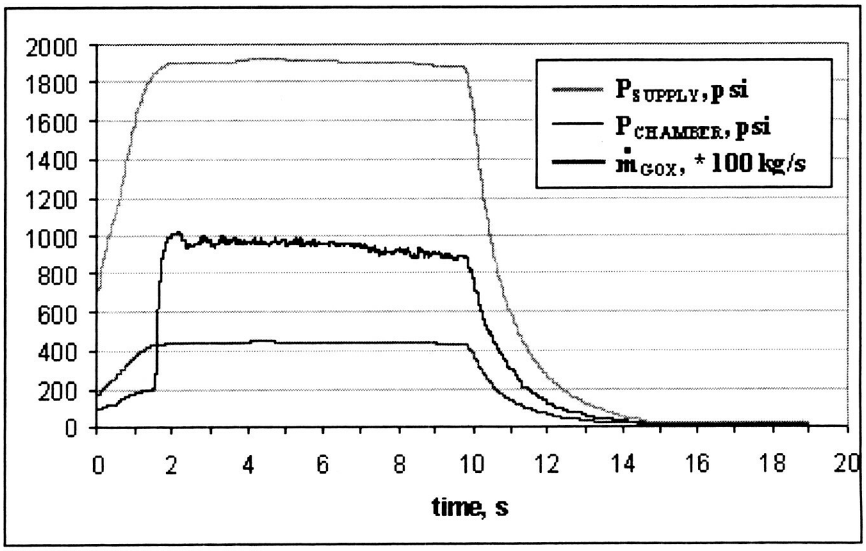


Figure 94. Time-histories of a 1,000-psi chamber pressure run.

The supply pressure is the pressure measured upstream of the sonic orifice. The oxidizer flow is initiated at approximately t = 0 sec and ignition takes place at t = 1.6 sec. At t = 10.2 sec, the oxidizer shutoff valves are closed. As can be seen in the traces, thrust termination takes a few seconds because of the fairly large volume of oxidizer in the lines between the shutoff valves and the combustion chamber. Toward the end of the run, nozzle erosion causes the chamber pressure to decrease slightly.

REFERENCES

1. Cantwell, B; Karabeyoglu, M.A.; and Altman, D: High Regression Rate Hybrid Rocket Fuels. JIAA TR-122, Stanford University, Stanford, Calif., Aug. 1999.

2. NSS 1740.15: Safety Standard for Oxygen and Oxygen Systems.

3. Idelchik, I.E.: Handbook of Hydraulic Resistance. 3rd ed., CRC Press, Boca Raton, Fla., 1994.

4. Compressed Gas Association 4.7: Installation Guide for Horizontal, Stationary, Electric-Motor-Driven Liquid Oxygen Pumps. CGA, Arlington, Va., 1997.

5. Compressed Gas Association 4.4: Industrial Practices for Gaseous Oxygen Transmission, and Distribution Piping Systems. CGA, Arlington, Va., 1993.

6. Mark's Standard Handbook for Mechanical Engineers 10th ed., E.A. Avallone, and T. Baumeister, eds. McGraw Hill, 1996.

7. Ames Health and Safety Manual AHB1700.1, 1999.

8. Compressed Gas Association 4.1: Cleaning Equipment for Oxygen Service. CGA, Arlington, Va., 1996.

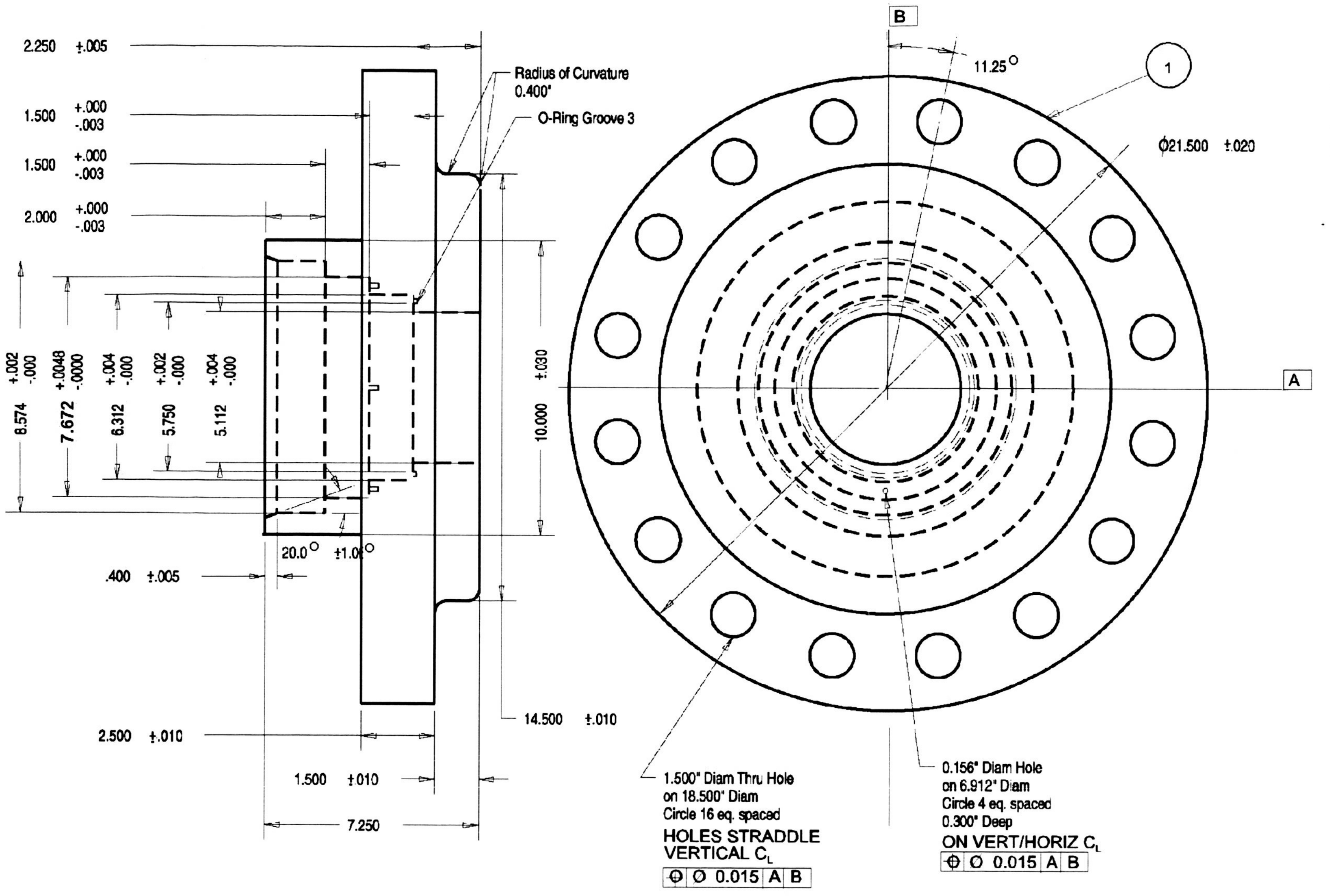
9. McInery, S.: Rocket Noise: A Review. AIAA Paper 90-3981, AIAA 13th Aeroacoustics Conference, Tallahassee, Fla., Oct. 1990.

APPENDIX A—ARCHIVED ENGINEERING DRAWINGS

DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS			
REV	DESCRIPTION	DATE	APPROVAL

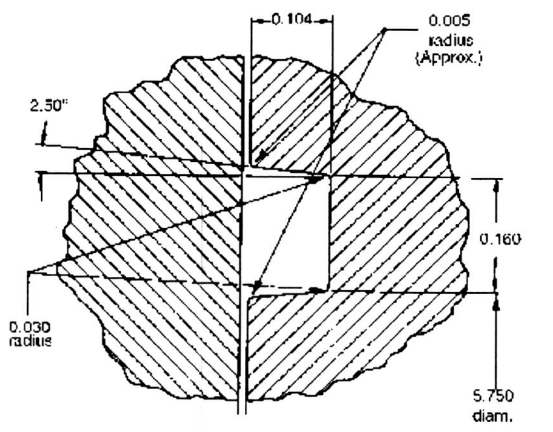
QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		POST-COMBUSTION CHAMBER CASING	A36 OR A576	1
				2



NOTES:

1.) THE 16 1.5 HOLES IN ON THE 18.5 IN BOLT CIRCLE STRADDLE THE VERTICAL

2.) O-RING GROOVE FINISH 64 TO 125 MICROINCH



O-RING GROOVE 3 DETAIL

						AMES HYBRID COMBUSTION FAC		5 A1	
QTY REQ'D PER ASSY				CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY
	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 8/4/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 8/3/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 8/3/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

POST-COMBUSTION CHAMBER CASING

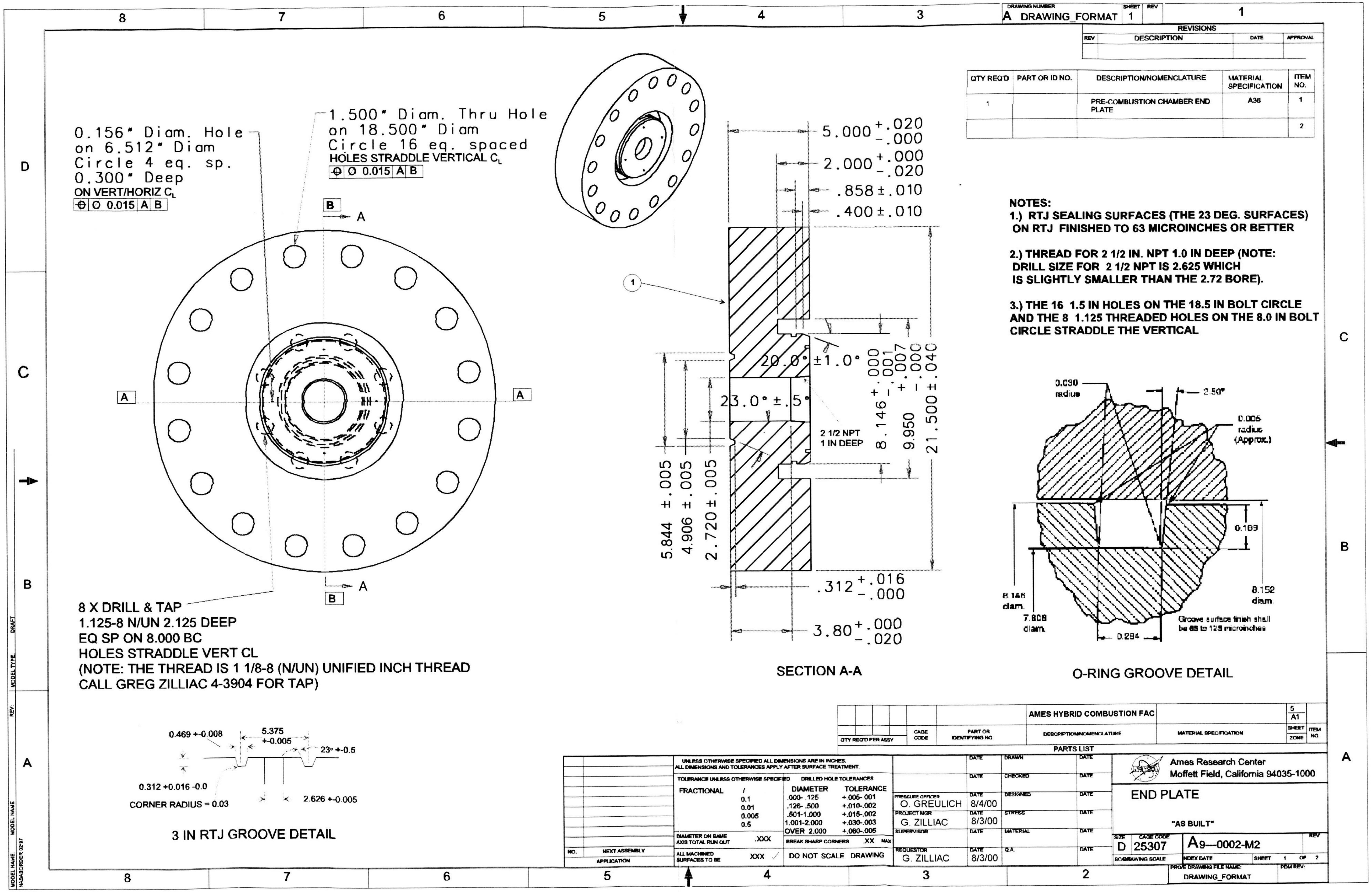
AS-BUILT

SIZE	CAGE CODE		REV
D	25307	A9---0002-M1	
SCALE	DRAWING SCALE	INDEX DATE	SHEET 1 OF 2

PROE DRAWING FILE NAME: DRAWING_FORMAT

PDM REV:

MODEL NAME: NASABORDER 02/97 MODEL NAME REV: MODEL TYPE: DRAFT



NOTES:

1.) RTJ SEALING SURFACES (THE 23 DEG. SURFACES) ON RTJ FINISHED TO 63 MICROINCHES OR BETTER

2.) THREAD FOR 2 1/2 IN. NPT 1.0 IN DEEP (NOTE: DRILL SIZE FOR 2 1/2 NPT IS 2.625 WHICH IS SLIGHTLY SMALLER THAN THE 2.72 BORE).

3.) THE 16 1.5 IN HOLES ON THE 18.5 IN BOLT CIRCLE AND THE 8 1.125 THREADED HOLES ON THE 8.0 IN BOLT CIRCLE STRADDLE THE VERTICAL

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		PRE-COMBUSTION CHAMBER END PLATE	A36	1
				2

AMES HYBRID COMBUSTION FAC

5/A1

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES. ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED — DRILLED HOLE TOLERANCES

FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000-.125	+.005-.001
	0.01	.126-.500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX — BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓ — DO NOT SCALE DRAWING

PRESSURE OFFICER O. GREULICH	DATE 8/4/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 8/3/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 8/3/00	Q.A.	DATE

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END PLATE

"AS BUILT"

SIZE D CAGE CODE 25307 A9---0002-M2 REV

SHEET 1 OF 2

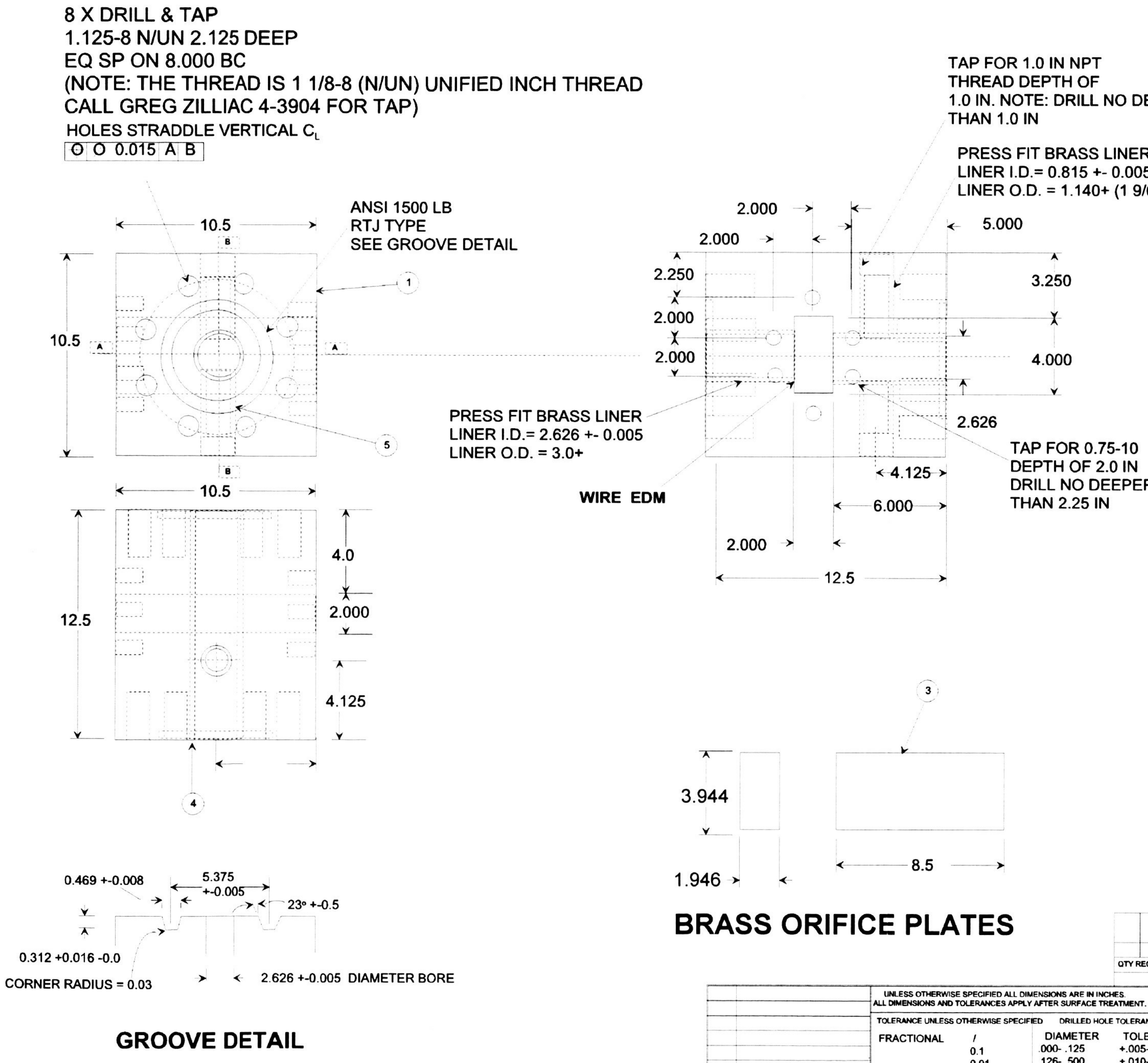
PRO/E DRAWING FILE NAME: DRAWING_FORMAT

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REV	DESCRIPTION	DATE	APPROVAL

REVISIONS

8 X DRILL & TAP
1.125-8 N/UN 2.125 DEEP
EQ SP ON 8.000 BC
(NOTE: THE THREAD IS 1 1/8-8 (N/UN) UNIFIED INCH THREAD
CALL GREG ZILLIAC 4-3904 FOR TAP)
HOLES STRADDLE VERTICAL C_L
| ○ | ○ 0.015 | A | B |



BRASS ORIFICE PLATES

GROOVE DETAIL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		SONIC NOZZLE HOLDER	A36	1
2		END CAPS	A276 grade F304	2
4		BRASS ORIFICE PLATES (GREG ZILLIAC WILL SUPPLY MATERIAL)	ASTM B-187	3
1		BRASS LINER (PRESS FIT)		4
2		BRASS LINER (PRESS FIT) OD = 1.140+ WALL = 0.250		5

NOTES:

1.) WIRE EDM 2.000 +0.000/-0.002 x 4.000 +0.000 -0.010 RECTANGULAR CUTOUT

2.) CAPS SHOULD BE MACHINED TO FIT THE RECTANGULAR CUTOUT WITH AS SNUG OF A FIT AS POSSIBLE YET REMOVABLE BY HAND (MATCH MARK IF NECESSARY).

3.) SEALING SURFACES ON RTJ FINISHED TO 63 MICROINCHES OR BETTER

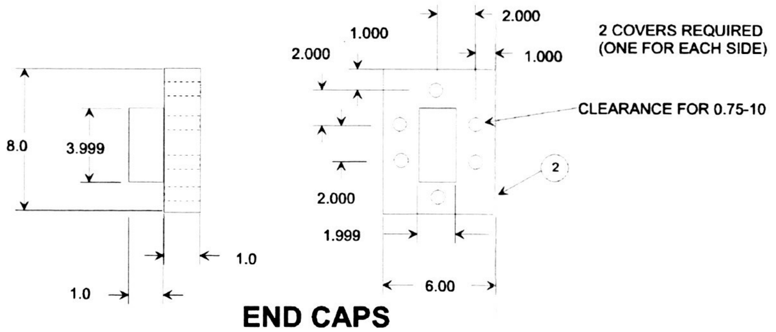
4.) PRESS FIT BRASS TUBE (I.D.=2.626 +- 0.005, O.D = 3.0+) FULL LENGTH

5.) PRESS FIT BRASS TUBE (I.D.=0.815, W=0.25) THEN BORE OUT 2.626 HOLE AFTER TO PREVENT STEPS

6.) NICKEL-COPPER ORIFICE PLATES SHOULD BE A LIGHT SLIP FIT IN RECTANGULAR BORE IN THE ORIFICE HOLDER

7.) SOLVENT CLEAN THE BORES AND LINERS PRIOR TO THE PRESS FITS TO REMOVE ALL HYDROCARBONS (OILS). THIS COMPONENT WILL BE USED IN AN OXYGEN SYSTEM

8.) ADVISE ACTUAL THICKNESS OF MATERIAL AVAILABLE



2 COVERS REQUIRED
(ONE FOR EACH SIDE)

END CAPS

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET / ZONE	ITEM NO.
					5 A1	

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED		DRILLED HOLE TOLERANCES	
FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000- .125	+.005-.001
	0.01	.126- .500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005
DIAMETER ON SAME AXIS TOTAL RUN OUT	.XXX	BREAK SHARP CORNERS	.XX MAX
ALL MACHINED SURFACES TO BE	XXX	DO NOT SCALE DRAWING	

NO.	NEXT ASSEMBLY
	APPLICATION

	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 8/4/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 8/3/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 8/3/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

SONIC NOZZLE HOLDER

"AS BUILT"

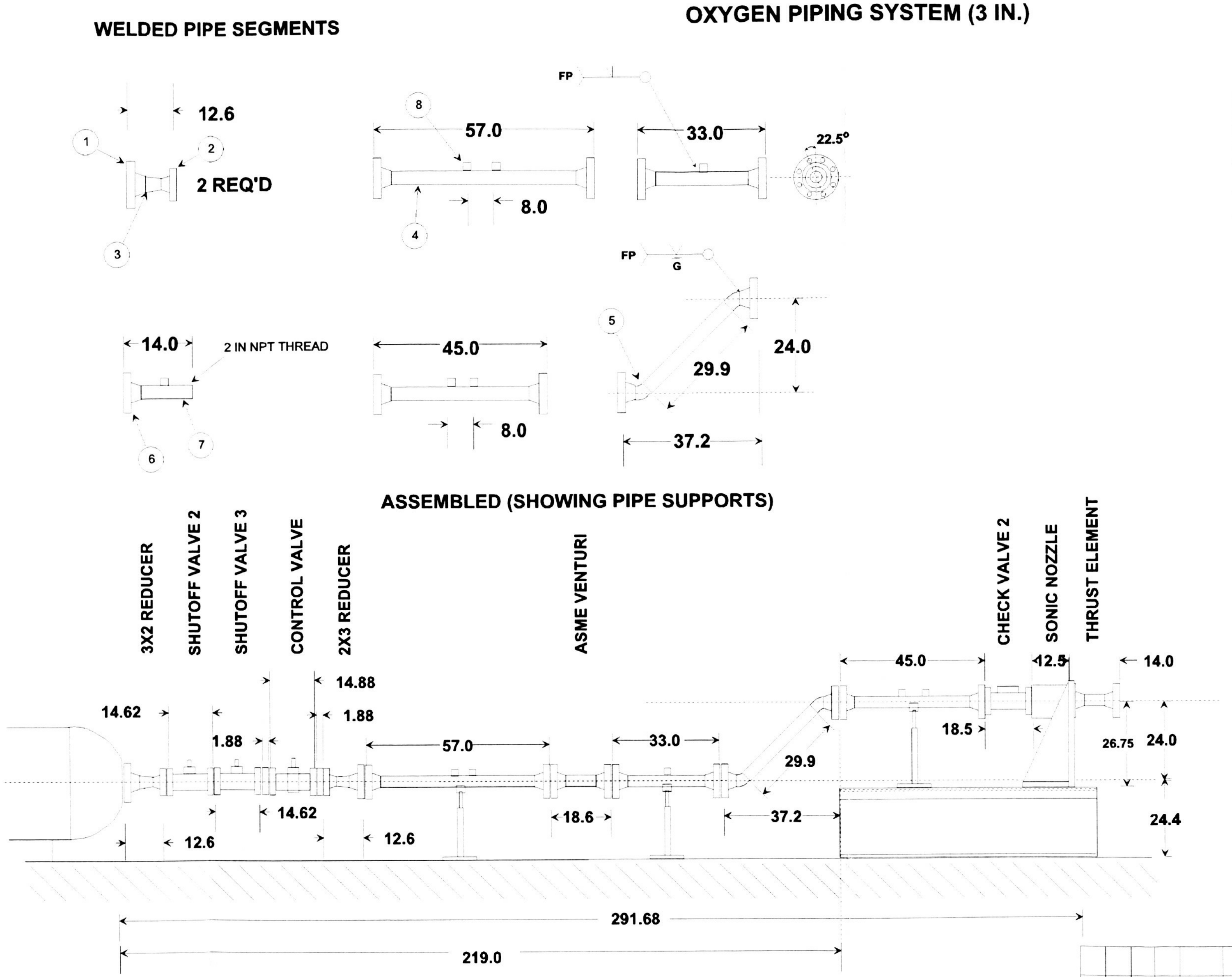
SIZE D CAGE CODE 25307 A9---0002-M3 REV
SCALE DRAWING SCALE INDEX DATE SHEET 1 OF 2
PRO/E DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

MODEL NAME NASABORDER 02/97 MODEL NAME REV MODEL TYPE DRAFT

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REVISIONS			
REV	DESCRIPTION	DATE	APPROVAL

OXYGEN PIPING SYSTEM (3 IN.)



QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
7 + 3		FLANGE, 3 IN. ASME CLASS 1500 WELD NECK RTJ-TYPE, 2.626 IN. BORE (HAVE 3, NEED ONLY 7)	A182 grade F304	1
2		FLANGE, 2 IN. ASME CLASS 1500 WELD NECK, RTJ-TYPE	A182 grade F304	2
2		CONCENTRIC REDUCER, 3X2, SCHEDULE 160	A403 grade WP304	3
12 FT		PIPE, 3 IN. SCHEDULE 160, SEAMLESS	A312 grade TP304	4
2		ELBOW, 3 IN. SCHEDULE 160 LONG RADIUS, 45 DEG	A403 grade WP304	5
1		FLANGE, 2 IN. ASME CLASS 1500 WELD NEC, RTJ-TYPE (1.689 IN BORE)	A182 grade F304	6
1FT		PIPE, 2 IN. SCHEDULE 160, SEAMLESS, ID=1.689 IN	A312 grade TP304	7
6		THREDOLET, 1/2 NPT RATED FOR 3000 PSI MIN.	A182 grade F304	8

NOTES:
1.) ALL FABRICATION CAN BE DONE IN SHOP (NO FIELD WELDS REQUIRED)
2.) NO BACKUP RINGS
3.) ALL FULL PENETRATION WELDS
4.) WELDS GROUND FLUSH ON INTERIOR
5.) X-RAY AND DYE PEN. WELDS
6.) MUST BE CERTIFIED WELDS
7.) TOLERANCE ON ALL LENGTH DIMENSIONS ARE +- 0.25 IN.
8.) DIMENSIONS INCLUDE RAISED FACE
9.) ALL FLANGES ARE 3 IN. UNLESS NOTED
10.) ALL PIPE IS 3 IN. SCHEDULE 160 (2.626 IN BORE) UNLESS NOTED
11.) EVERYTHING IS STAINLESS STEEL
12.) FLANGE BOLT HOLES STRADDLE VERTICAL CENTERLINE
13.) THREDOLETS ARE POSITIONED ON VERTICAL CENTERLINE
14.) NO EXCESS WELD MATERIAL ON WETTED SURFACES OF PIPE
15.) FABRICATION MUST MEET ASME B31.3

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.
					5 A1	

PARTS LIST

NO.	NEXT ASSEMBLY	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED		DRILLED HOLE TOLERANCES	
FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000- .125	+.005-.001
	0.01	.126- .500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005
DIAMETER ON SAME AXIS TOTAL RUN OUT	.XXX	BREAK SHARP CORNERS	.XX MAX
ALL MACHINED SURFACES TO BE	XXX	DO NOT SCALE DRAWING	

	DATE		DATE
	DATE	DRAWN G. ZILLIAC	DATE 7/7/00
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 7/7/00	DESIGNED G. ZILLIAC	DATE 7/7/00
PROJECT MGR G. ZILLIAC	DATE 7/7/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 7/7/00	Q A.	DATE

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Moffett Field, California 94035-1000

WELDED PIPE SEGMENTS
"AS BUILT"

SIZE D
CAGE CODE 25307
A9—0002-M4
REV
SCALE DRAWING SCALE
INDEX DATE
SHEET 1 OF 2
PRO/E DRAWING FILE NAME: DRAWING_FORMAT
PDM REV:

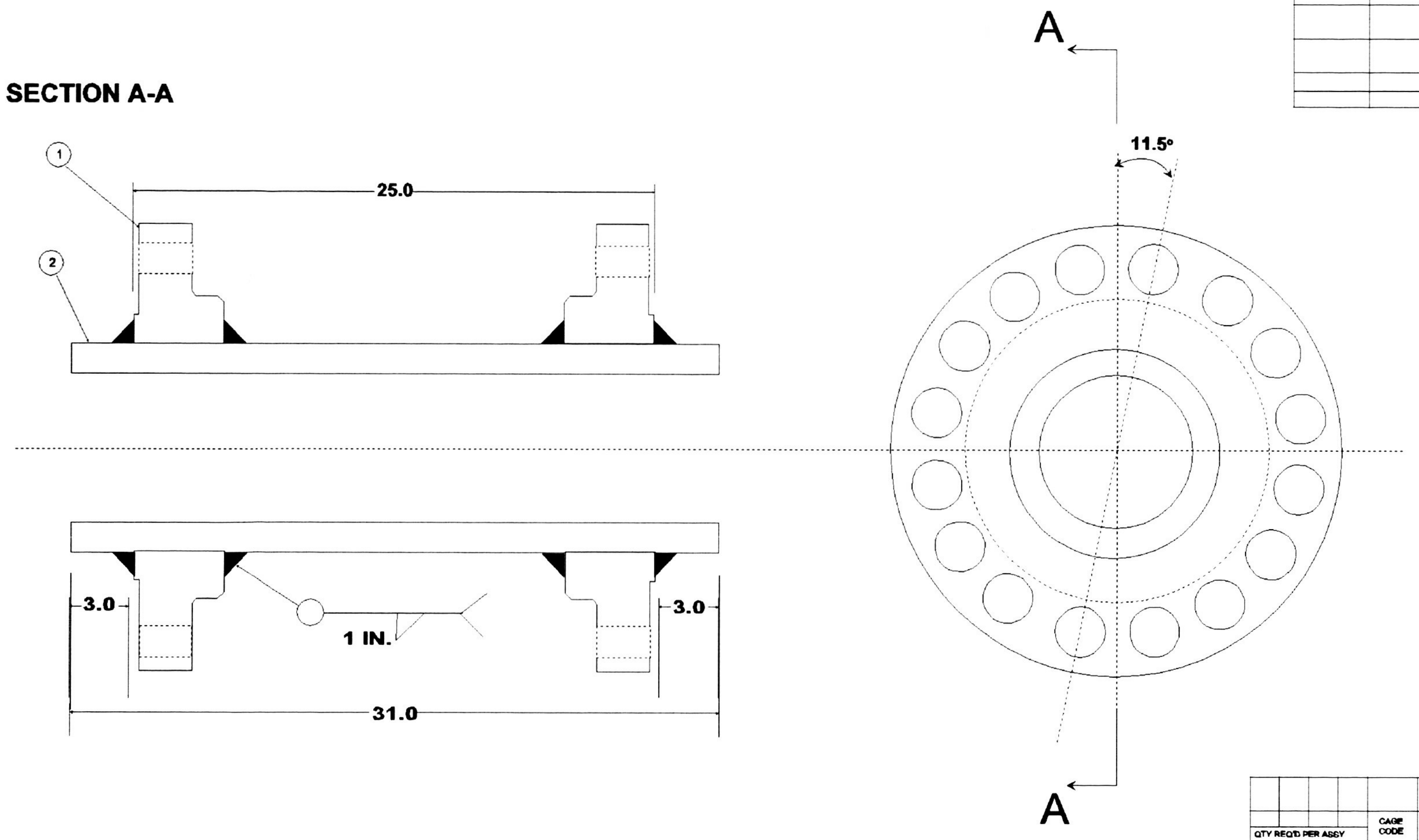
MODEL NAME: NASABORDER 02/97 MODEL NAME REV. MODEL TYPE: DRAFT

DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS			
REV	DESCRIPTION	DATE	APPROVAL

COMBUSTION CHAMBER CASING

SECTION A-A



QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
2		10 IN. ASME CLASS 900 SLIP-ON FLANGE WITH 10.050 BORE	A105	1
6 FT		SMLS TUBING, 10 IN. OD X 1.25 W ID = 7.5 PROVIDE EXCESS TUBE, AVAILABLE FROM TUBULAR STEEL (314) 851-9200	SA106	2
				5
				6
				7
				8

NOTES:

1.) ALL FABRICATION CAN BE DONE IN SHOP
(NO FIELD WELDS REQUIRED)

2.) MUST BE CERTIFIED WELDS

3.) TOLERANCE ON ALL LENGTH DIMENSIONS ARE +- 0.05 IN.

4.) FLANGE BOLT HOLES STRADDLE VERTICAL CENTERLINE

5.) FABRICATION MUST MEET ASME B31.3

AMES HYBRID COMBUSTION FACILITY				5 A1	
QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY
APPLICATION	

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED		DRILLED HOLE TOLERANCES	
FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000- .125	+.005-.001
	0.01	.126- .500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005
DIAMETER ON SAME AXIS TOTAL RUN OUT	.XXX	BREAK SHARP CORNERS	.XX MAX
ALL MACHINED SURFACES TO BE	XXX ✓	DO NOT SCALE DRAWING	

	DATE	DRAWN	DATE
		G. ZILLIAC	7/6/00
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 7/7/00	DESIGNED G. ZILLIAC	DATE 7/6/00
PROJECT MGR G. ZILLIAC	DATE 7/6/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 7/6/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

COMBUSTION CHAMBER CASING

"AS BUILT"

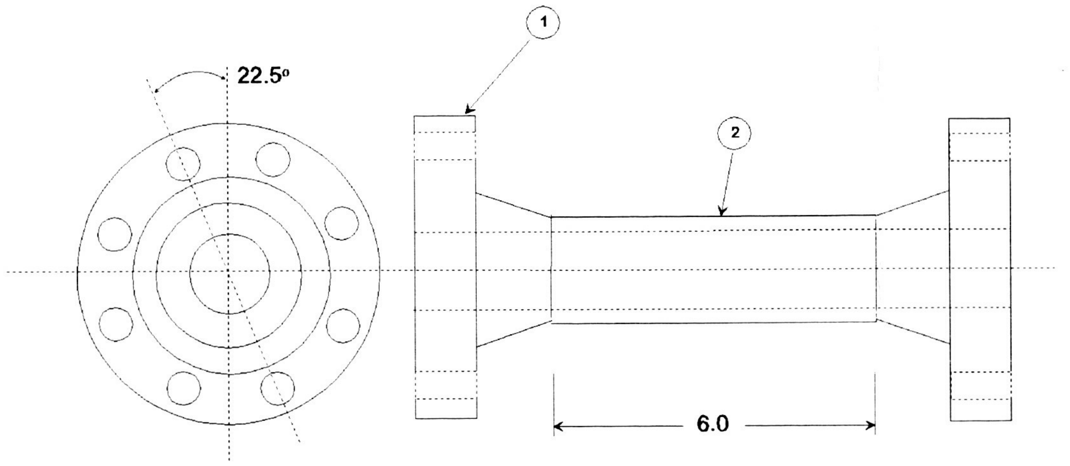
SIZE	CAGE CODE		REV
D	25307	A9—0002-M5	
SCALE	DRAWING SCALE	INDEX DATE	SHEET 1 OF 2
		PROE DRAWING FILE NAME: DRAWING_FORMAT	PDM REV:

MODEL NAME NASABORDER 02/97 | MODEL NAME | REV | MODEL TYPE | DRAFT

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REVISIONS			
REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
2		FLANGE, 3 IN. ASME CLASS 1500 WELD NECK RTJ-TYPE, 2.626 IN. BORE	A182 grade F304	1
0.5 FT		PIPE, 3 IN. SCHEDULE 160, SEAMLESS	A312 grade TP304	2



THRUST SEGMENT

NOTES:
1.) NO BACKUP RINGS ON WELDS
2.) ALL FULL PENETRATION WELDS
3.) WELDS GROUND FLUSH ON INTERIOR
4.) X-RAY AND DYE PEN. WELDS
5.) HYDRO-TEST TO 5600 PSI
6.) MUST BE CERTIFIED-U CODE STAMPED WELDS
7.) FLANGES ARE 3 IN. CLASS 1500 WELD NECK RTJ
8.) PIPE IS 3 IN. SCHEDULE 160 (2.626 IN BORE)
9.) NO EXCESS WELD MATERIAL ON WETTED SURFACES OF PIPE
10.) FABRICATION MUST MEET ASME B31.3

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	5/A1 SHEET ZONE	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

	DATE	DRAWN G. ZILLIAC	DATE 9/15/00
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 10/3/00	DESIGNED G. ZILLIAC	DATE 9/15/00
PROJECT MGR G. ZILLIAC	DATE 9/15/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 9/15/00	Q.A.	DATE

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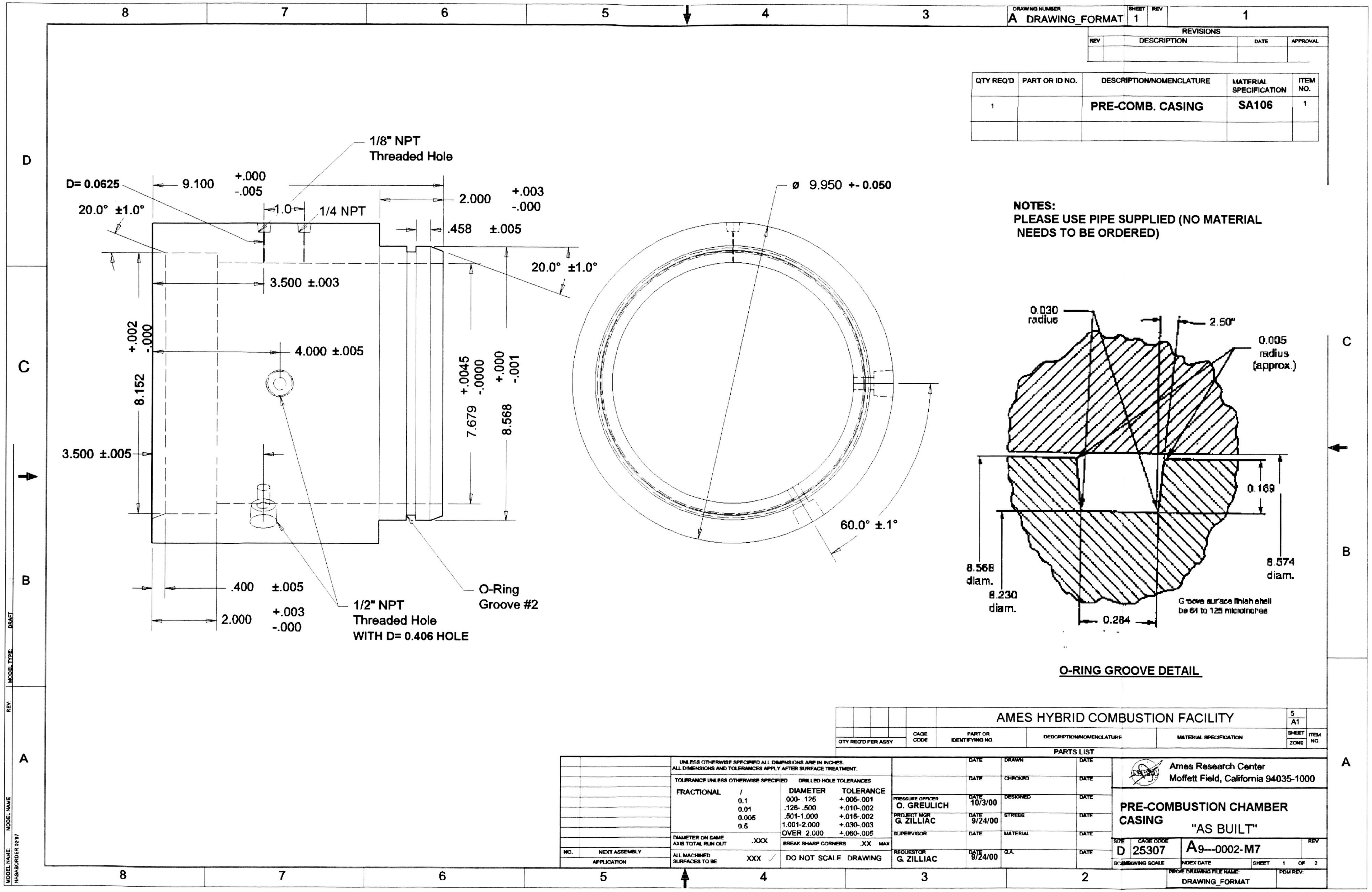
Moffett Field, California 94035-1000

THRUST SEGMENT
"AS BUILT"

SIZE D CAGE CODE 25307 A9---0002-M6 REV
SCALE DRAWING SCALE INDEX DATE SHEET 1 OF 2
PRO/E DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

MODEL NAME NASABORDER 02-97 MODEL NAME REV. MODEL TYPE DRAFT



NOTES:
PLEASE USE PIPE SUPPLIED (NO MATERIAL NEEDS TO BE ORDERED)

O-RING GROOVE DETAIL

DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		PRE-COMB. CASING	SA106	1

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET 5 / ZONE A1	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY
APPLICATION	

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED		DRILLED HOLE TOLERANCES	
FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000- .125	+.005-.001
	0.01	.126- .500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005
DIAMETER ON SAME AXIS TOTAL RUN OUT	.XXX	BREAK SHARP CORNERS	.XX MAX
ALL MACHINED SURFACES TO BE	XXX ✓	DO NOT SCALE DRAWING	

	DATE		DATE
	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 10/3/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 9/24/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 9/24/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

PRE-COMBUSTION CHAMBER CASING
"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002-M7	
SCALE DRAWING SCALE		INDEX DATE	SHEET 1 OF 2
		PRO/E DRAWING FILE NAME: DRAWING_FORMAT	PDM REV:

DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS

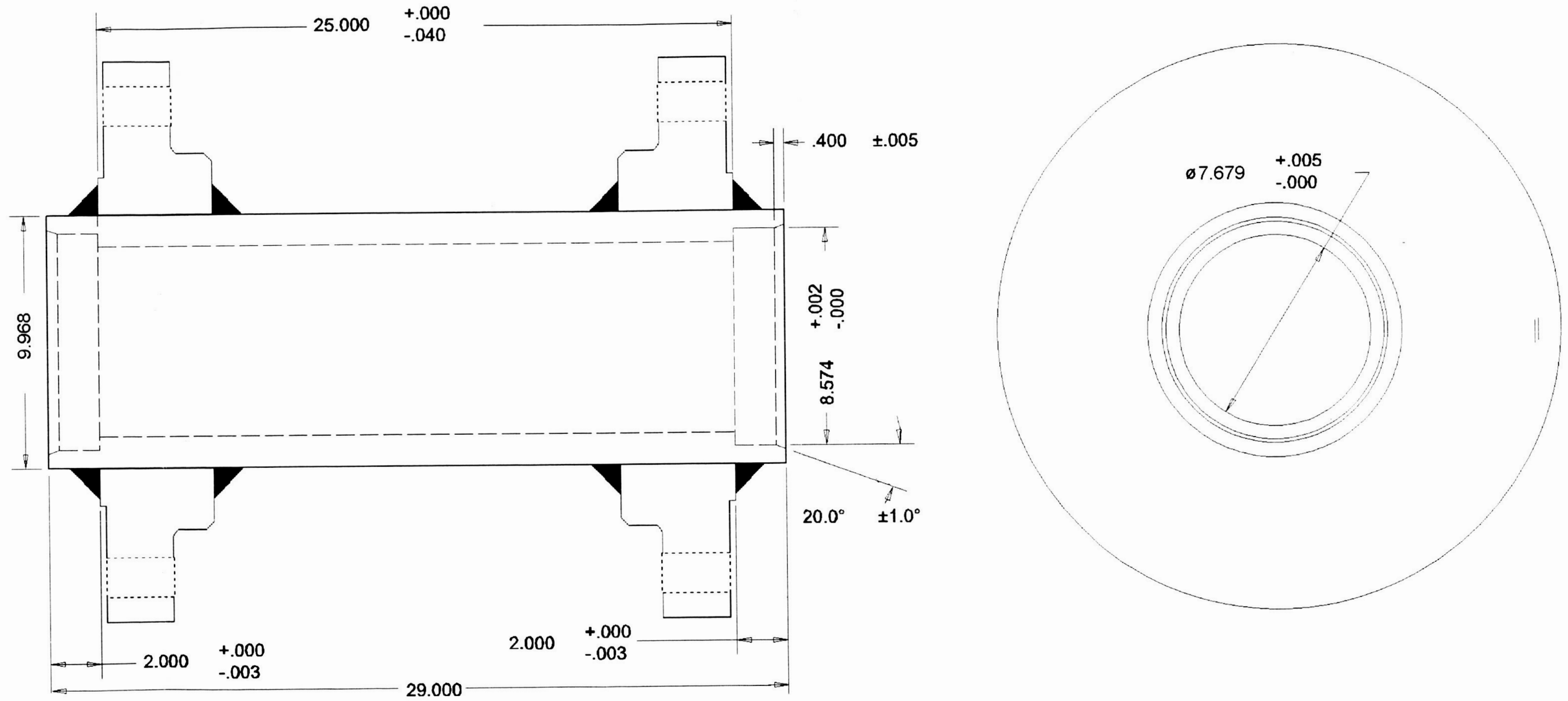
REV	DESCRIPTION	DATE	APPROVAL

NOTES:

1.) PLEASE USE PIPE SUPPLIED (NO MATERIAL NEEDS TO BE ORDERED)

2.) FLANGES NOT SHOWN ON DRAWING SEE A9—0002-M5

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		FUEL CASING	SA106	1



AMES HYBRID COMBUSTION FACILITY

5 A1

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED		DRILLED HOLE TOLERANCES	
FRACTIONAL	/	DIAMETER	TOLERANCE
	0.1	.000- .125	+.005-.001
	0.01	.126- .500	+.010-.002
	0.005	.501-1.000	+.015-.002
	0.5	1.001-2.000	+.030-.003
		OVER 2.000	+.060-.005
DIAMETER ON SAME AXIS TOTAL RUN OUT	.XXX	BREAK SHARP CORNERS	.XX MAX
ALL MACHINED SURFACES TO BE	XXX ✓	DO NOT SCALE DRAWING	

	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 10/3/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 9/24/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 9/24/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

FUEL CASING
"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002- M8	
SCALE/DRAWING SCALE		INDEX DATE	SHEET 1 OF 2

PRO/E DRAWING FILE NAME: DRAWING_FORMAT
PDM REV:

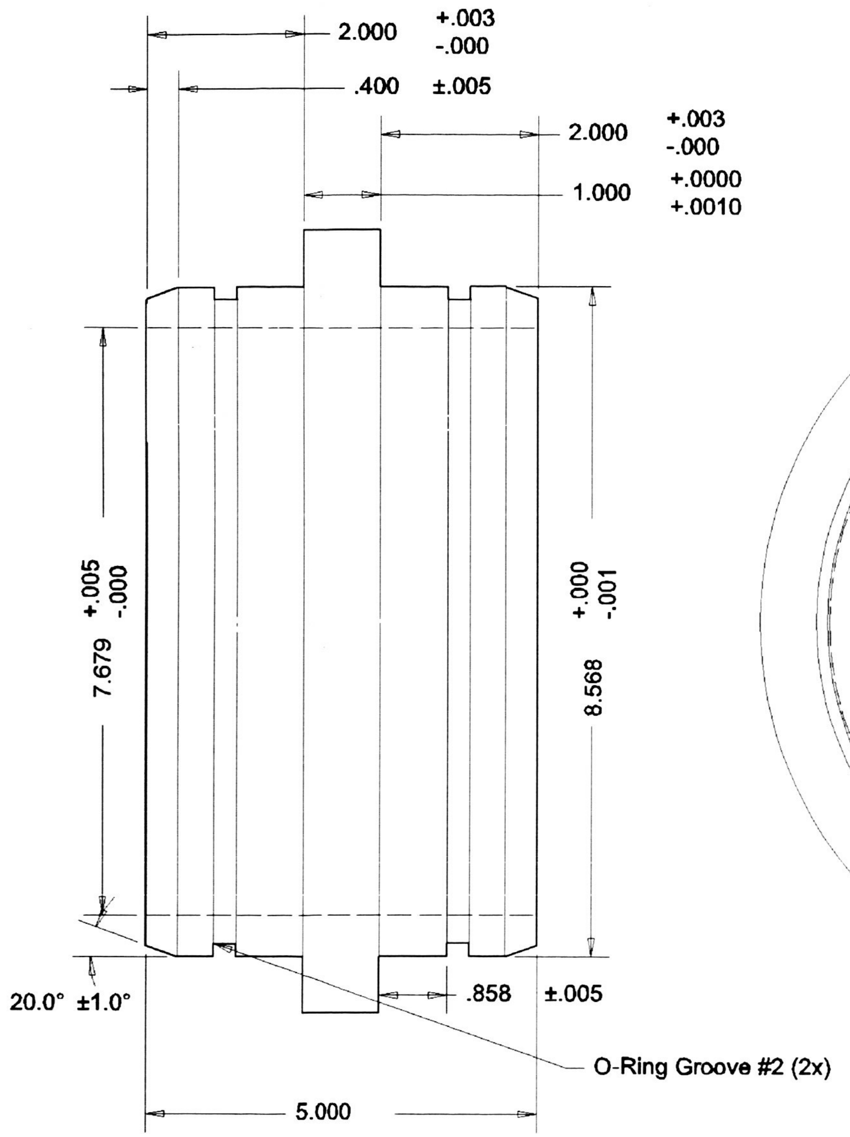
MODEL NAME NASA/BORDER 32/97
MODEL NAME
REV
MODEL TYPE DRAFT

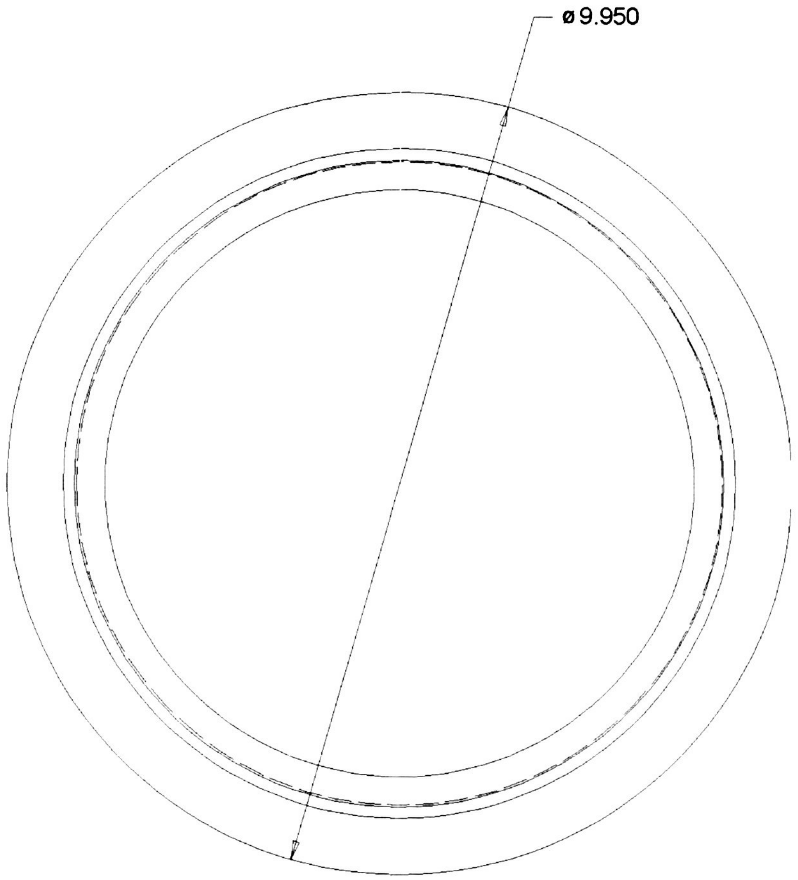
DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS

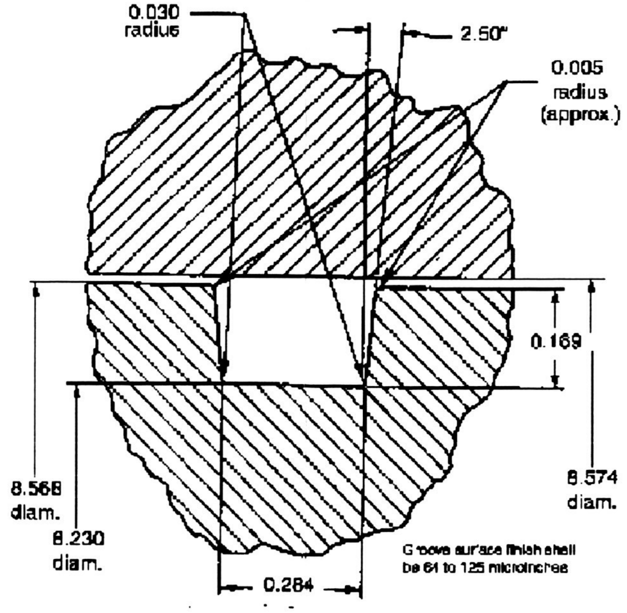
REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		COUPLER	SA106	1





NOTES:
PLEASE USE PIPE SUPPLIED (NO MATERIAL NEEDS TO BE ORDERED)



O-RING GROOVE DETAIL

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.
					5 A1	

PARTS LIST

NO.	NEXT ASSEMBLY	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
BREAK SHARP CORNERS .XX MAX
ALL MACHINED SURFACES TO BE XXX ✓
DO NOT SCALE DRAWING

	DATE		DATE
	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 10/3/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 9/24/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 9/24/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

COUPLER
"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002- M9	

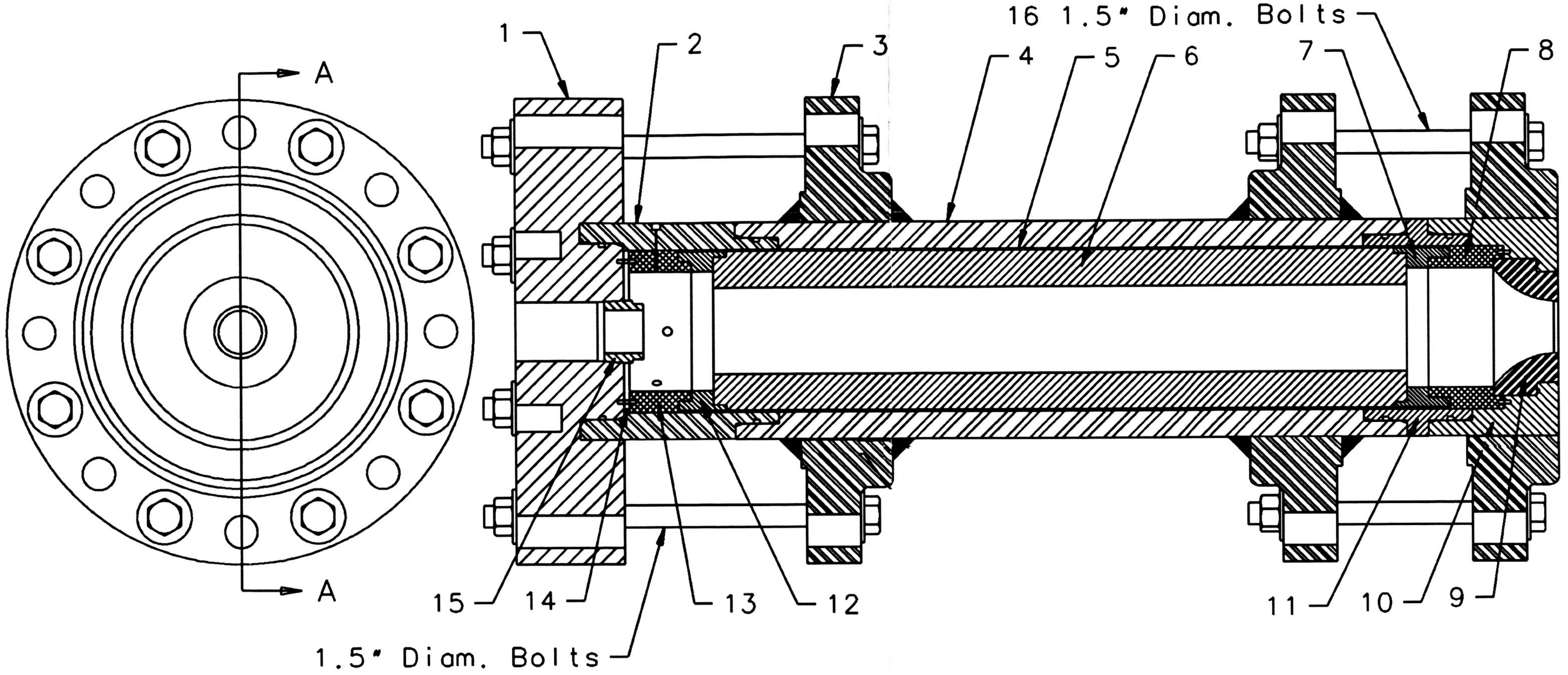
SCALE DRAWING SCALE | INDEX DATE | SHEET 1 OF 2

PRO/E DRAWING FILE NAME: DRAWING_FORMAT | PDM REV:

MODEL NAME NASABORDER 02-97 | MODEL NAME | REV | MODEL TYPE DRAFT

NASA Ames Research Center
Hybrid Combustion Facility

1. End Plate, ASTM A36
2. Pre-Combustion Chamber Casing, ASTM A519
3. 10" Class 900 Slip on Flange, ASTM A182
4. Fuel Casing, ASTM A519
5. Fuel Insulator, Phenolic
6. Fuel
7. Aft Insulator 1, ATJ Graphite
8. Aft Insulator 2, ATJ Graphite



9. Nozzle, ATJ Graphite
10. Post-Combustion Chamber Casing, ASTM A576
11. Coupler, ASTM A519
12. Fore Insulator 1, ATJ Graphite
13. Fore Insulator 2, ATJ Graphite
14. End Plate Insulator, ATJ Graphite
15. Injector, ASTM A479

AMES HYBRID COMBUSTION FACILITY

MATERIAL SPECIFICATION

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

NO. NEXT ASSEMBLY APPLICATION

PRESSURE OFFICER DATE
PROJECT MGR DATE
SUPERVISOR DATE
REQUESTOR DATE
DRAWN DATE
CHECKED DATE
DESIGNED DATE
STRESS DATE
MATERIAL DATE
Q.A. DATE

Ames Research Center
Moffett Field, California 94035-1000

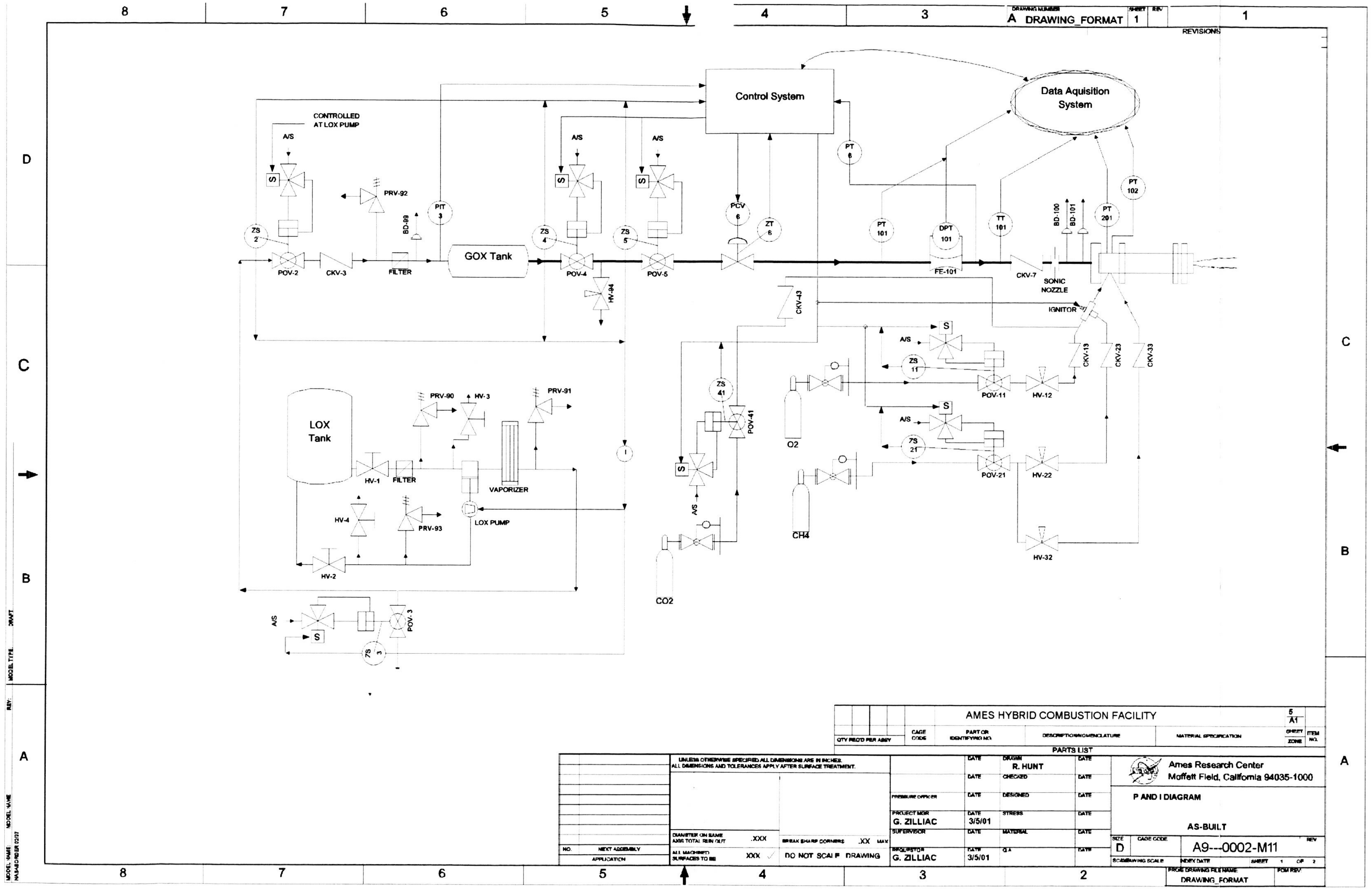
AMES ASSEMBLY
"AS BUILT"

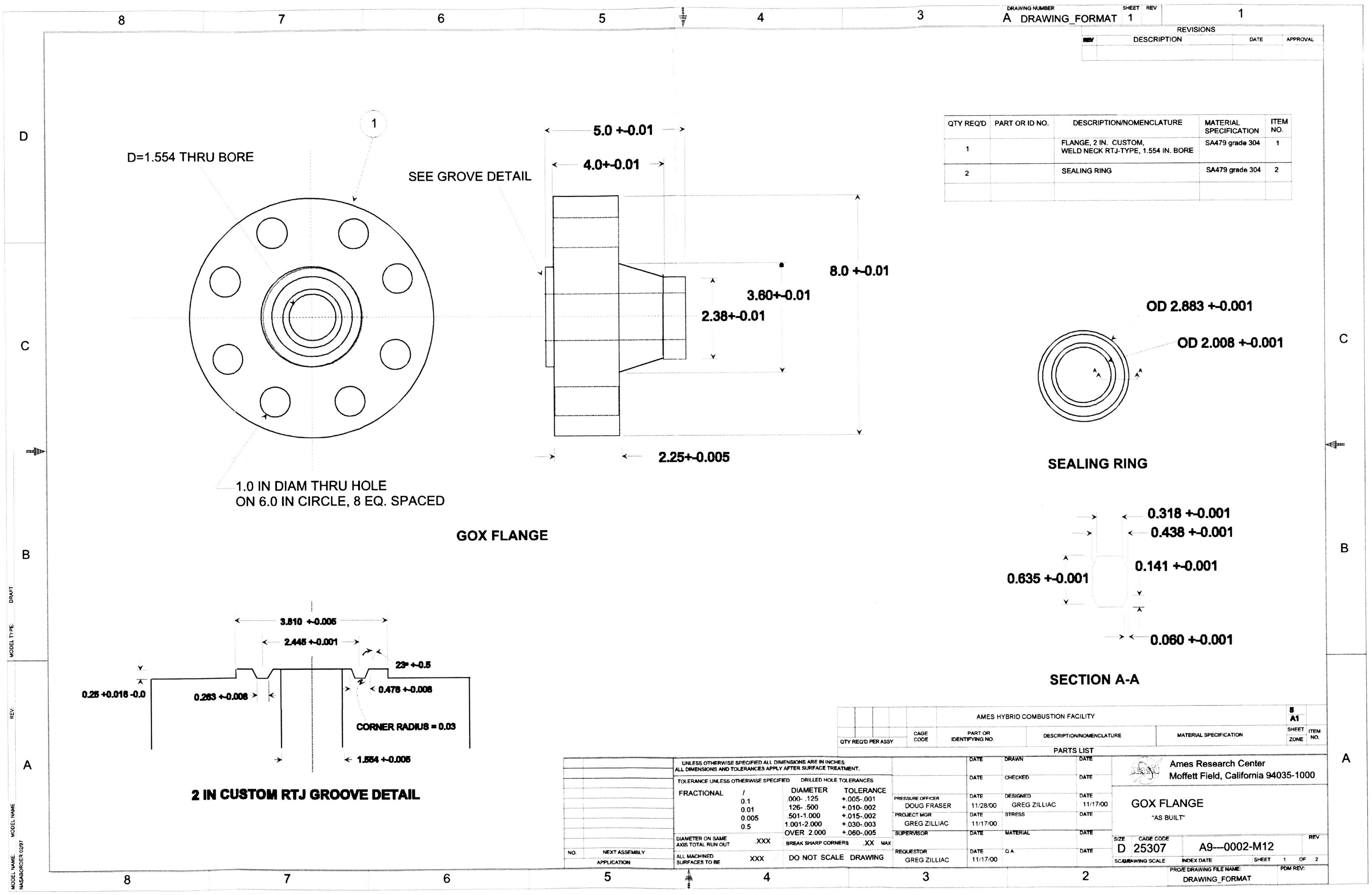
SIZE D CAGE CODE 25307 A9—0002- M10 REV

DRAWING SCALE INDEX DATE SHEET 1 OF 2

PRO/E DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV


Control System
Data Aquisition System
CONTROLLED AT LOX PUMP
A/S
S
ZS 2
POV-2
CKV-3
PRV-92
BD-99
FILTER
PIT 3
GOX Tank
ZS 4
POV-4
HV-94
ZS 5
POV-5
PCV 6
ZT 6
PT 6
PT 101
DPT 101
FE-101
TT 101
CKV-7
SONIC NOZZLE
BD-100
BD-101
PT 201
PT 102
IGNITOR
CKV-43
CKV-13
CKV-23
CKV-33
ZS 11
POV-11
HV-12
ZS 21
POV-21
HV-22
HV-32
O2
CH4
ZS 41
POV-41
CO2
LOX Tank
HV-1
FILTER
PRV-90
HV-3
PRV-91
VAPORIZER
LOX PUMP
HV-4
PRV-93
HV-2
POV-3
ZS 3
REVISIONS
DRAWING NUMBER
A DRAWING_FORMAT
SHEET 1
REV
AMES HYBRID COMBUSTION FACILITY
QTY REQ'D PER ASSY
CAGE CODE
PART OR IDENTIFYING NO.
DESCRIPTION/NOMENCLATURE
MATERIAL SPECIFICATION
SHEET ZONE
5 A1
ITEM NO.
PARTS LIST
UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.
DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
ALL MACHINED SURFACES TO BE XXX
BREAK SHARP CORNERS .XX MAX
DO NOT SCALE DRAWING
NO.
NEXT ASSEMBLY
APPLICATION
PRESSURE OFFICER
PROJECT MGR G. ZILLIAC
SUPERVISOR
REQUESTOR G. ZILLIAC
DATE 3/5/01
DATE 3/5/01
DRAWN R. HUNT
CHECKED
DESIGNED
STRESS
MATERIAL
Q.A
DATE
Ames Research Center
Moffett Field, California 94035-1000
P AND I DIAGRAM
AS-BUILT
SIZE D
CAGE CODE
A9---0002-M11
REV
SCALE
DRAWING SCALE
INDEX DATE
SHEET 1 OF 2
PROE DRAWING FILE NAME:
DRAWING_FORMAT
PDM REV:
MODEL NAME
MODEL TYPE
DRAFT
8
7
6
5
4
3
2
1
D
C
B
A

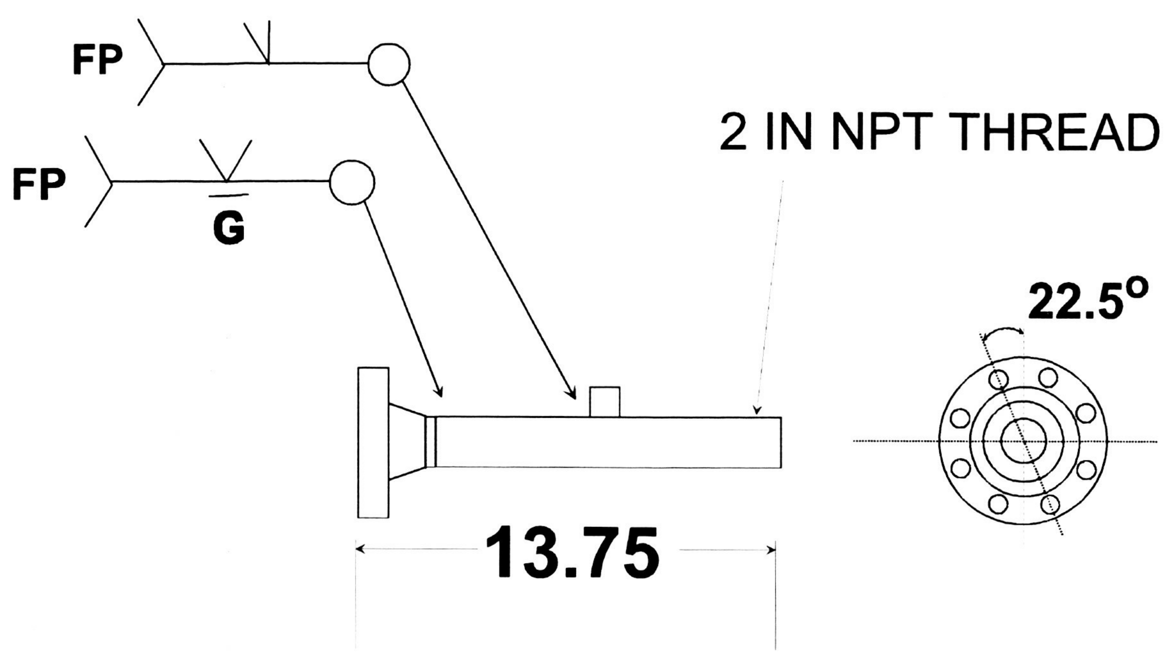


QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		FLANGE, 2 IN. CUSTOM, WELD NECK RTJ-TYPE, 1.554 IN. BORE	SA479 grade 304	1
2		SEALING RING	SA479 grade 304	2

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REV	DESCRIPTION	DATE	APPROVAL
REVISIONS			

WELDED PIPE SEGMENT



QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1 (SUPPLIED)		FLANGE, 2 IN. ASME CLASS 1500 WELD NECK, RTJ-TYPE (CUSTOM)	A182 grade F304	1
2		RTJ RINGS	A182 grade F304	2
1		PIPE, 2 IN. SCHEDULE 160, SEAMLESS, ID=1.689 IN	A312 grade TP304	3

NOTES:

1.) ALL FABRICATION CAN BE DONE IN SHOP (NO FIELD WELDS REQUIRED)
2.) NO BACKUP RINGS
3.) ALL FULL PENETRATION WELDS
4.) WELDS GROUND FLUSH ON INTERIOR
5.) X-RAY AND DYE PEN. WELDS
6.) MUST BE CERTIFIED WELDS
7.) TOLERANCE ON ALL LENGTH DIMENSIONS ARE +- 0.5 IN.
8.) DIMENSIONS INCLUDE RAISED FACE
9.) FLANGE BOLT HOLES STRADDLE VERTICAL CENTERLINE
10.) THREDOLET IS POSITIONED ON VERTICAL CENTERLINE
11.) NO EXCESS WELD MATERIAL ON WETTED SURFACES OF PIPE
12.) FABRICATION MUST MEET ASME B31.3
13.) HYDROTEST TO 4750 PSI
14.) ALL MATERIAL SUPPLIED BY NASA
15.) A MATCHING FLANGE WITH A GRAYLOC FITTING ON THE END OF A PIPE STUB IS AVAILABLE TO USE FOR THE HYDROTEST

AMES HYBRID COMBUSTION FACILITY

5
A1

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000- .125	+.005-.001
.126- .500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
BREAK SHARP CORNERS .XX MAX
ALL MACHINED SURFACES TO BE XXX
DO NOT SCALE DRAWING

NO. NEXT ASSEMBLY
APPLICATION

	DATE		DATE
	DATE	DRAWN GREG ZILLIAC	12/11/00
	DATE	CHECKED	DATE
PRESSURE OFFICER	DATE	DESIGNED GREG ZILLIAC	DATE 12/11/00
PROJECT MGR GREG ZILLIAC	DATE 12/11/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR GREG ZILLIAC	DATE 12/11/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

GOX FLANGE WELD
"AS BUILT"

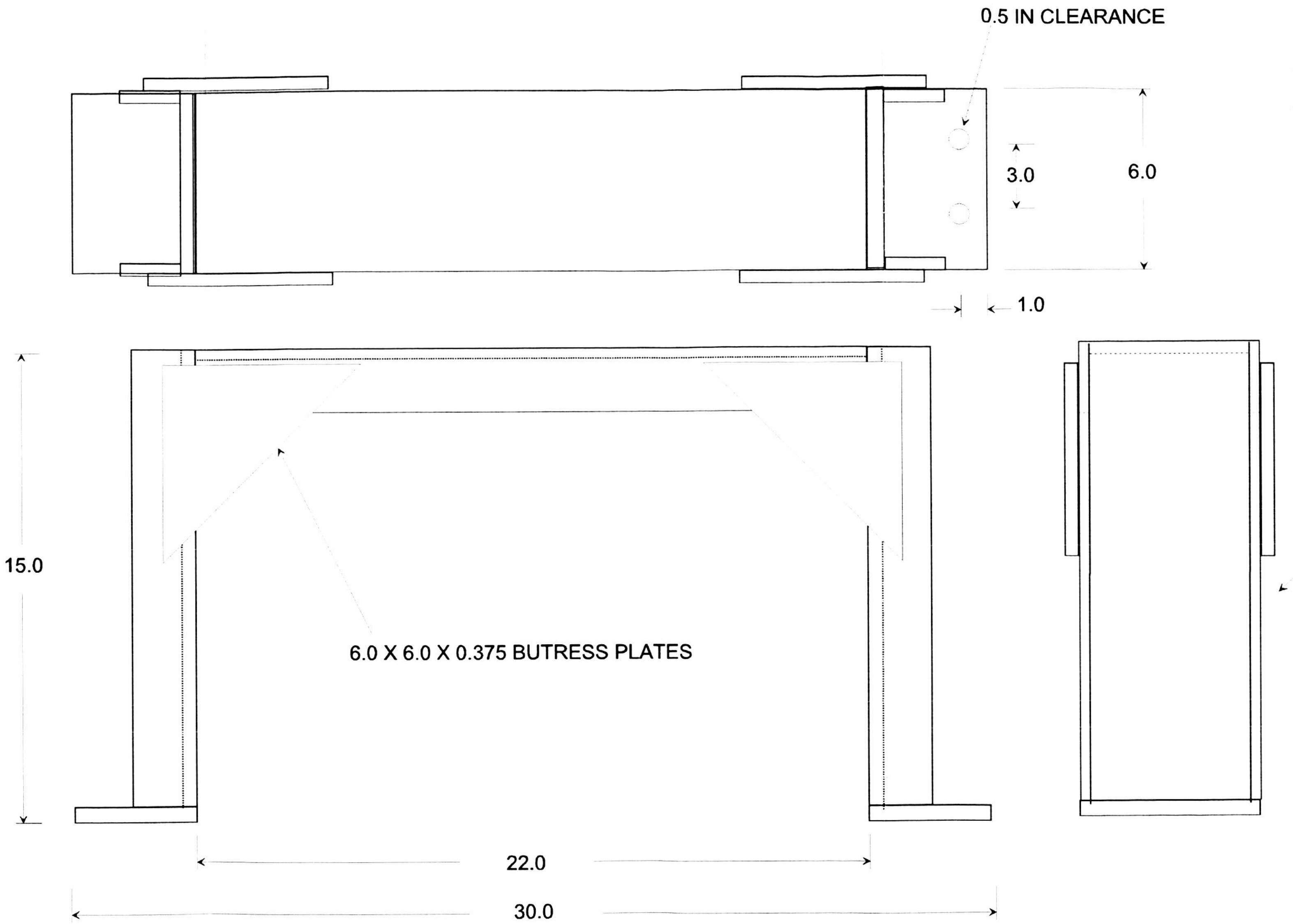
SIZE D CAGE CODE 25307 A9---0002-M13 REV
SCALE DRAWING SCALE INDEX DATE SHEET 1 OF 2
PRO/E DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

MODEL NAME: NASABORDER 02/97 MODEL NAME REV: MODEL TYPE: DRAFT

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REVISIONS			
REV	DESCRIPTION	DATE	APPROVAL

PRE-COMBUSTION CHAMBER SUPPORT



QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		PRECOMBUSTION CHAMBER SUPPORT	STRUCTRUAL STEEL	1

NOTES:
1.) ALL LENGTH DIMENSIONS ARE +-0.125
2.)

AMES HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000- .125	+.005-.001
.126- .500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
BREAK SHARP CORNERS .XX MAX
ALL MACHINED SURFACES TO BE XXX
DO NOT SCALE DRAWING

	DATE		DATE
		DRAWN GREG ZILLIAC	12/13/00
		CHECKED	
PRESSURE OFFICER		DESIGNED GREG ZILLIAC	12/13/00
PROJECT MGR GREG ZILLIAC	12/13/00	STRESS	
SUPERVISOR		MATERIAL	
REQUESTOR GREG ZILLIAC	12/13/00	Q.A.	

Ames Research Center
Moffett Field, California 94035-1000

PRE-COMBUSTION CHAMBER SUPPORT
"AS BUILT"

SIZE D CAGE CODE 25307 A9---0002-M14 REV
SCALE DRAWING SCALE INDEX DATE SHEET 1 OF 2
PRO/E DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

NO. NEXT ASSEMBLY APPLICATION

MODEL NAME: NASABORDER 02/97 MODEL NAME: REV: MODEL TYPE: DRAFT

DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

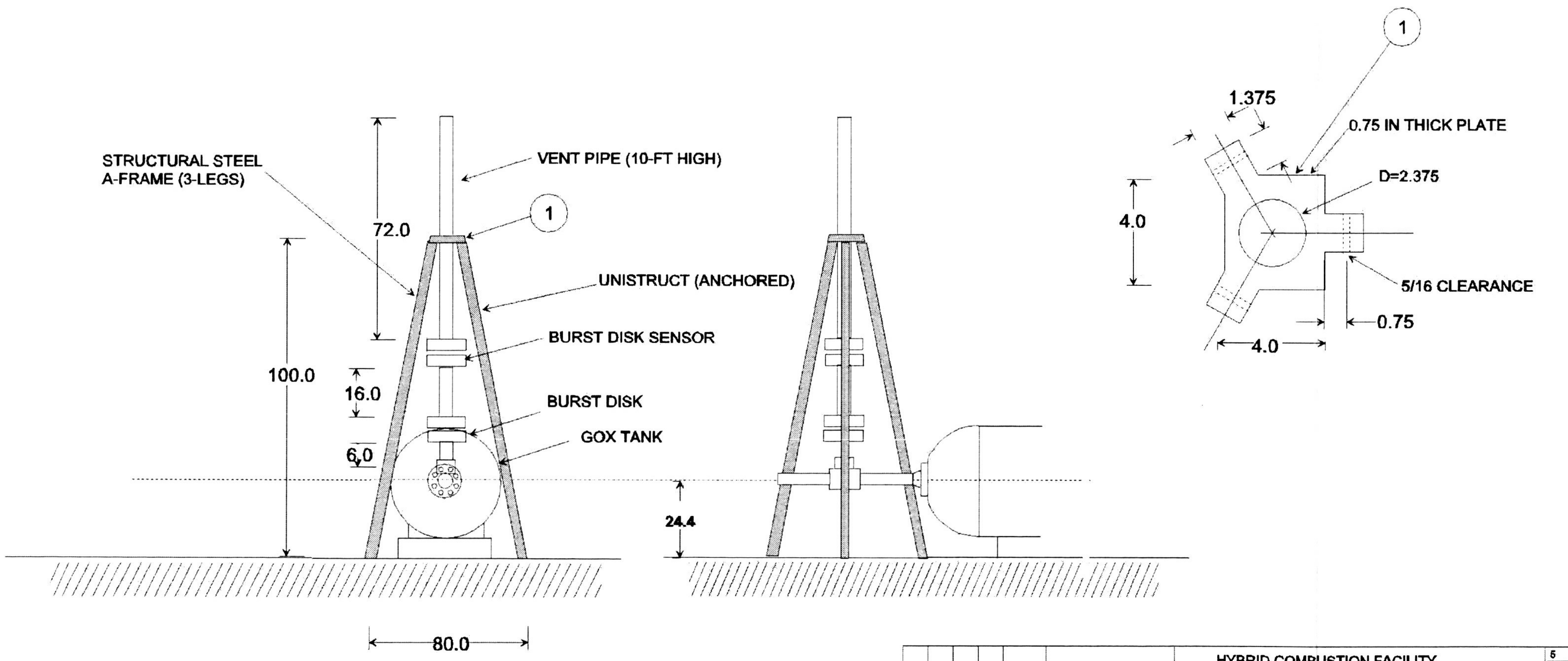
REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

BURST DISK VENT PIPE AND SUPPORT

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO
1		SUPPORT RING	ALUMINUM	1
				2

SUPPORT RING DETAIL



QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.
			HYBRID COMBUSTION FACILITY		5 A1	

PARTS LIST

NO.	NEXT ASSEMBLY
	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

	DATE		DATE
		DRAWN GREG ZILLIAC	3/20/01
		CHECKED	
PRESSURE OFFICER		DESIGNED GREG ZILLIAC	3/20/01
PROJECT MGR GREG ZILLIAC	3/20/01	STRESS	
SUPERVISOR		MATERIAL	
REQUESTOR GREG ZILLIAC	3/20/01	Q.A.	

Ames Research Center
Moffett Field, California 94035-1000

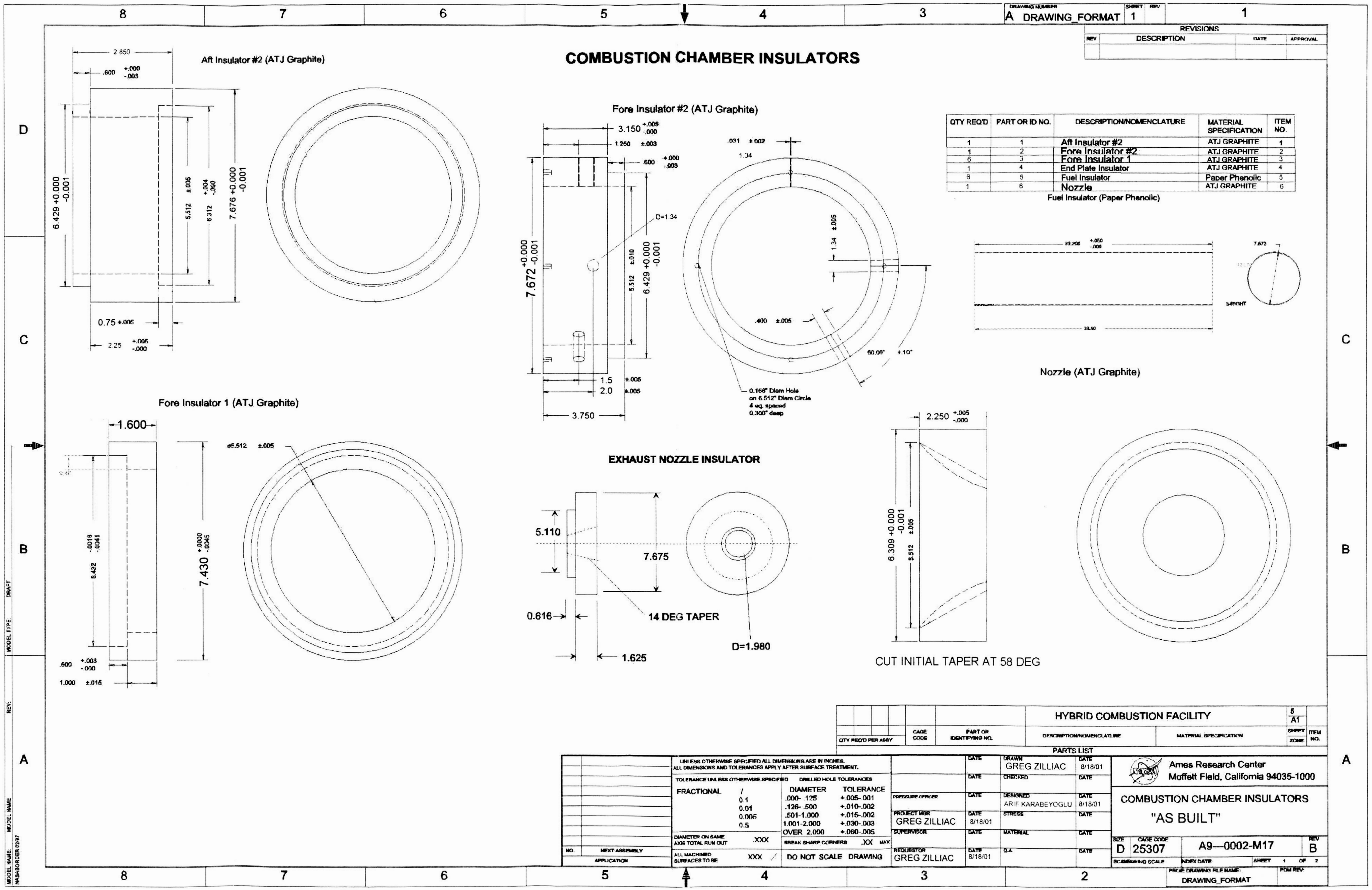
BURST DISK VENT PIPE AND SUPPORT
"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002-M16	

SCALE DRAWING SCALE | INDEX DATE | SHEET 1 OF 2

PROE DRAWING FILE NAME: DRAWING_FORMAT | PDM REV:

COMBUSTION CHAMBER INSULATORS



QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1	1	Aft Insulator #2	ATJ GRAPHITE	1
1	2	Fore Insulator #2	ATJ GRAPHITE	2
6	3	Fore Insulator 1	ATJ GRAPHITE	3
1	4	End Plate Insulator	ATJ GRAPHITE	4
6	5	Fuel Insulator	Paper Phenolic	5
1	6	Nozzle	ATJ GRAPHITE	6

Fuel Insulator (Paper Phenolic)

DRAWING NUMBER A DRAWING_FORMAT SHEET 1 REV

REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

HYBRID COMBUSTION FACILITY

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET 5 / ZONE A1	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY
	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

	DATE		DATE
		DRAWN GREG ZILLIAC	8/18/01
		CHECKED	
PRESSURE OFFICER		DESIGNED ARIF KARABEYOGLU	8/18/01
PROJECT MGR GREG ZILLIAC	8/18/01	STRESS	
SUPERVISOR		MATERIAL	
REQUESTOR GREG ZILLIAC	8/18/01	Q.A.	

Ames Research Center
Moffett Field, California 94035-1000

COMBUSTION CHAMBER INSULATORS
"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002-M17	B

SCALE/DRAWING SCALE INDEX DATE SHEET 1 OF 2

PROE DRAWING FILE NAME: DRAWING_FORMAT PDM REV:

MODEL NAME NASABORDER 02-97 MODEL NAME MODEL TYPE DRAFT REV:

A DRAWING_FORMAT 1

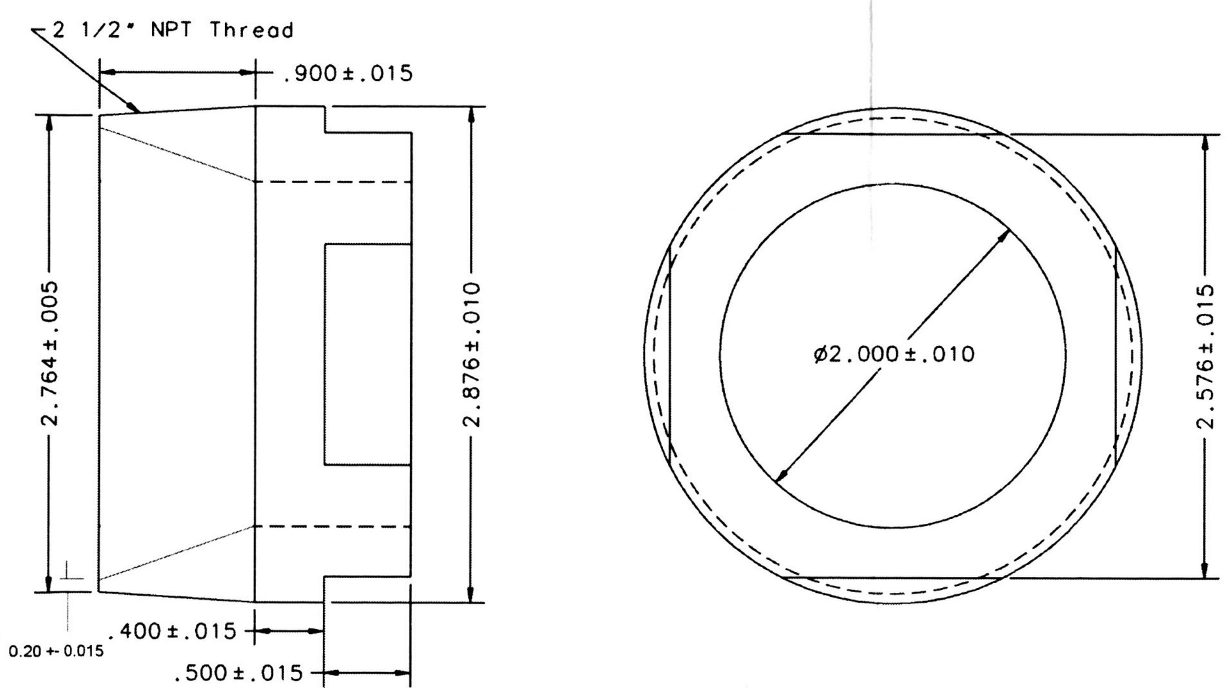
REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

INJECTOR

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		INJECTOR	STAINLESS STEEL	1
				2

Axial Injector



HYBRID COMBUSTION FACILITY

5
A1

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000- .125	+.005-.001
.126- .500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
BREAK SHARP CORNERS .XX MAX
ALL MACHINED SURFACES TO BE XXX ✓
DO NOT SCALE DRAWING

NO. NEXT ASSEMBLY APPLICATION

PRESSURE OFFICER DATE
PROJECT MGR GREG ZILLIAC DATE 7/30/01
SUPERVISOR DATE
REQUESTOR GREG ZILLIAC DATE 7/30/01

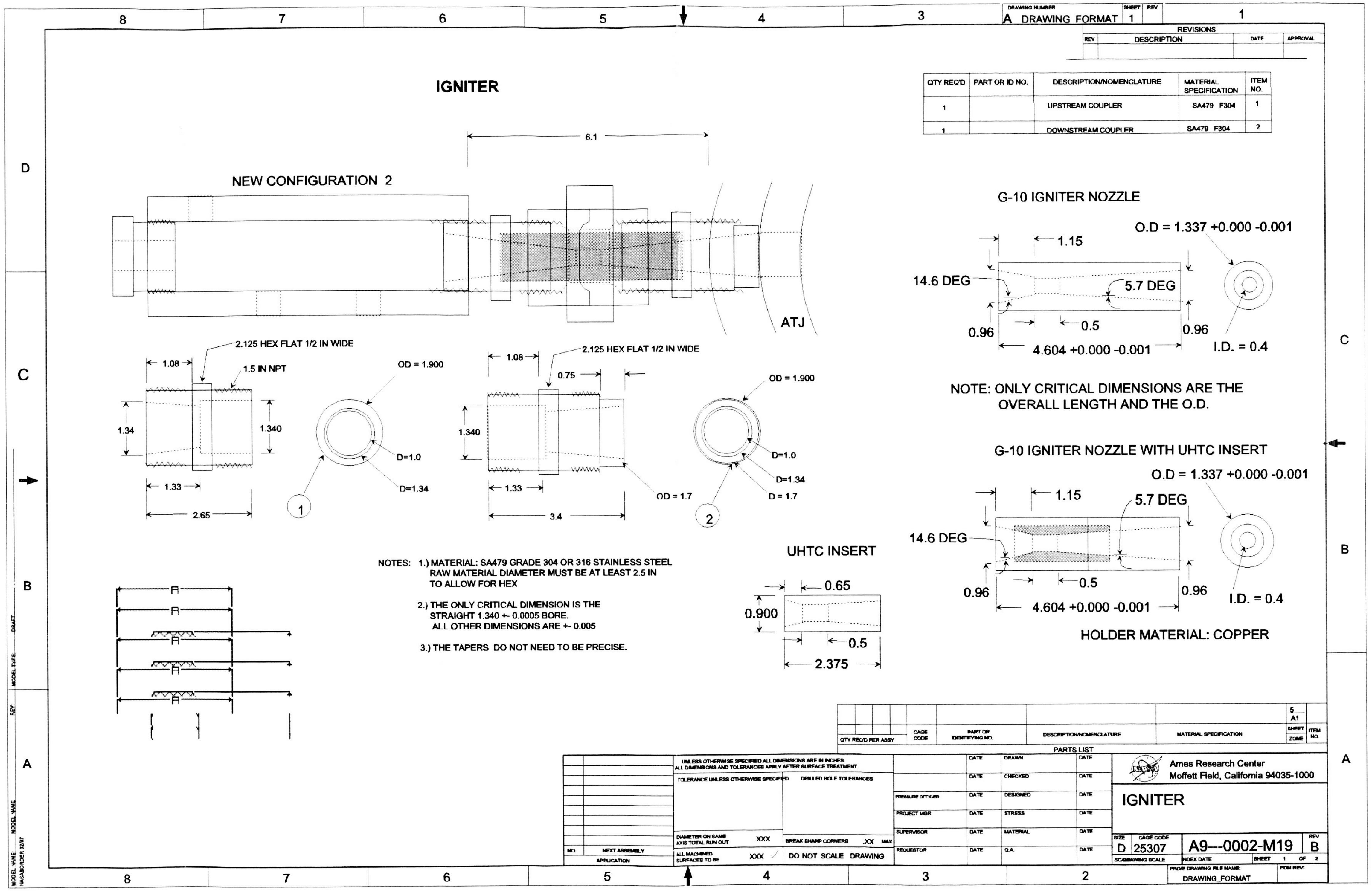
DRAWN GREG ZILLIAC DATE 7/30/01
CHECKED DATE
DESIGNED ARIF KARABEYOGLU DATE 7/30/01
STRESS DATE
MATERIAL DATE
Q.A. DATE

Ames Research Center
Moffett Field, California 94035-1000

INJECTOR
"AS BUILT"

SIZE D
CAGE CODE 25307
A9---0002-M18
REV A
SCALE/DRAWING SCALE
INDEX DATE
SHEET 1 OF 2
PROE DRAWING FILE NAME: DRAWING_FORMAT
PDM REV:

MODEL NAME: NASA/ORDER 02/97
MODEL NAME
REV:
MODEL TYPE: DRAFT



NOTE: ONLY CRITICAL DIMENSIONS ARE THE OVERALL LENGTH AND THE O.D.

HOLDER MATERIAL: COPPER

NOTES:
1.) MATERIAL: SA479 GRADE 304 OR 316 STAINLESS STEEL RAW MATERIAL DIAMETER MUST BE AT LEAST 2.5 IN TO ALLOW FOR HEX

2.) THE ONLY CRITICAL DIMENSION IS THE STRAIGHT 1.340 +- 0.0005 BORE. ALL OTHER DIMENSIONS ARE +- 0.005

3.) THE TAPERS DO NOT NEED TO BE PRECISE.

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		UPSTREAM COUPLER	SA479 F304	1
1		DOWNSTREAM COUPLER	SA479 F304	2

DRAWING NUMBER A DRAWING FORMAT SHEET 1 REV

REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

PARTS LIST

QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.
					5 A1	

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES. ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED DRILLED HOLE TOLERANCES

DIAMETER ON SAME AXIS TOTAL RUN OUT XXX BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓ DO NOT SCALE DRAWING

NO. NEXT ASSEMBLY APPLICATION

	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER	DATE	DESIGNED	DATE
PROJECT MGR	DATE	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR	DATE	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

IGNITER

SIZE D CAGE CODE 25307 A9---0002-M19 REV B

SCAMBLING SCALE INDEX DATE SHEET 1 OF 2

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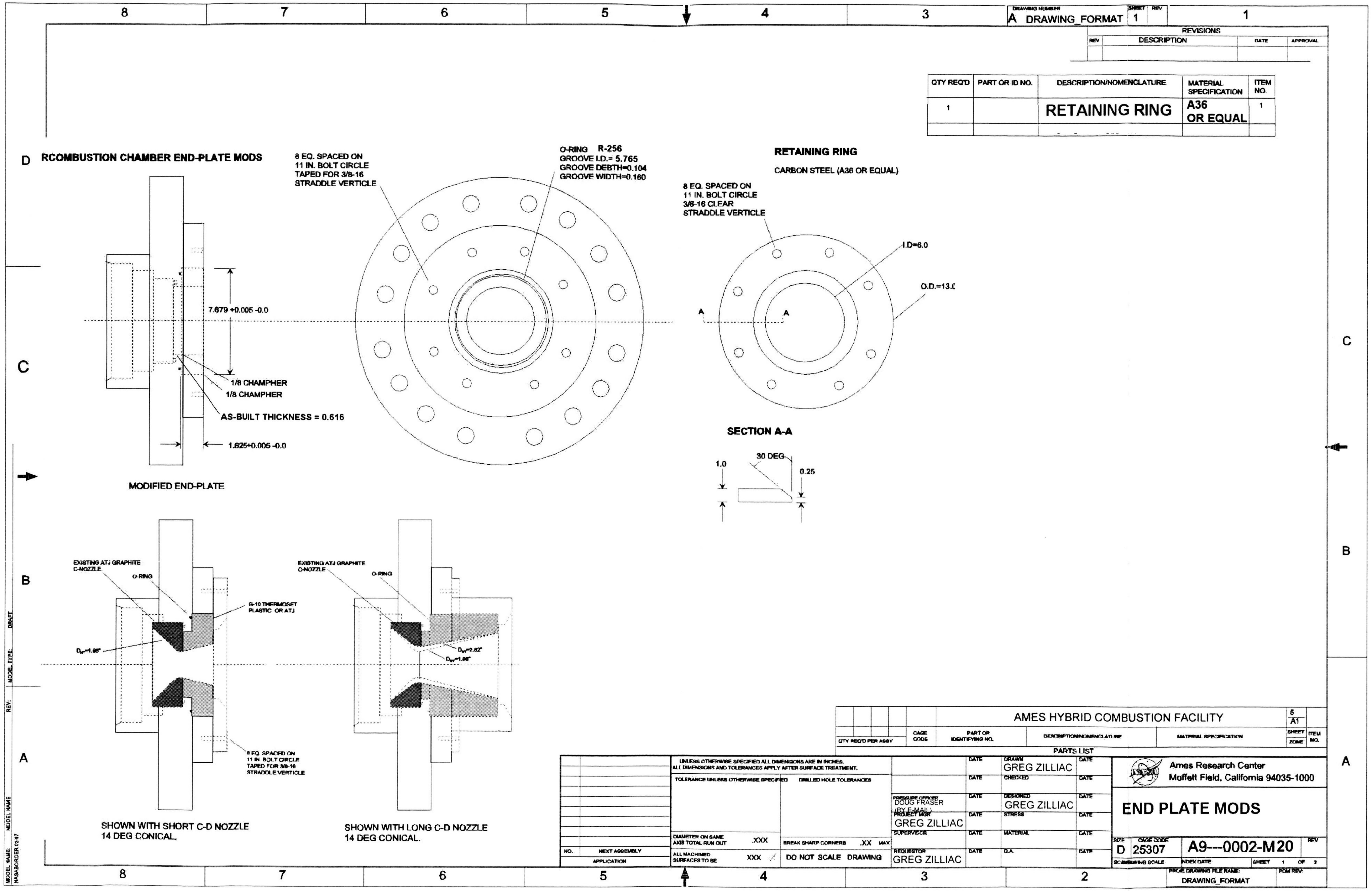
MODEL NAME MODEL NAME NASA/ORDER 32/87 REV MODEL TYPE DRAFT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A DRAWING_FORMAT
SHEET 1
REV
REVISIONS
REV
DESCRIPTION
DATE
APPROVAL
QTY REQ'D
PART OR ID NO.
DESCRIPTION/NOMENCLATURE
MATERIAL SPECIFICATION
ITEM NO.
1
RETAINING RING
A36 OR EQUAL
1
RCOMBUSTION CHAMBER END-PLATE MODS
8 EQ. SPACED ON 11 IN. BOLT CIRCLE TAPED FOR 3/8-16 STRADDLE VERTICLE
O-RING R-256
GROOVE I.D.= 5.765
GROOVE DEBTH=0.104
GROOVE WIDTH=0.160
7.679 +0.005 -0.0
1/8 CHAMPHER
1/8 CHAMPHER
AS-BUILT THICKNESS = 0.616
1.625+0.005 -0.0
MODIFIED END-PLATE
RETAINING RING
CARBON STEEL (A36 OR EQUAL)
8 EQ. SPACED ON 11 IN. BOLT CIRCLE 3/8-16 CLEAR STRADDLE VERTICLE
I.D=6.0
O.D.=13.0
A
A
SECTION A-A
30 DEG
1.0
0.25
EXISTING ATJ GRAPHITE C-NOZZLE
O-RING
G-10 THERMOSET PLASTIC OR ATJ
Dw=1.98"
8 EQ. SPACED ON 11 IN. BOLT CIRCLE TAPED FOR 3/8-16 STRADDLE VERTICLE
SHOWN WITH SHORT C-D NOZZLE 14 DEG CONICAL
EXISTING ATJ GRAPHITE C-NOZZLE
O-RING
Dw=2.82"
Dw=1.98"
SHOWN WITH LONG C-D NOZZLE 14 DEG CONICAL
AMES HYBRID COMBUSTION FACILITY
5
A1
QTY REQ'D PER ASSY
CAGE CODE
PART OR IDENTIFYING NO.
DESCRIPTION/NOMENCLATURE
MATERIAL SPECIFICATION
SHEET
ZONE
ITEM NO.
PARTS LIST
UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.
TOLERANCE UNLESS OTHERWISE SPECIFIED
DRILLED HOLE TOLERANCES
DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX
BREAK SHARP CORNERS .XX MAX
ALL MACHINED SURFACES TO BE XXX
DO NOT SCALE DRAWING
NO.
NEXT ASSEMBLY
APPLICATION
PRESSURE OFFICER
DOUG FRASER (BY E-MAIL)
PROJECT MGR
GREG ZILLIAC
SUPERVISOR
REQUESTOR
GREG ZILLIAC
DATE
DRAWN
GREG ZILLIAC
CHECKED
DESIGNED
GREG ZILLIAC
STRESS
MATERIAL
Q.A.
Ames Research Center
Moffett Field, California 94035-1000
END PLATE MODS
SIZE D
CAGE CODE 25307
A9---0002-M20
REV
SCALE
INDEX DATE
SHEET 1 OF 2
PROE DRAWING FILE NAME:
DRAWING_FORMAT
PDM REV:
MODEL NAME
MODEL TYPE
DRAFT
REV:
NASABORDER 02/97
8
7
6
5
4
3
2
1
D
C
B
A

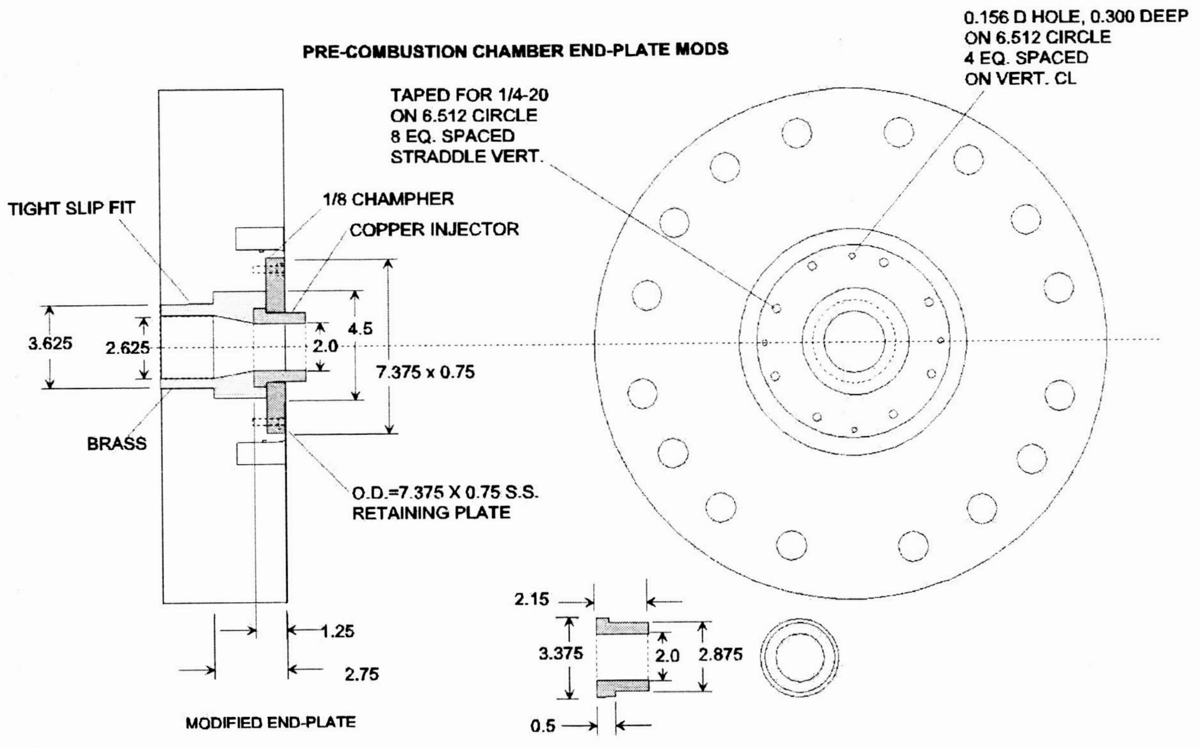
DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		PRE-COMBUSTION CHAMBER END PLATE	A36	1
				2

PRE-COMBUSTION CHAMBER END-PLATE MODS



QTY REQ'D PER ASSY	CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.
			AMES HYBRID COMBUSTION FAC		5 A1	

PARTS LIST

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000-.125	+.005-.001
.126-.500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

NO.	NEXT ASSEMBLY	APPLICATION

	DATE		DATE
		DRAWN	
		CHECKED	
PRESSURE OFFICER O. GREULICH	8/4/00	DESIGNED	
PROJECT MGR G. ZILLIAC	8/3/00	STRESS	
SUPERVISOR		MATERIAL	
REQUESTOR G. ZILLIAC	8/3/00	Q.A.	

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PRE-COMBUSTION CHAMBER
END PLATE MODS

"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002-M21	

SCALE/DRAWING SCALE | INDEX DATE | SHEET 1 OF 2

PROE DRAWING FILE NAME: DRAWING_FORMAT | PDM REV:

MODEL NAME NASABORDER 02/97 | MODEL NAME | REV | MODEL TYPE DRAFT

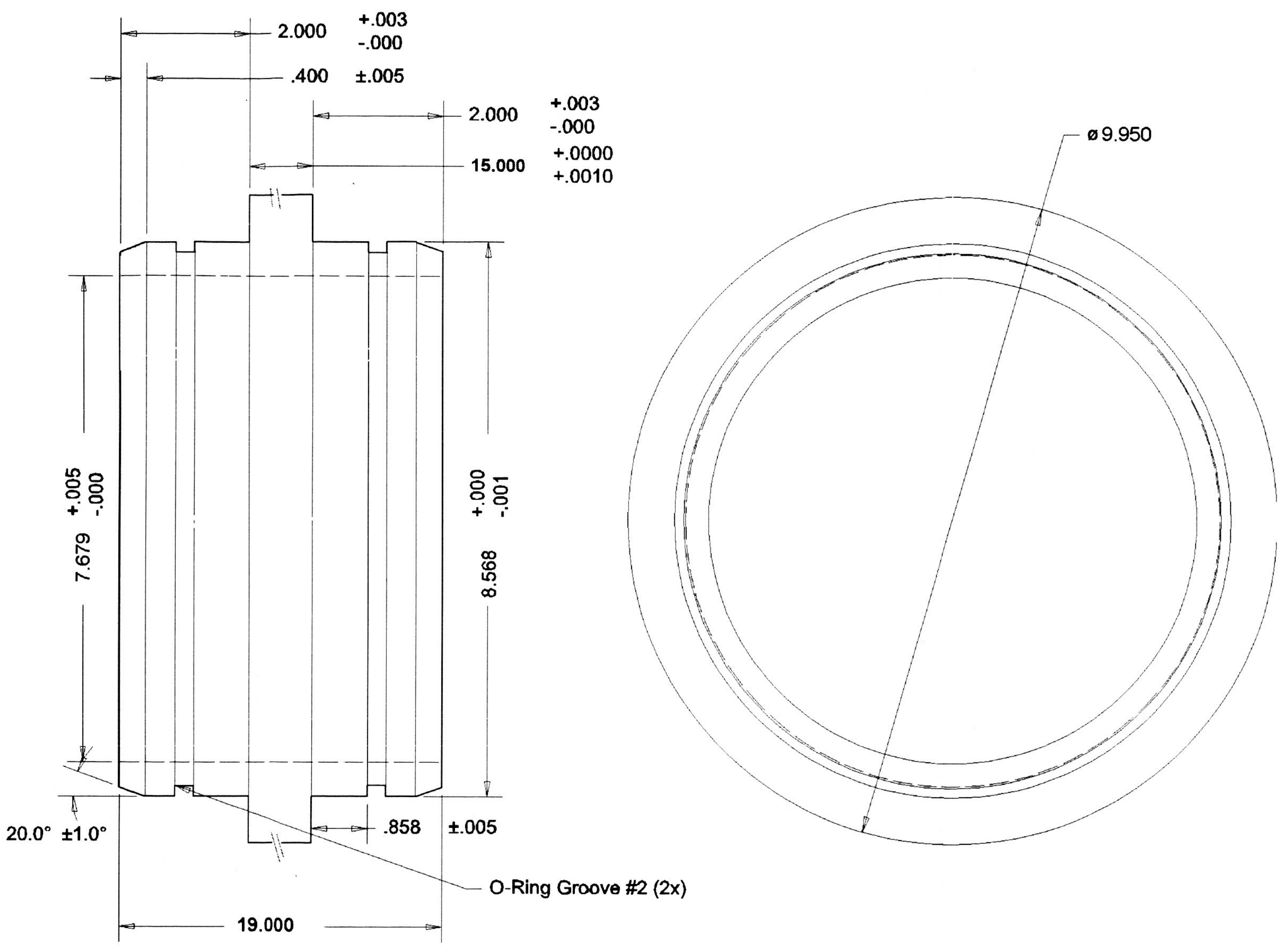
DRAWING NUMBER	SHEET	REV
A DRAWING_FORMAT	1	

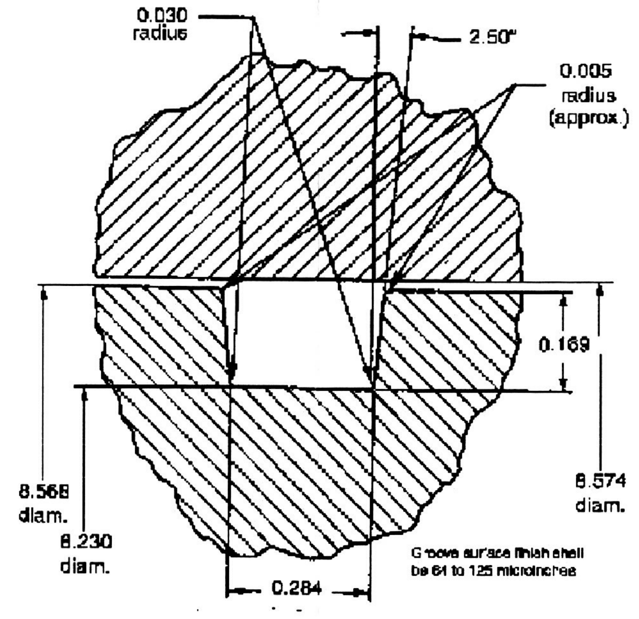
REVISIONS

REV	DESCRIPTION	DATE	APPROVAL

QTY REQ'D	PART OR ID NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	ITEM NO.
1		COUPLER	SA106	1

NOTES:
PLEASE USE PIPE SUPPLIED (NO MATERIAL NEEDS TO BE ORDERED)





Groove surface finish shall be 64 to 125 microinches

O-RING GROOVE DETAIL

					AMES HYBRID COMBUSTION FACILITY			5 A1	
QTY REQ'D PER ASSY				CAGE CODE	PART OR IDENTIFYING NO.	DESCRIPTION/NOMENCLATURE	MATERIAL SPECIFICATION	SHEET ZONE	ITEM NO.

PARTS LIST

NO.	NEXT ASSEMBLY
	APPLICATION

UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN INCHES.
ALL DIMENSIONS AND TOLERANCES APPLY AFTER SURFACE TREATMENT.

TOLERANCE UNLESS OTHERWISE SPECIFIED

FRACTIONAL	/
	0.1
	0.01
	0.005
	0.5

DRILLED HOLE TOLERANCES

DIAMETER	TOLERANCE
.000- .125	+.005-.001
.126- .500	+.010-.002
.501-1.000	+.015-.002
1.001-2.000	+.030-.003
OVER 2.000	+.060-.005

DIAMETER ON SAME AXIS TOTAL RUN OUT .XXX

BREAK SHARP CORNERS .XX MAX

ALL MACHINED SURFACES TO BE XXX ✓

DO NOT SCALE DRAWING

	DATE		DATE
	DATE	DRAWN	DATE
	DATE	CHECKED	DATE
PRESSURE OFFICER O. GREULICH	DATE 10/3/00	DESIGNED	DATE
PROJECT MGR G. ZILLIAC	DATE 9/24/00	STRESS	DATE
SUPERVISOR	DATE	MATERIAL	DATE
REQUESTOR G. ZILLIAC	DATE 9/24/00	Q.A.	DATE

Ames Research Center
Moffett Field, California 94035-1000

15" COUPLER

"AS BUILT"

SIZE	CAGE CODE		REV
D	25307	A9---0002- M22	
SCALE/DRAWING SCALE		INDEX DATE	SHEET 1 OF 2

PRO/E DRAWING FILE NAME: DRAWING_FORMAT
PDM REV:

MODEL NAME NASABORDER 02-97 | MODEL NAME | REV: | MODEL TYPE: DRAFT

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Greg Zilliac, Mustafa A. Karabeyoglu*, Brian Cantwell*, Rusty Hunt,
Shane DeZilwa, Mike Shoffstall**, Paul T. Soderman

5d. PROJECT NUMBER

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5f. WORK UNIT NUMBER
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Ames Research Center, Moffett Field, California 94035-1000;
* Stanford University, Stanford, California 94305;
** White Sands Test Facility, Las Cruces, New Mexico 88012

8. PERFORMING ORGANIZATION REPORT NUMBER
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Point of Contact: Gregory G. Zilliac, Ames Research Center, M.S. 260-1, Moffett Field, CA 94035-1000
(650) 604-3904

14. ABSTRACT

The report summarizes the design, fabrication, safety features, environmental impact, and operation of the Ames Hybrid-Fuel Combustion Facility (HCF). The facility is used in conducting research into the scalability and combustion processes of advanced paraffin-based hybrid fuels for the purpose of assessing their applicability to practical rocket systems. The facility was designed to deliver gaseous oxygen at rates between 0.5 and 16.0 kg/sec to a combustion chamber operating at pressures ranging from 300 to 900 The required run times were of the order of 10 to 20 sec. The facility proved to be robust and reliable and has been used to generate a database of regression-rate measurements of paraffin at oxygen mass flux levels comparable to those of moderate-sized hybrid rocket motors.

15. SUBJECT TERMS
Rocket, Combustion, Fuel, Hybrid

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19b. NAME OF RESPONSIBLE PERSON
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