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Analysis and Design of the NASA Langley Cryogenic Pressure Box

David E. Glass
Analytical Services and Materials, Inc., Hampton, VA

Jonathan C. Stevens and R. Frank Vause
Lockheed Martin Engineering and Sciences Co., Hampton, VA

Peter M. Winn, James F. Maguire, and Glenn C. Driscoll
Applied Engineering Technologies, Ltd., Woburn, MA

Charles L. Blackburn and Brian H. Mason
Analytical Services and Materials, Inc., Hampton, VA

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Peter M. Winn, James F. Maguire, and Glenn C. Driscoll
Applied Engineering Technologies, Ltd.

Charles L. Blackburn, and Brian H. Mason[†]
Analytical Services & Materials, Inc.

Abstract

A cryogenic pressure box was designed and fabricated for use at NASA Langley Research Center (LaRC) to subject 76 in. x 65 in. curved panels to cryogenic temperatures and biaxial tensile loads. The cryogenic pressure box is capable of testing curved panels down to -423°F (20K) with 52 psig maximum pressure on the concave side, and elevated temperatures and atmospheric pressure on the convex surface. The internal surface of the panel is cooled by high pressure helium gas that is cooled to -423°F by liquid helium heat exchangers. An array of twelve independently controlled fans circulate the high pressure gaseous helium to provide uniform cooling on the panel surface. The convex surface may be heated up to 1000°F by an array of quartz lamps. The tensile loads are applied with pneumatic pressure on the inside surface of the panel and tensile loads on the edges of the panel. The tensile load in the circumferential direction (hoop load) of the panel is reacted through rods with turnbuckles that are attached to the frames and skin of the panel. The tensile load in the axial direction of the panel is applied by means of four hydraulic actuators. The load introduction structure, consisting of four stainless steel load plates and numerous fingers attaching the load plates to the test panel, is designed to introduce loads into the test panel that represent stresses that will be observed in the actual tank structure. The load plates are trace cooled with liquid nitrogen to reduce thermal gradients that may result in bending the load plates, and thus additional stresses in the test panel. The design of the cryogenic systems, load introduction structure, and control system are discussed in this report, but the heating system and various support facilities are not discussed here as they were the responsibility of NASA Langley Research Center.

[†]Currently with NASA Langley Research Center, Hampton, VA
[§]Currently with the College of William and Mary, Williamsburg, VA
[*]Currently with NYMA, Inc., Hampton, VA

Table of Contents

List of Figures

List of Tables

Nomenclature and Acronyms

<u>English</u>

A_b	bolt shear area
A_{bf}	bearing area
A_v	area for shear stress on actuator pin
A_t	net finger area
A_p	bearing area on load plate
A_s	shear area
c	distance between finger
C_p	specific heat
d	bolt diameter
d_1	bolt diameter
D	diameter
E	modulus of elasticity
f_{wb}	applied web bearing stress
f_{sp}	applied shear stress on the pin
f_{ta}	applied tensile stress at the net section
f_{tc}	applied shear stress
F_{bru}	allowable bearing stress
F_{bf}	allowable bearing stress on the pad is then
F_{sv}	allowable shear stress
F_{wb}	allowable web bearing stress
F_{max}	maximum load at a single bolt
h	heat transfer coefficient
k	thermal conductivity
l	hoop edge length per frame
$\dot{m}$	mass flowrate
n_b	number of bolts
Nu	Nusselt number
P	load
P	internal tank pressure
P_f	frame turnbuckle load
Pr	Prandtl number
Q	heat flux
r	radius
Re	Reynolds number
t_f	finger thickness
t_p	test panel thickness
T	temperature
V	velocity
w_1	finger width
w_2	centerline finger spacing

<u>Greek</u>

α	percentage of the load to the frame
δ	contraction
σ_B	bearing stress on load plate
σ_t	tension load
τ_P	load pad shear stress
τ_B	bolt shear strength
τ	shear stress
ν	viscosity

Acronyms

CTE	coefficient of thermal expansion
DOF	degrees of freedom
FEM	finite element model
HX1	heat exchanger 1
HX2	heat exchanger 2
HXN	nitrogen heat exchanger
LaRC	Langley Research Center
LH2	liquid hydrogen
LHe	liquid helium
LOX	liquid oxygen
MPC	multi point constraint
RLV	reusable launch vehicle
scf	standard cubic feet
SSTO	single-stage-to-orbit
STP	standard temperature and pressure
TPS	thermal protection system

Introduction

A new reusable launch vehicle (RLV) is being planned that will be a single-stage-to-orbit (SSTO) vehicle, as illustrated in Figure 1. One of the hurdles to overcome in the successful operation of an RLV is the design and fabrication of cryogenic propellant tanks, shown in Figure 1. Both liquid oxygen (LOX) and liquid hydrogen (LH_2) tanks must be built that are light weight, can carry the structural and thermal loads, and can contain the cryogens.

To test RLV tank designs, a cryogenic pressure box (cryobox) has been designed and fabricated that will enable representative tank panel sections to be tested at actual operating conditions and loads (-423°F (LH_2 temperature) with an internal pressure up to 52 psig) [1-3]. The cryobox, located at the NASA Langley Research Center (LaRC), will subject curved, stiffened panels to biaxial tensile loads by applying pneumatic pressure on the internal surface of the panel and tensile loads on the edges of the panel. The tensile load in the circumferential direction (hoop load) of the panel will be reacted through rods with turnbuckles that will be attached to the ring frames and skin of the panel. The tensile load in the axial direction of the panel will be applied by means of four hydraulic actuators. The load introduction structure, consisting of four stainless steel load plates and numerous fingers attaching the load plates to the test panel, is designed to introduce loads into the test panel that represent stresses in the actual tank structure. Fingers are used to minimize load interactions between the panel and the load plates. The load plates are trace cooled with liquid nitrogen (LN_2) to reduce thermal gradients that may produce bending in the load plates, and thus introduce additional stresses into the test panel. An additional benefit is lower heat loads conducted into the panel.

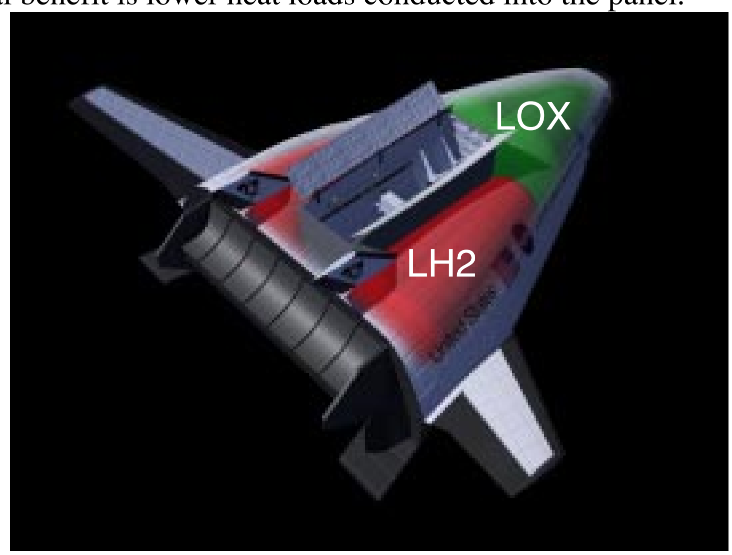

Figure 1: Conceptual drawing of the Lockheed Martin reusable launch vehicle showing the liquid hydrogen (LH2) and liquid oxygen (LOX) tanks.

The design of the cryogenic pressure box can be divided into several areas: load introduction structure, controls, cryogenic systems, heating system, and support facilities. This report discusses the first three topics (load introduction structure, controls, and cryogenic systems) which were contracted to AS&M and Lockheed Martin Engineering & Sciences by NASA LaRC. The heating system and support facilities were designed by NASA and are thus not discussed in this report. After a brief discussion of the design requirements, the load introduction structure, controls, and cryogenic systems will be discussed in detail. (It should be pointed out that several different groups performed the work discussed here. Each technical group has certain sets of units with which they prefer to use. Attempts have been made to convert to English units. However, in some cases in is not reasonable. As a result, this report contains both English and metric units.)

Cryogenic Pressure Box

To simulate hydrogen tank conditions, test panels need to be subjected to 34 psig internal pressure, as well as cooled to an internal temperature of -423°F (20K). For re-entry simulation, the internal pressure needs to be 5-10 psi, with an internal temperature of 50-200°F and a panel temperature from 250°F to 350°F depending on the panel material. Since the cryogenic pressure box needs to be capable of testing various panels, it must be able to handle the worst case conditions from each panel. The pressure box needs to be able to accommodate both LOX and LH2 tank panels, with radii ranging from 130 in. to 266 in. The internal pressure required in the pressure box increases to 52 psi for LOX panels.

The cryogenic pressure box consists of two main components. The first is the pressure box itself. The pressure box is where the test panels are mounted, cooled, pressurized and tested. Since space is limited in the pressure box, a second, separate component was designed to house the heat exchangers and liquid nitrogen boiler required to cool the test panels efficiently. The second component is called the boiler pod. The two components are connected via vacuum jacketed piping. Figure 2 is an overall view of the cryogenic pressure box system, showing the pressure box, boiler pod, supply vessels, and vacuum system.

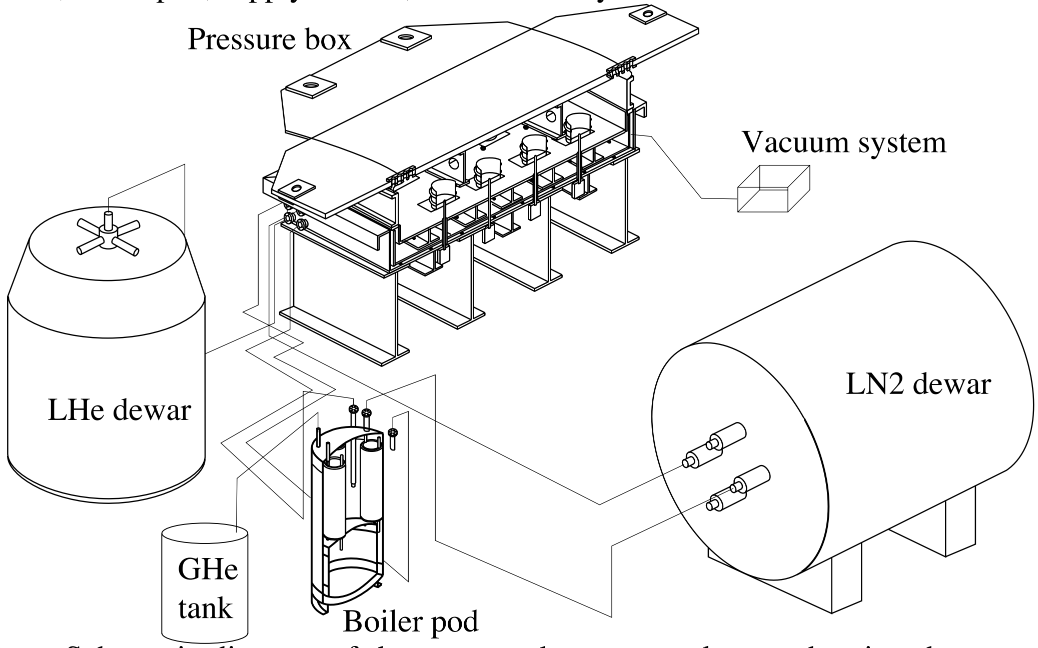

Figure 2: Schematic diagram of the pressure box system layout showing the pressure box, boiler pod supply vessels, and vacuum pump.

Figure 3 is a scale drawing of a cross-sectional view of the pressure box. The cross-section is along the axial axis of symmetry, and shows some of the cooling system components located inside the box. Only one finger connection is shown on each side. Both the hoop and axial load plates are shown in the figure. The test panel with the two ring frames is shown attached to the load plates. The C-seal, between the load plates and the transition channel is also shown. The fan heat exchangers (cooling plates) are located inside the pressure box, and the fan motors are located outside the pressure box.

Figure 4 is a high level system flow diagram that represents the system block diagram schematically. The flow diagram consists of two components - the boiler pod (shown in gray on the left) and the pressure box (shown in gray on the right). LN2, LHe, and GHe dewars are shown in the figure. The boiler pod contains the heat exchangers (HX1, HX2, and HXN) and a boiler. Several photographs of the as built pressure box are shown in Appendix A and a description of the test panel planform is given in Appendix B.

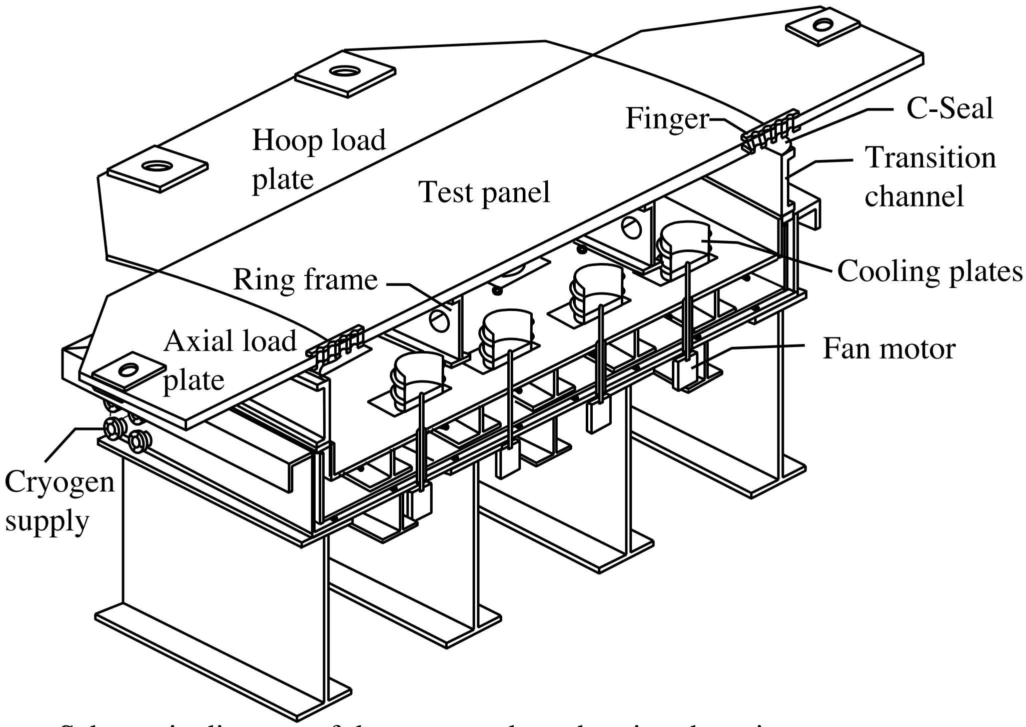

Figure 3: Schematic diagram of the pressure box showing the primary components.

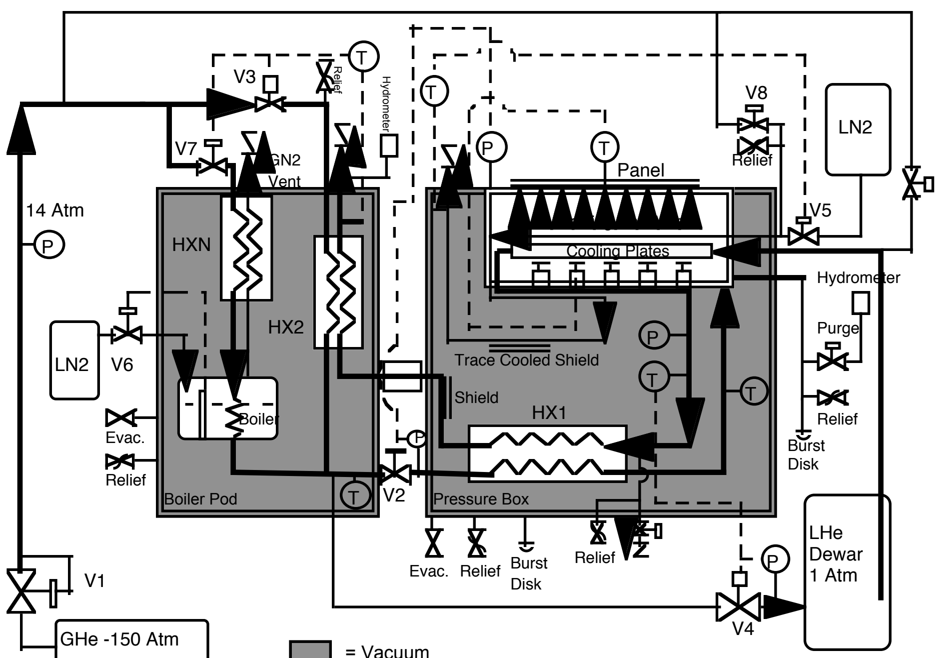

Figure 4: System flow diagram of the cryogenic systems.

Design Requirements

The pressure box was thermally designed to test a 0.080-in-thick Gr/Ep panel with 1-in-thick Rohacell® foam insulation. The two test conditions that were to be met correspond to a ground hold and a descent condition, as shown in Table 1. For the ground hold, the inside surface of the panel is maintained at -423°F, and the outside temperature is allowed to float. For the descent condition, the outside surface of the TPS is heated to 1000°F and the inside surface is allowed to float, though the Gr/Ep must be maintained below 250°F. The axial and hoop loads are also shown in Table 1, and correspond to P • r for the hoop load and (P • r)/2 for the axial load.

Table 1: Gr/Ep Panel (r = 192 in.) Test Conditions (LH2)

Condition	Pressure, psig	Temp., °F inside	Temp., °F outside	Loads, lb/in. Hoop	Loads, lb/in. Axial
With TPS					
First cycle (40% full load)	14	-423	float	2688	1344
Subsequent cycles	35	-423	float	6720	3360
	35	<250	1000	6720	3360

The original design parameters called for ambient conditions on the outer surface while the inner surface was cooled to -423°F (20K). Assuming 1 in. of Rohacell foam and natural convection on the outer surface, 2047 Btu/hr (600 W) was estimated to enter through the panel. If a heat flux of greater than 2047 Btu/hr (600 W) enters through the panel, -423°F (20K) will likely not be able to be maintained on the cold surface. Figure 5 gives an approximate internal panel temperature as a function of the heat flux through the panel. The pressure box has been designed to provide a panel temperature of -423°F (20K) with 2047 Btu/hr (600 W) heat through the panel while cooling with LHe. The panel temperature increases linearly to -387°F (40K) with a heat load of approximately 10,235 Btu/hr (3000 W). If a LOX panel is used and assuming the same heat flux, LN2 could be used as the coolant and a panel test temperature of approximately -190°F (150K) would be obtainable.

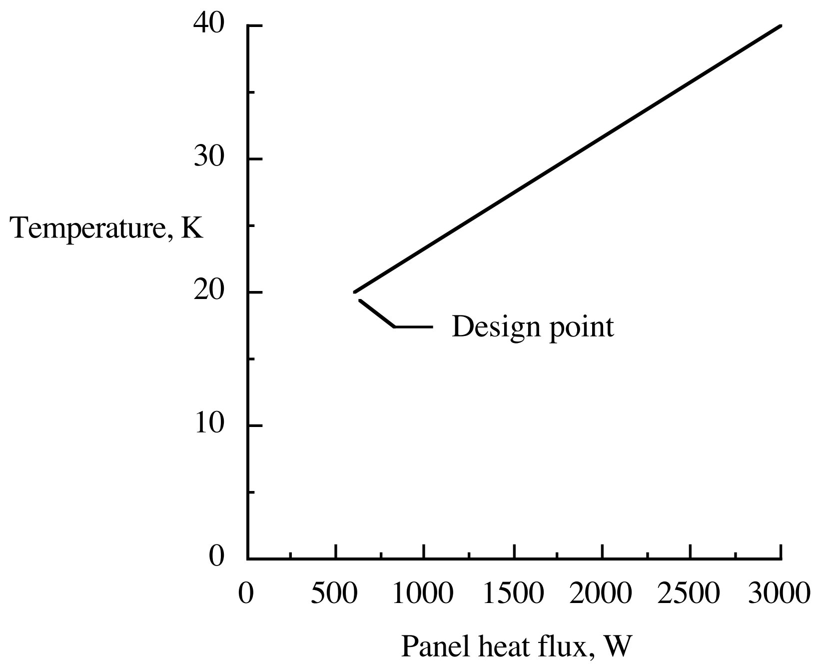

Figure 5: Approximate attainable panel temperature as a function of the heat flux through the panel.

After the initial design requirements were incorporated into the design, an additional test condition, with both heating on the outside and cooling to -423°F on the inside, was requested. Heat fluxes of greater than 2047 Btu/hr (600 W) are expected when the outside surface is heated or the cryogenic insulation has less insulating capacity than 1 in. of Rohacell foam. If the inner surface is not required to be maintained at -423°F, the inner surface temperature can likely be achieved. However, an inside temperature of -423°F cannot be met with heating on the outside with the current levels of insulation. The inside surface temperature of -423°F will be a goal for these tests, but will likely not be met.

Structural Analysis

This section describes the structural analysis that was performed for the design of the cryogenic pressure box for testing panels. The system is broken down into two major subsystems: the pressure box itself and the boiler pod. Due to the odd geometry of the pressure box, a detailed finite element model was constructed to calculate the stresses in the pressure box as well as expected deflections of the walls under pressure loading. The calculated stresses were then compared to the requirements of the ASME code and a margin of safety was calculated. Hand calculations were also performed for initial sizing. The boiler pod contains heat exchangers and vessels which will also be subjected to pressure. The geometry of these items is very straightforward, therefore simple code calculations were performed and the results are included.

Boiler Pod Code Calculations

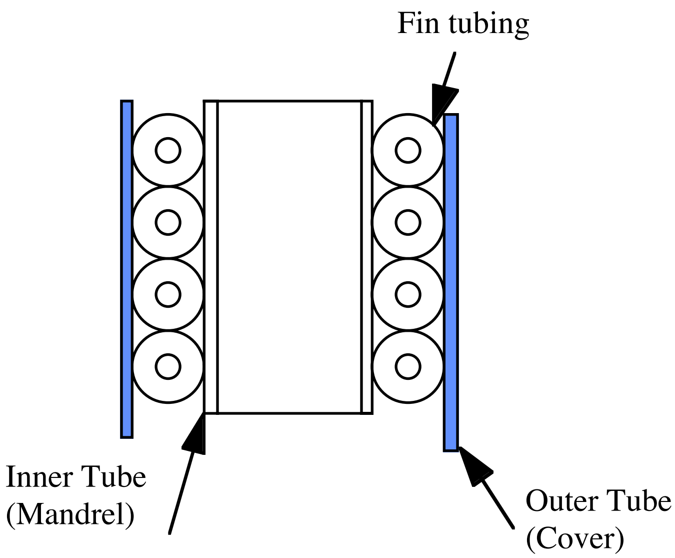

Figure 6: Schematic diagram of the heat exchanger.

This section describes the structural analysis of the major components of the boiler pod. The vessel consists of a 24 in. diameter x 60 in. high outer vacuum vessel with a 20 in. diameter by 16 in. high inner boiler vessel. The HX2 and HXN heat exchanger assemblies are also mounted inside the vessel above the boiler. HX1 is located in a vessel mounted on the side of the boiler pod. The heat exchangers are directly supported off the top head and the boiler vessel is supported off the bottom of the heat exchanger bundle. A schematic diagram of the inside of the HEX is shown in Figure 6.

Outer Vacuum Vessel

The outer vacuum vessel is fabricated in three parts: the top head, the middle cylinder, and the bottom head. The vessel will have a 20 psig burst disk for redundancy. The top and bottom heads are ASME flanged and dished heads with an outside diameter of 24 in. The material is 304 stainless steel. To accommodate vacuum loads, the required thickness is 0.104 in. The thickness used will be 0.125 in. The outer shell is a 24 in. diameter by 48 in. long 304 stainless steel cylinder with a stiffening ring half way down. The required thickness is 0.078 in., and 0.09 in. will be used.

Inner Boiler Vessel

The inner boiler vessel is fabricated in three parts: the top head, the middle cylinder, and the bottom head. The vessel will have a 30 psig relief valve. The bottom and top heads are ASME flanges and dished heads with an outside diameter of 20 in. The material will be 304 stainless steel. The maximum external load will be 15 psig and will occur during leak test. The maximum internal load will be 30 psig (relief valve). The required thickness is 0.09 in. and the thickness used will be 0.09 in. This thickness includes a safety factor built in from the ASME vessel code. The shell is a 20-in. diameter by 14-in. long 304 stainless steel cylinder. The required thickness is 0.055 in. and the thickness used will be 0.09 in.

HX2 and HXN Heat Exchangers

Because the HX2 and HXN heat exchangers are of identical design, the worst case pressures will be used. The outer shell side of HXN is about 7.0 in. in diameter and 24-in. long. This shell can experience the 30 psig from the boiler and its required thickness is 0.038 in. The thickness used for this shell and the outer shell of the HX2 heat exchangers is 0.049 in. The inner shell of HX2 and HXN is a 5.5 in., schedule 5 pipe 0.109-in. thick. The length of this inner shell is also 24 in. The maximum internal pressure will be 15 psig during leak checking and the maximum external pressure will be 30 psig from the boiler. The required thickness for this shell is 0.045 in., and 0.060 in. will be used. All welds will be helium leak checked to 1 x 10^{-8} cc/sec. No hydro tests will be performed due to the fact that water can be problematic in heat exchangers.

HX1 Heat Exchanger

The HX1 heat exchanger is mounted in a vessel that is attached to the boiler pod. It consists of three parallel heat exchangers that cool the incoming pressurization gas with the boil-off from the liquid helium cooling plate. The internal shell is a 3-in. diameter by 36-in. long stainless steel cylinder. The maximum internal pressure it will experience is 15 psig due to leak checking. The maximum external pressure will be 10 psig from the liquid helium vessel. The required thickness for the inner cylinder is 0.035 in. and 0.06 in. will be used. The external shell is a 4.25-in-diameter cylinder that is 36-in. long. The maximum internal pressure it will experience is 10 psig from the liquid helium vessel. The maximum external pressure will be 15 psig that will occur during leak checking. The required thickness for the outer cylinder is 0.036 in., and 0.049 in. will used.

Vacuum Jacketed Transfer Lines

There are a total of seven transfer lines for the LHe. Three have 0.5 in internal lines, and four have 1.5 in. internal lines. All the lines are fabricated from 304 stainless steel. The analysis covers the stresses due to both the maximum pressure and the thermal shrinkage of the inner lines. It should be noted that the spacers are G-10 square sheets, 1/16 in thick. They typically have a sloppy fit to minimize heat transfer to the inner tube and to allow for some flexibility in the assembly. In the FEA models, they are assumed to be rigid connections with a degree of freedom only along the axis of the line. This is a conservative assumption. There are also flex sections in some of the lines. These flex sections were modeled as tubes with a modulus ~ 1/30 that of stainless steel (28 x 10^6 psi). The actual flexibility of these sections is quite a bit more than this, thus making this a conservative assumption. The transfer lines analyzed are given in Table 2. Each line has a wall thickness of 0.035 in.

Table 2: LHe Transfer Lines Structurally Analyzed

Line No.	Inner Line Size, in.	Notes
E-13	0.5	Includes 2 flex sections and V1
E-14	0.5	
E-16	0.5	Includes 2 flex sections and V4
E-17	0.5	Includes V2
E-18	1.5	With 0.065-in-thick wall elbows
E-25	1.5	Includes one flex section
E-26	1.5	With 0.065-in-thick wall elbows

The transfer lines were analyzed using the Images 3D FEA software package. The material properties that were used are as follows:

$E = 28 \times 10^6$ psi

E flex sections = 1×10^6 psi

$\gamma = 0.305$

$dL/dt = 1.07 \times 10^{-5}$ in/in-°C

The ends of each line were grounded in the x, y, and z axes, at the location of each spacer, and at the top of each bayonet the nodes were held in two axes with the axis in the parallel with the line free. If a valve is included in the line, the top of the valve is assumed to be grounded in the x, y, and z axes. Each line was assumed to be cooled to helium temperatures and therefore each line was allowed to shrink 306×10^{-5} in/in. Each valve is assumed to shrink half that amount. Table 3 lists the load conditions on the transfer lines. In all cases the temperature was taken to be 5K.

Table 3: Load Conditions on the Transfer Lines

Line No.	Pressure (psig)	Notes
E-13	30	V-10 included, no spacers except at bayonets
E-14	30	4 spacers not including bayonets
E-16	250	V-4 included, no spacers except at bayonets
E-17	250	V-2 included, no spacers except at bayonets
E-18	25	One spacer in middle of line
E-25	75	4 spacers, one flex section
E-26	25	4 spacers not including bayonets

Table 4 lists the maximum stress and the safety factors for the analysis. The factors of safety are based on a maximum stress of 18,800 psi. The maximum stresses are membrane, Von Mises stresses.

Table 4: Maximum Stress and Safety Factors on Transfer Lines

Line No.	Pressure (psi)	Factor of Safety	Notes
E-13	7560	2.5	Inner radius of elbow near V-10
E-14	3350	5.6	Inner radius of elbow near BC-1
E-16	4180	4.5	Inner radius of elbow near BC-11
E-17	16,700	1.13	Top/bottom of tube at V2 interface
E-18	10,300	1.82	Top/bottom of tube at middle of line
E-25	3140	6	Outside radius of elbow on BC-5 leg
E-26	7920	2.3	Elbow on BC-3 leg

Thermal Analysis

This section describes the thermal analysis that was performed on the design of the cryogenic pressure box for testing panels currently being considered for use in cryogenic tanks. The analysis first generates the system cooling requirements by estimating the heat loads from a typical panel and adds to this the heat influx from the vessel used to test the specimen, and the load introduction system. Once the heat inputs are calculated, the cooling system and thermodynamic processes used to provide the required cooling are described and analyzed. This analysis produces the total heat load on the cryogens The system analysis finally calculates the individual cooling, process, fluid flow, and component analysis that were done to minimize cryogen usage and optimize performance of the pressure box.

The thermal properties of the panel are not known at cryogenic temperatures. Therefore, room temperature properties were used. This is a safe assumption as the thermal conductivity will decrease with temperature, resulting in lower thermal loads than estimated.

Panel and Load Plate Thermal Analysis

A finite element model was created using the IMAGES 3D software package to determine the heat loads and thermal gradients developed by cooling the test panel with a fan arrangement. This test panel consists of a ribbed graphite/epoxy (Gr/Ep) sheet approximately 61.25 in. x 72 in. with a nominal thickness of .088 in. and a radius of 192 in. The panel consists of a 1-in-thick layer of Rohacell foam sandwiched between two layers of 0.040-in-thick Gr/Ep sheets

Figure 7 is a layout of the finite element model of the test panel and the load plates. It consists of 2332 nodes with 1796 plate elements and 360 solid elements. The solid elements model the foam insulator. This model includes the load introduction fingers along with the lateral load plates. The model assumes a -441°F (10K) inner gas temperature with a 81°F (300K) ambient atmosphere. The internal heat transfer coefficient required to keep the inner sections of the sample plate at about -423°F (20K) was also studied. Three load cases were run to determine the effect of the end conditions of the load plates on the lateral heat input. The load cases are: 1) load plates not insulated, 2) load plates very well insulated and the end of the load plates maintained at a constant 81°F (300K), and 3) load plates moderately insulated, with the actuator attachment temperature allowed to float.

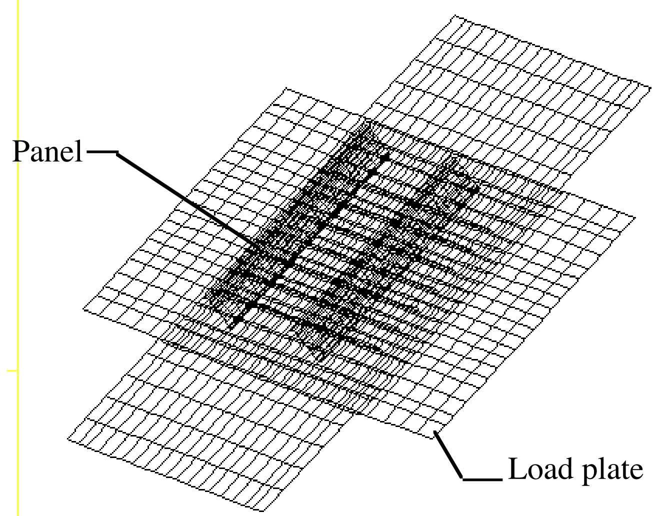

Figure 7: Finite element model of the test panel and load plates used for thermal analysis.

The first condition assumed no insulation on the load plates. A 0.88 Btu/hr-ft^2-°F (5 W/m^2-K) heat transfer coefficient was assumed on the upper surface of the plates and the test panel, and a 1 W/m^2-K heat transfer coefficient was assumed on the bottom of the plates. The fingers are assumed to be insulated. A heat transfer coefficient of 4.6 Btu/hr-ft^2-°F (26 W/m^2-K) was calculated for the internal fans. The results of the FEA are shown in Figure 8. The ends of the load introduction plates are essentially at room temperature and the inside of the panel runs at about -425°F (19K). The lateral load through the fingers is approximately 3071 Btu/hr (900 W) with this assumption. This load is greater than the allowed external loading assumed earlier in the design phase (about 1365 Btu/hr (400 W)). This thermal loading will increase the helium consumption by about 200 liters per test.

Figure 9 shows the temperature contours of the test panel and the load plates for load case 1. The top view is shown in the figure. Figure 10 shows how the test panel temperature varies through the thickness. The outside temperature is -24°F (242K), and the internal temperature is maintained at approximately -425°F (19K).

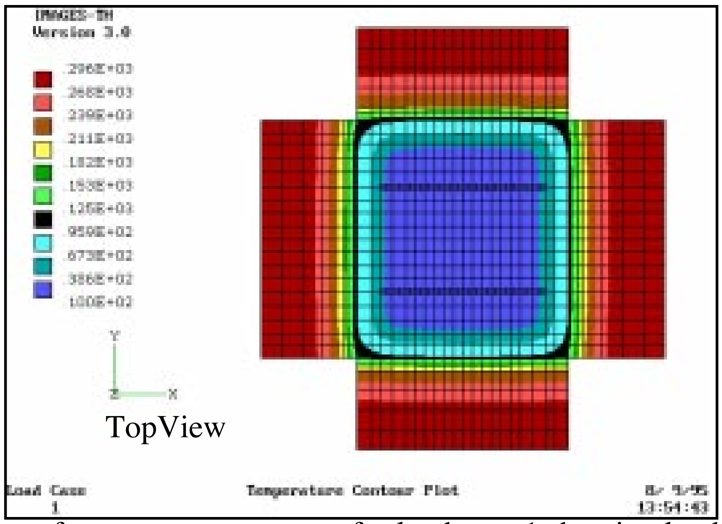

Figure 8: Top view of temperature contours for load case 1 showing load plates and test panel (temperature in Kelvin).

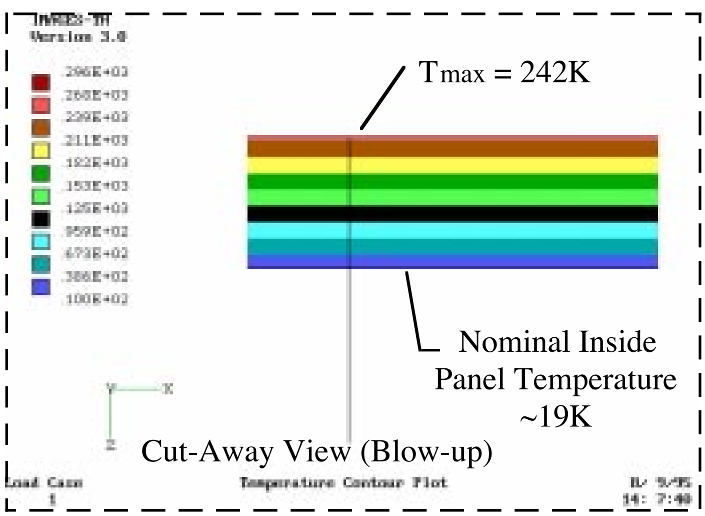

Figure 9: Cross sectional view of panel and ring frame (temperature in Kelvin)

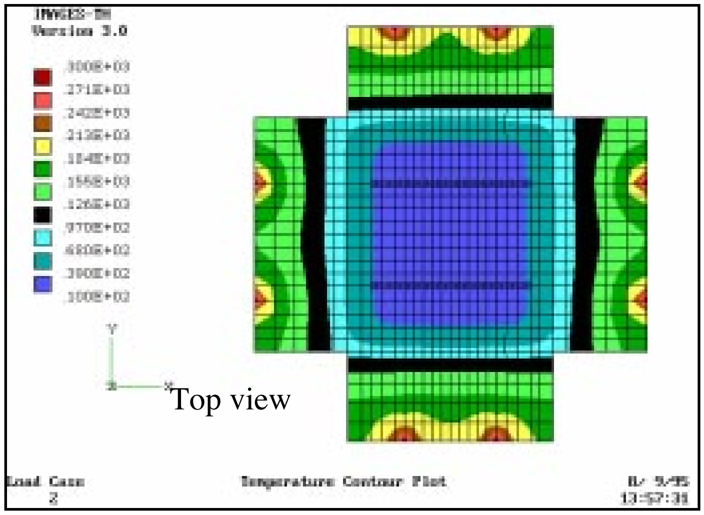

Figure 10: Top view of test panel and load plate temperature contours for load case 2 (temperature in Kelvin).

A second case was run assuming that the load introduction plates are very well insulated and the ends are maintained at a constant 81°F (300K) at the actuator attachment points (two per plate). The results are given in Figure 10. The load introduction plates become quite cold (about -189°F (150K) on average) and the load through the fingers is reduced to about 683 Btu/hr (200 W). This is well below the initial assumptions. The internal sample temperature remained about the same as the previous case (about -427°F (18K)). This shows that the lateral heat loads have very little effect on the ultimate temperature of the panel, but directly contribute to the helium consumption.

The temperature distribution of the load plates is nearly uniform through the thickness, but such is not the case for the test panel. A cross sectional view of the test panel temperature distribution is shown in Figure 11. The outside temperature is -24°F (242K), while the internal temperature is approximately -425°F (19K).

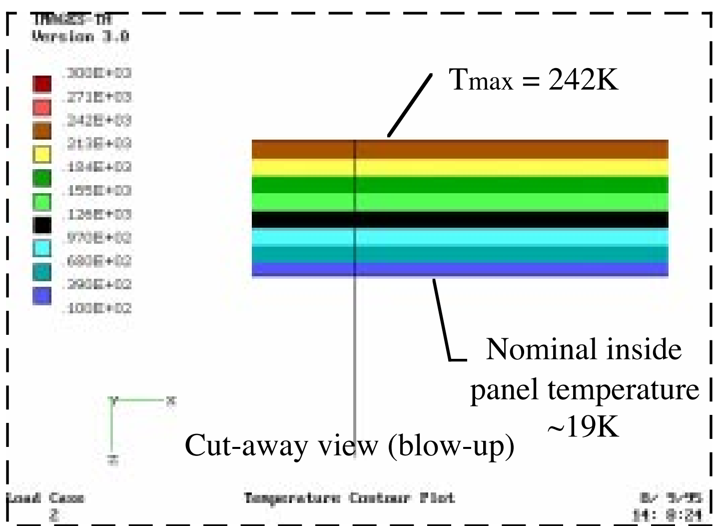

Figure 11: Cross-sectional view of the test panel temperature contours for load case 2 (temperature in Kelvin).

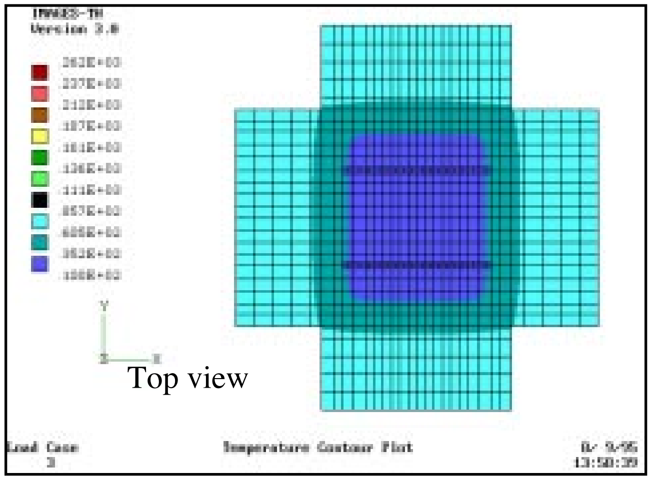

Figure 12: Top view of the temperature contours of the test panel and load plates for load case 3 (temperature in Kelvin).

A third case was run assuming a moderate amount of insulation on the load introduction plates (h_c = 0.88 Btu/hr-ft^2-°F (0.5 W/m^2-K)) and the ring frame attachment point was allowed to float (assuming some insulation at these points). The results of the third case are shown in Figure 12. The load introduction plates run cold and the load through the fingers is about 171 Btu/hr (50 W). From this model, the load through the test panel is calculated to be about 1876 Btu/hr (550 W) with an outer skin temperature of about 14°F (-10°C). This appears to be an achievable design point if the load introduction plates are insulated and allowed to cool.

As in the earlier cases, the load plate temperature distribution is fairly uniform through the thickness, but the test panel distribution is not uniform. Figure 13 shows the temperature distribution contours through the thickness of the test panel.

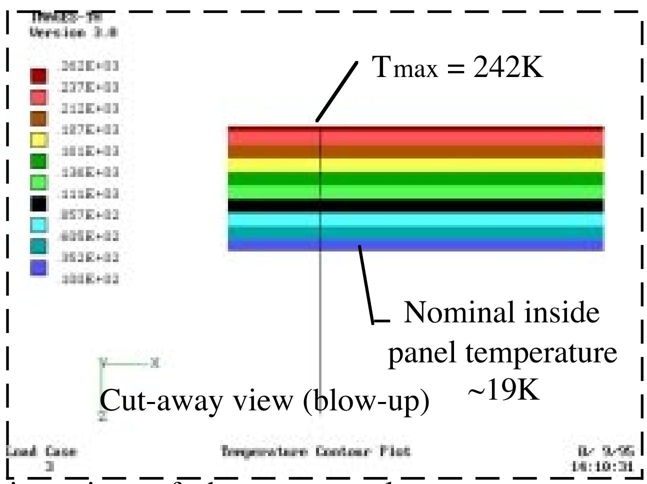

Figure 13: Cross-section view of the test panel temperature contours for load case 3 (temperature in Kelvin).

Pressure Box Thermal Analysis

The inner pressure vessel is a ribbed plate which is insulated on its inner surface, and has shielded vacuum insulation up to the attachment flange at the outer vacuum vessel. The upper vessel section is a removable transition channel which is bolted to the attachment plate on the bottom, and the C-seal on the top of the pressure box. This channel has foam insulation running from the inner vessel past the attachment plate and up to the seal. An axis-symmetric FEA model of this arrangement was created to estimate the heat load into the vessel from the vessel walls and the radiation through the vacuum space. The inputs to this model are that the outer vacuum chamber is grounded to the lower frame at 81°F (300K), with the side wall having a 0.88 Btu/hr-ft^2-°F (5 W/m^2-K) heat transfer coefficient on the surface. The inner vessel has a radiative heat load of 0.16 Btu/hr-ft^2-°F (0.5 W/m^2) on the bottom and sides. The inner-most portion of the vessel has a 4.6 Btu/hr-ft^2-°F (26 W/m^2-K) heat transfer coefficient due to the fans with a -441°F (10K) gas temperature. The results of this analysis are shown in Figure 14. With this load case, the thermal load from the edges of the pressure box was calculated to be between 512 - 682 Btu/hr (150 - 200 W).

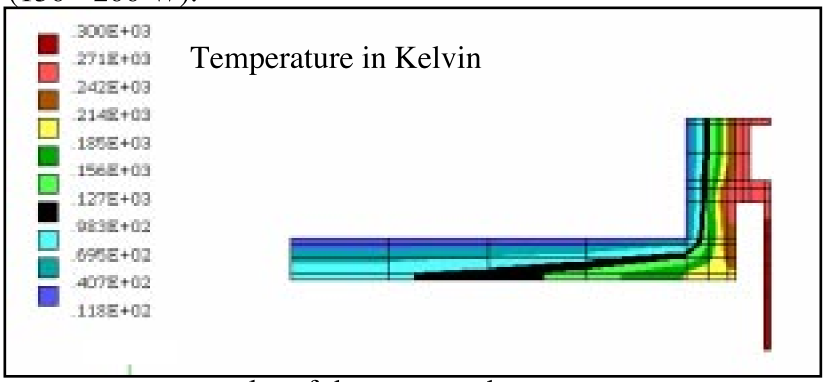

Figure 14: Temperature contour plot of the pressure box.

Summary of Heat Loads to Cryogens

From the prior analysis, the total heat load to the cryogens at steady state is as follows:

Panel load	1876 Btu/hr	(550 W)
End effects from the load introduction plates	171 Btu/hr	(50 W)
Box assembly loads	682 Btu/hr	(200 W)
Rib tension rod loads (insulated)	341 Btu/hr	(100 W)
Total	3070 Btu/hr	(900 W)

The tension rods are assumed to have a 1-in. diameter and to be insulated. This is within the 3412 Btu/hr (1000 W) load assumption used in the previous analysis. To assure a proper margin, the 3412 Btu/hr (1000 W) load will be assumed in all the process analysis.

Cooling Analysis

A number of test panel cooling options were considered and these choices were narrowed to a fan cooled design. This design will use an array of twelve fans to flow the pressurization gas through a cooled plate (fan heat exchanger) and directly onto the test specimen. The advantages of this design are: the cooling control and pressurization control are separated; and the rib height of the sample should not have a large effect on the cooling stream.

A study was done to analyze the best way to cool the panel. A fan cooling arrangement was determined to be the best choice in combination with a fan heat exchanger. Figure 15 shows a schematic diagram of the fan heat exchangers, which consist of a cylindrical cooling plate with LHe and LN2 tubes wrapped around the cylinder. The fan is placed inside the cylindrical cooling plate. A second cooled plate is located below the fan, with foam insulation below the flat cooling plate. The He gas is pulled between the cooling plates and up through the fan heat exchanger. The fan motor is located outside the cooled portion of the pressure box, but is within the high pressure boundary of the box.

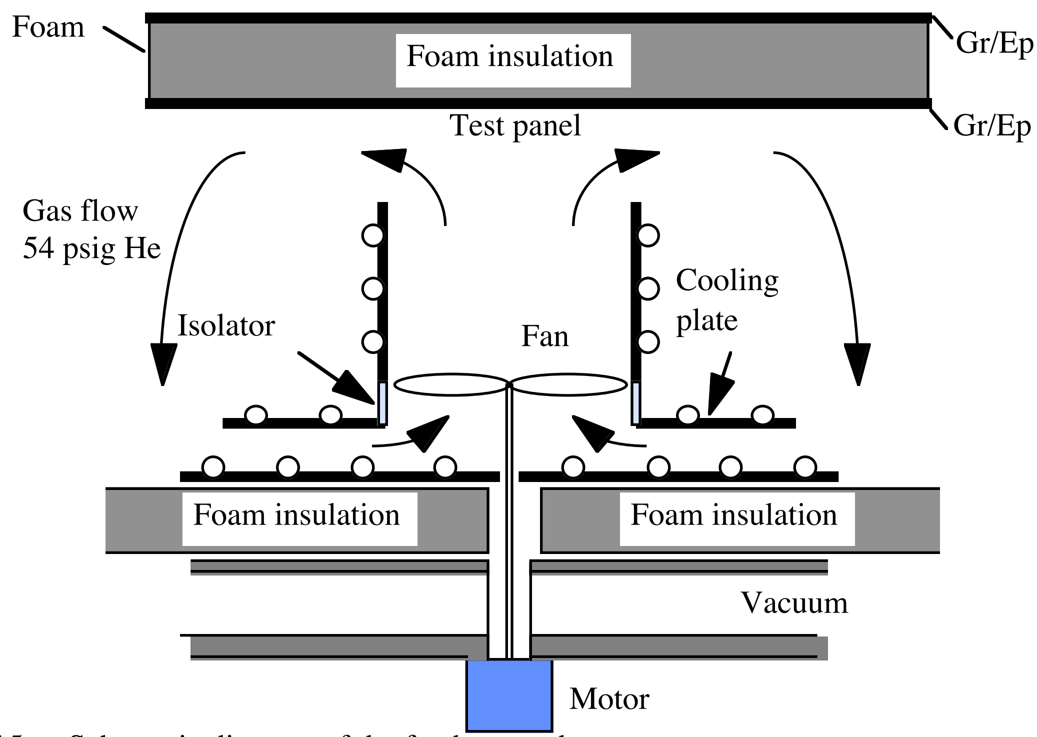

Figure 15: Schematic diagram of the fan heat exchanger.

To properly size the fan, the required coolant velocity must first be calculated. Because the first tests were conducted at room temperature and pressure with air, a correlation from this state to the actual cooling state must be calculated. A summary is as follows. With,

$$h_c = Nu \cdot k/D \quad \text{and} \quad k_{(air)} \sim k_{(He\ @\ T,P\ of\ test)}$$

Then

$$h_c \ \alpha \ Nu$$

with

$$Re = V \cdot D/\nu \qquad \text{where} \quad Re \ \alpha \ \nu$$

Typically,

$$Nu = X \cdot Re^{Y} \cdot Pr^{1/3}$$

with $Y = 0.8$ for turbulent flow

$Y = 0.3$ for laminar flow

and $Pr_{(air)} \sim Pr_{(He\ @\ T,P\ of\ test)}$

Therefore:

$$h_{c(air)} \quad \alpha \quad (1/\nu_{(He)})^{0.8}$$

$$h_{c(He)} \quad \alpha \quad (1/\nu_{(air)})^{0.8}$$

The heat transfer coefficient for a given velocity is 10 - 30 times greater for helium (1 - 4 atm, (-432°F (15K)) than for room temperature air. However, because $dP = V^2 \cdot r/2$, for a given velocity the pressure drop of the fan/duct will be proportional to the ratios of the densities. In this case, the density ratio is 3 - 12 times greater for the helium (at 15K and 1 - 4.5 atm), than for air at room temperature. Therefore, despite the relatively large gain in the heat transfer coefficient, the pressure drop versus flow for the fans must be determined to assure proper cooling.

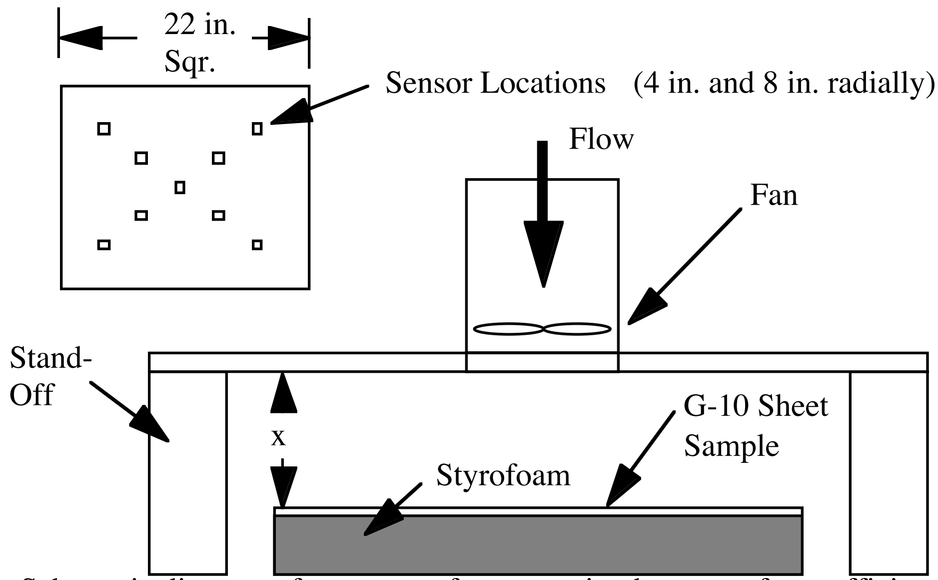

Figure 16: Schematic diagram of test set-up for measuring heat transfer coefficient.

A number of fans were studied to determine the size and velocity required to cool a sample panel with an equivalent heat flux imposed on it. Figure 16 shows the basic test arrangement. By varying the distance from the plate and the impinging velocity of the air, it was determined that a velocity of only 10 ft/min will sufficiently cool a 22 in. x 22 in. plate with a heat flux of 0.57 Btu/hr-in^2 (0.167 W/in^2) (2559 Btu/hr (750 W) from the test panel) at a distance of 15.5 in. A 5.5-in-diameter fan was found to meet this air flow requirement.

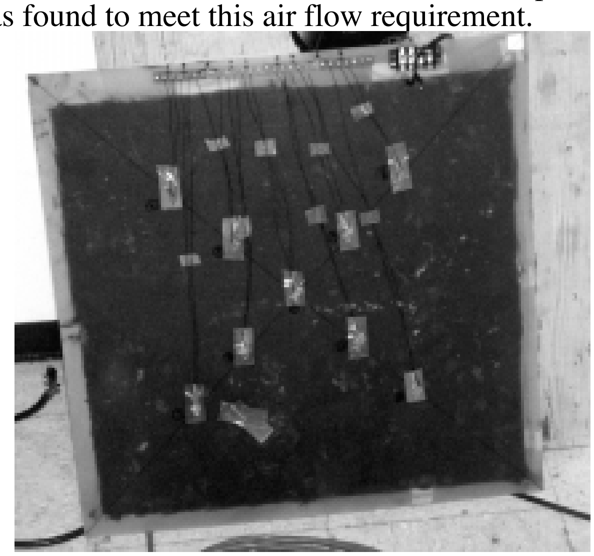

Figure 17: Photograph of the test specimen with the sensors.

The fan was then characterized to determine the power required to produce the velocities required for cooling. This fan will easily achieve the 10 ft/min required and evenly cool the plate. However, the flow does drop off rapidly with high pressure drops. Therefore, further testing was required.

Figure 18: Photograph of the 12 in. x 12 in. test box during testing.

A 12 in. x 12 in. test box was constructed to test the fan at higher pressures and lower temperatures. A photograph of the outside of the test box during testing is shown in Figure 18, and a photograph of the inside of the box, showing the fan heat exchanger is shown in Figure 19. The heat transfer coefficient of the fan was verified down to -351°F (60K). A full size fan heat exchanger was constructed. In this way, the heat transfer coefficient of the entire assembly was tested in a scale model of the pressure box in conjunction with the 5.5-in-diameter fan.

The measured heat transfer coefficient of the fan and fan heat exchanger combined was approximately 23 Btu/hr-ft^2 (130 W/m^2-K) at maximum fan speed. That is 5 times greater than what the thermal analysis indicated was necessary (4.6 Btu/hr-ft^2 (26 W/m^2-K)). The amount of turndown for the fans will be determined during future testing. The fans will run in a continuous mode.

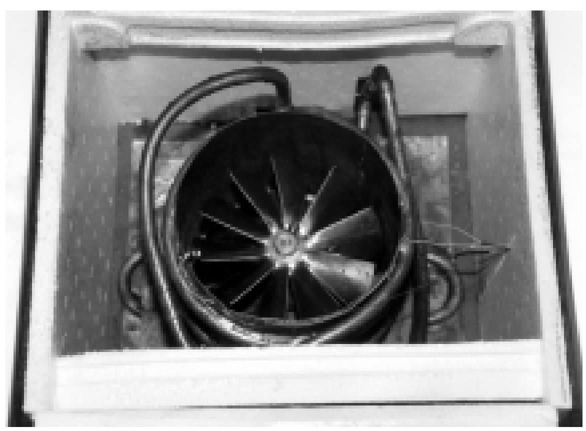

Figure 19: Photograph of the fan and fan heat exchanger inside the test box.

Process Analysis

Figure 15 shows the schematic diagram of the fan-cooling method. It incorporates an internal plate arrangement which has dual nitrogen and helium parallel loops. This will enable the assembly to be pre-cooled with nitrogen prior to cooling with helium and also allow the panel to be cooled during the hot tests without contaminating the helium loop. A cooldown sequence could be as follows:

1. Purge. The box will need to be purged after the panel is assembled (at low pressure) to assure that contamination will not effect the fans or the panel. The purge valve is opened and the

fans are activated to create adequate mixing flow. V2 is used to control the GHe flow into the box during this sequence.

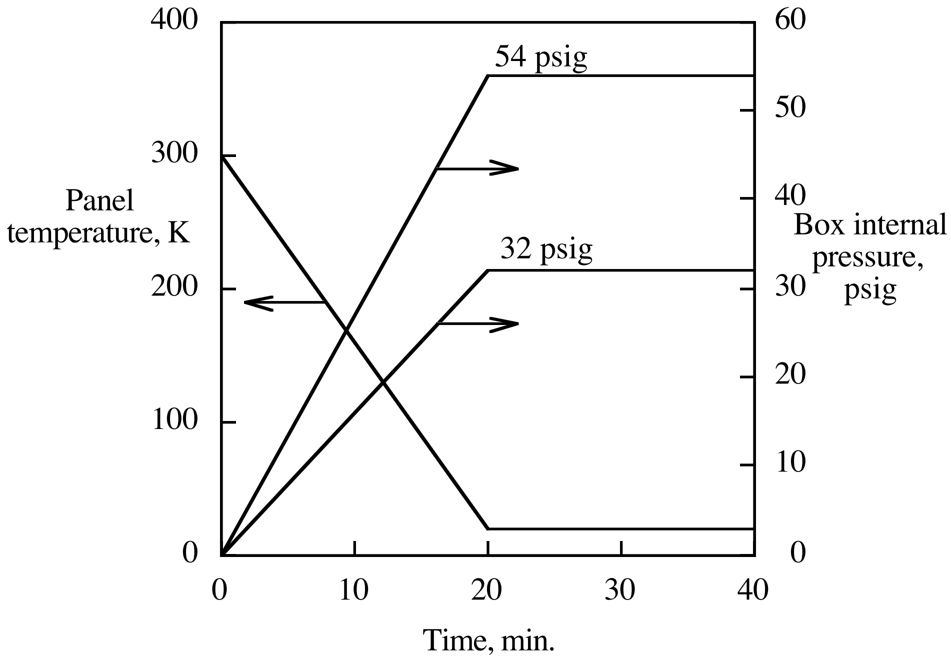

Figure 20: Panel temperature and box internal pressure as a function of time for both a 32 psig test and a 52 psig test (actual cooldown times will be significantly longer).

2. Pressurization and cooldown start-up. It is assumed that pressurization and cooling to the working temperature and pressure will take about 20 minutes. (This assumption is very non-conservative, as the actual cooldown time, though unknown, is anticipated to take significantly longer.) The panel will then be held there for an additional 20 minutes. Typical pressure versus temperature curves for a 32 psig and a 52 psig test are shown in Figure 20.

After purging, the LN2 valves V5 and V6 are opened and the fans are activated. This one nitrogen loop will also cool the lower internal plate of the pressure box and the radiation shields. The flow of nitrogen through the fan heat exchanger is controlled via the outlet temperature of the heat exchanger, and the helium gas cooling boiler is controlled via a level sensor. The box is then pressurized by opening the V2 pressurization valve. The V3 and V7 control valves monitor the exhaust temperature of the return helium stream and V7 is fully open to the boiler at this time.

The above sequence runs until the internal gas temperature reaches approximately -315°F (80K) and the box pressure reaches about 25 psig for a 34 psig test and about 40 psig for a 52 psig test, then the helium cooling is begun.

3. Helium Cooling. The V5 nitrogen gas is shut off and the V4 helium valve is opened. The V8 purge valve removes the nitrogen in the plate stream. The chamber will then continue to pressurize to the test pressure as the sample cools to -423°F (20K). The sample is then maintained at -423°F (20K) and the test pressure for an additional 20 minutes. The V3 control valve senses the exhaust temperature of the low pressure return stream and switches over to the HX2 flow as the exhaust cools. At this time the exhaust gas cools the shield after exiting HX1 because the boiler is being used less and less (in fact due to the unbalanced flow in the system, the boiler will be completely deactivated with all of the flow running through HX2). V4 assures that the liquid helium dewar is constantly kept at a working pressure of about 3 psig. As the exhaust of the cooling plate rises above -441°F (10K), valve V4 opens to create more pressure in the dewar, and therefore more cooling flow.

Consumable Usage

Assuming the pressurization scenarios previously described in Figure 20, the liquid helium usage would not begin until the panel is less than -306°F (85K). The helium usage is a function of the exhaust temperature of the cooling plate and the minimum temperature of the pressurization gas required to cool the panel. A plot of the liquid helium consumption versus time for a -450°F (5K) plate temperature and a -441°F (10K) nominal pressurization gas temperature is shown in Figure 21. The total LHe usage is 560 liters for a 20 minute cool down and a 20 minute test. The curve is generated by assuming a 1000 W panel load and the energy required to cool the pressurization gas from the exhaust temperature of HX1 to the pressurization gas temperature inside the test box. A 95% effective heat exchanger is assumed for the HX1/HX2 combination. The 95% assumption is based on the large flow imbalance of the heat exchangers at this point in the cooldown. With this imbalance, the outlet temperature will be close to the venting helium temperature, and 95% effectiveness is assumed to be conservative. Calculations indicated that the heat exchangers to be fabricated are much larger than what is required. The exit temperature of HX1 (with this assumption) is 19.8K. The power required to cool this gas is:

$$Q = \dot{m}\, Cp\, (T_{exit} - T_{gas}) = (14.2 \text{ g/s})\ (5.2 \text{ J/g-K})\ (19.8\text{K} - 10\text{K}) = 730 \text{ W}$$

The 14.2 g/s LHe flowrate is based on a 34 psig gas pressure. For the 52 psig gas pressure case, a LHe flowrate of 20 g/s would be required, resulting in a heat load of 1030 W instead of 730 W. The total liquid helium load for the 34 psig case is (730 W to cool the gas + 1000 W through the panel) 1730 W. It is assumed here that the majority of the thermal mass of the system is pre-cooled with the LN2 during cooldown. With this heat load, the liquid helium flow can be calculated:

$$\dot{m} = Q/(h_{5K} - H_L) = (1730 \text{ W}) / (36.2 \text{ Ws/g} - 9.711 \text{ Ws/g}) = 65 \text{ g/s}$$

With the density of liquid helium 125 g/liters, the net boil-off is ((65 g/s)/(125 g/liter))•3600 sec/hr = 1,872 liters/hr. This boil-off drops to 1,410 liters/hr when the pressurization is complete and the only heat load is the 1000 W from the panel.

Figure 22 shows the effect of the cooling plate exit temperature on the liquid helium consumption rate. The ability to run the cooling plate up to at least 10K has a large payoff in the total helium consumption. This plate temperature is a function of both the pressurization gas temperature and the effective heat transfer from the sample to the gas as well as the effective heat transfer from the gas to the liquid. From this it could be assumed that turning the fans up, though they will draw more power, will raise the required pressurization gas temperature, and therefore the cooling plate temperature, and lessen the overall liquid helium consumption considerably.

The pressurization gas requirement is relatively straightforward. For a given internal volume of the pressure box (it is assumed to be 72 in. x 63 in. x 12 in. deep) the final temperature and pressure dictate gas usage. As an example, if the final pressure is to be 34 psig and the nominal minimum gas temperature is required to be 10K, the density of the gas in this state is 19 g/liter. With this given volume, the mass required to reach this condition is 17 kg. Therefore, the flow rate required to reach this condition is a function of how fast the panel is going to be pressurized (i.e., for a 20 minute pressurization, the flow rate will be (17 kg)/((20 min) (60 s/min)) = 14.2 g/s). With a density of helium at STP of 4.24 x 10^{-3} kg/ft^3, the amount of helium required is 17 kg/4.24 x 10^{-3} kg/ft^3 = 4000 SCF. It is important to note that this result assumes no leakage in the system. Therefore, a factor of safety should be added for this loss.

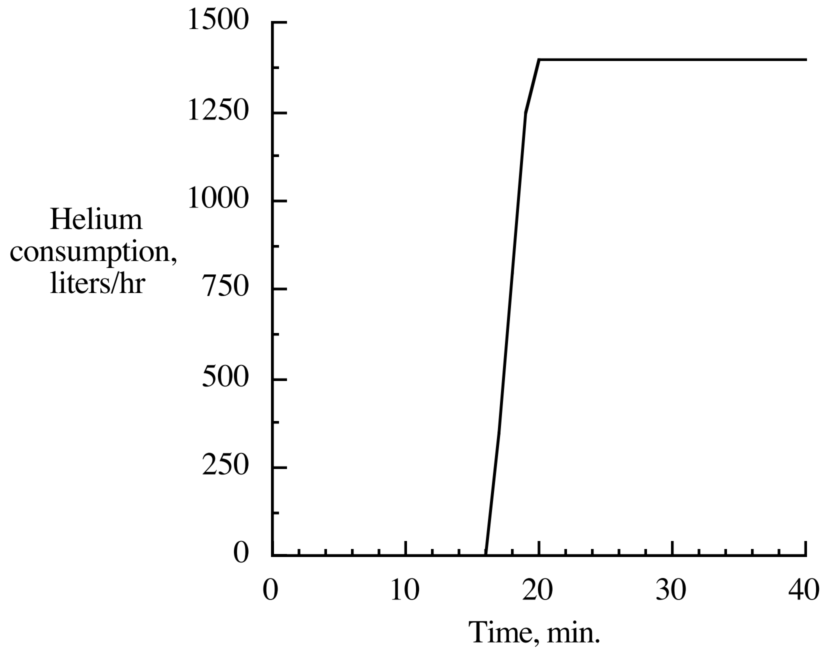

Figure 21: Estimated liquid helium consumption versus time for a 5K cooling plate and a 10K minimum pressurization gas.

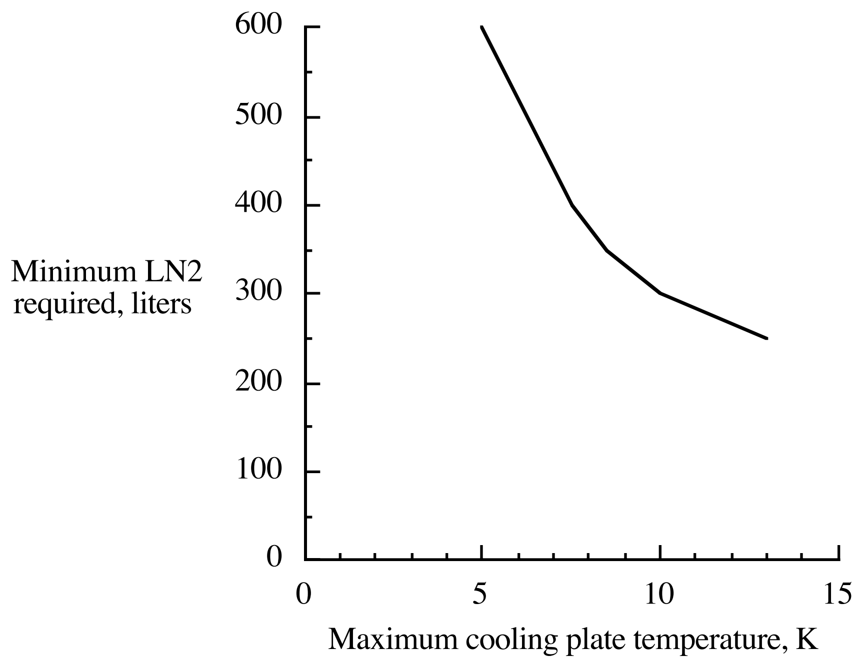

Figure 22: Estimated liquid helium required versus cooling plate maximum temperature for a 15K nominal minimum pressurization gas temperature.

Figure 23 shows the change in the high pressure helium gas usage as a function of final pressure and temperature for the pressure box. By increasing the required pressure box gas temperature (by turning up the fans) the amount of gas required can also be reduced substantially.

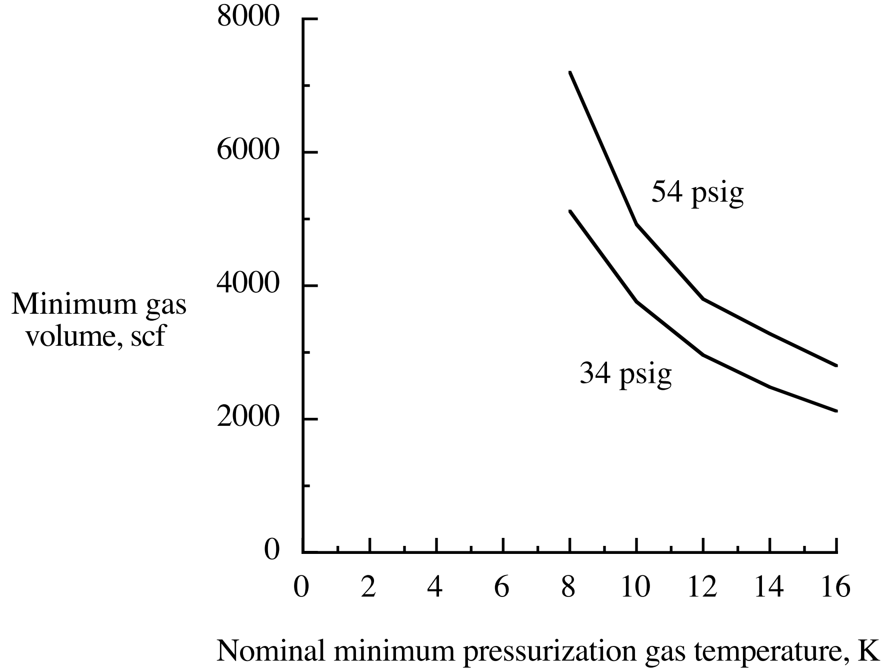

Figure 23: Estimated high pressure helium gas usage as a function of minimum gas temperature.

Figure 24 shows the estimated change in liquid nitrogen usage for differing pressure and temperature requirements of the pressure box. These curves are generated by calculating the power required to cool the incoming gas to 80K and adding the 1000 W maximum heat load from the sample. The sample load is zero at 300K and 1000 W at 80K. The liquid nitrogen required to cool the gas is calculated by:

$$Q = \dot{m}\, C_p\, (300K - 80K)$$

with C_p of helium = 5.2 J/g-K and with a LHe flow rate of 14.2 g/s,

$$Q = (14.2 \text{ g/s})\,(5.2 \text{ J/g-K})\,(300K - 80K) = 16 \text{ kW}.$$

The liquid nitrogen required is 44.7 W/(liter/hr) or (16 kW)/(44.7 W/liter-hr) = 360 L/hr over 20 minutes. This is (360 liters/hr) (20 min) / (60 min/hr) = 120 liters/hr. This will be reduced by approximately 1/3 by the HXN heat exchanger. This does not include purging and any gas used for warm-up.

It is also of interest to know the LN2 and LHe consumption as a function of the panel temperature. Due to high cost of LHe, it may be necessary to test the panel at temperatures higher than 20K if that would result in a significant cost savings. Testing at higher temperatures would also be dependent on how the materials responded at the higher temperatures, i.e., do the mechanical properties of Gr/Ep change significantly between 20K and 80K. Figure 25 shows the estimated liquid helium usage as a function of test panel internal temperature. At a panel temperature of 20K, the LHe usage is approximately 600 liters. The helium usage drops to approximately 400 liters at a panel temperature of 80K.

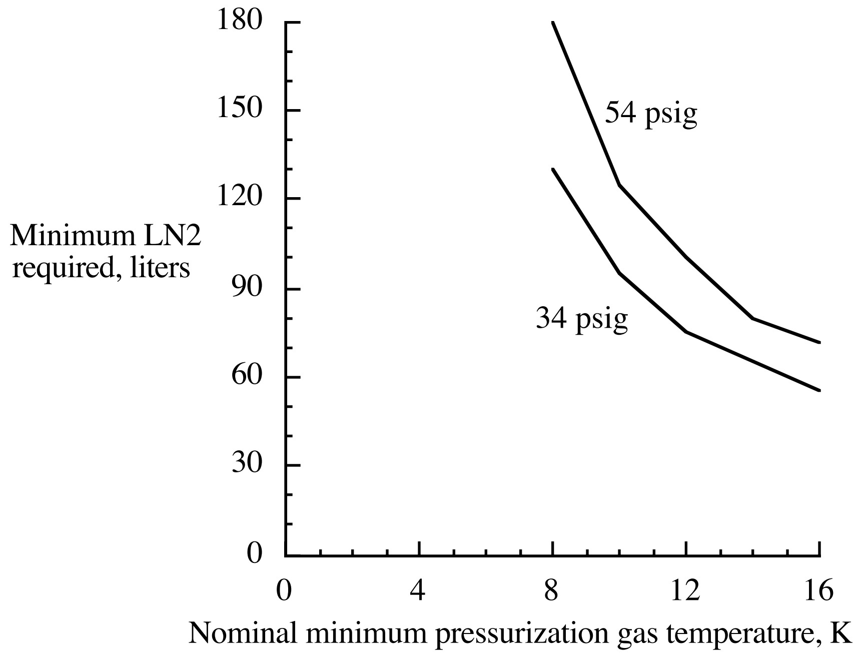

Figure 24: Estimated liquid nitrogen usage as a function of minimum pressurization gas temperature.

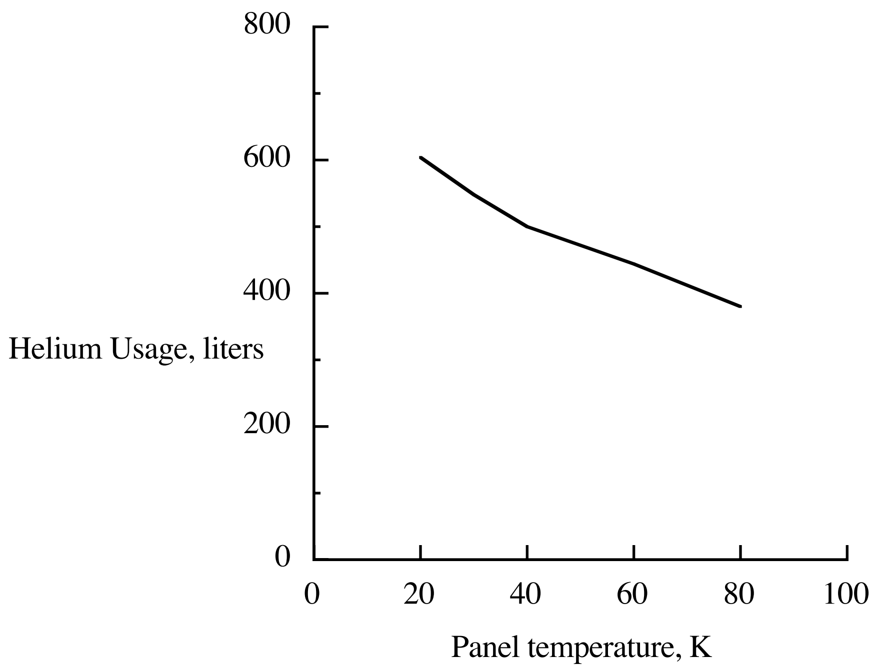

Figure 25: Estimated helium usage as a function of internal panel temperature.

Figure 26 shows the estimated liquid nitrogen usage as a function of test panel internal temperature. At a panel temperature of 20K, the LN2 usage is approximately 180 liters. The LN2 usage drops to approximately 40 liters at a panel temperature of 80K. The percentage drop in cryogen usage when the panel temperature is increased from 20K to 80K is much higher for the LN2 than for the LHe. However, the volume reduction of LHe is greater, and due to the significantly higher cost of LHe compared to LH2, the cost savings will lie in a reduction of LHe usage.

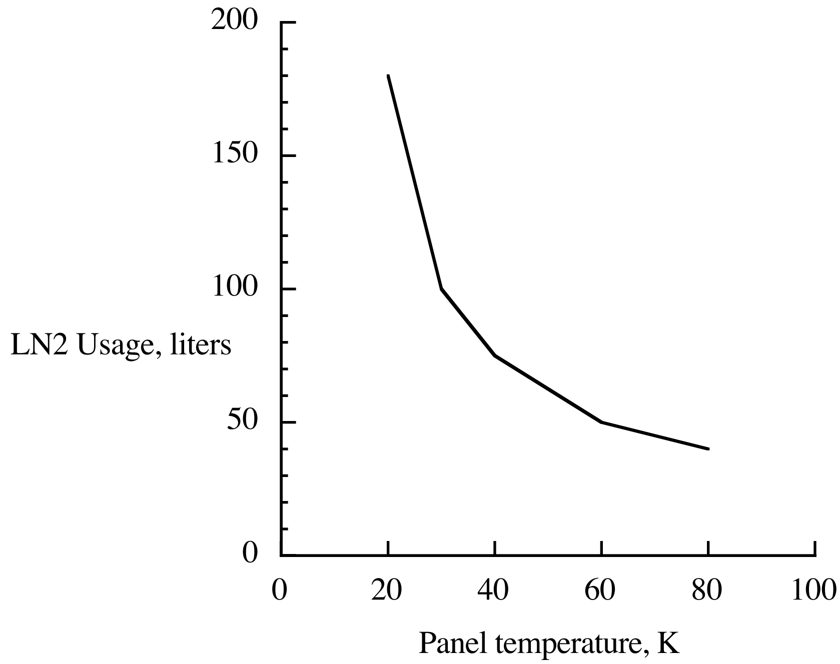

Figure 26: Estimated liquid nitrogen usage as a function of internal panel temperature.

Prior to operation, the pressure box will need to be purged of all air by the high pressure helium gas. With the fans running, a reasonable assumption is that every time the box volume is displaced, the air percentage is reduced by 50%. The volume of the box is slightly less than 50 ft^3. Table 5 shows the percentage of air as a function of the volume of GHe for every 50 ft^3 of GHe purge.

Table 5: Percentage of Air as a Function of GHe Purge Volume

Volume of GHe, ft3	Percentage of Air
50	50
100	25
150	12.5
200	6.25
250	3.13
300	1.6
350	0.6

As shown in the table, approximately 350 ft^3 of GHe is required to reduce the air concentration to less than 1%. The foam in the box will also hold a significant amount of air and will require more time to be replaced with GHe. The time for the foam to be purged will be relatively independent of the purge gas flow rate. For planning purposes, it would be wise to count of 700 ft^3 of purge gas rather than 350 ft^3. If the purge is required to be accomplished in 10 min, a flowrate of 35 ft^3/min would be required.

A consumables summary is shown in Table 6 based on the cooldown scenario shown in Figure 20. Since the times shown in Figure 20 under estimate the actual cooldown time, the costs shown in Table 6 under estimate the actual costs. The consumables consists of a cooldown and steady state operation. As can be seen from the table, the cost of the LHe is the major expense of testing.

Table 6: Summary of Consumables

Condition	LHe	LN2	99.999% Pure He Gas
Cooldown	300 liters	600 liters	40,000 scf
Steady state (20 min.)	1100 liters	200 liters	minimal
Steady state/min.	55 liters	10 liters	negligible
Cost of initial cooldown and 20 min. test	$5,600	$176	$3,100
Cost of steady state testing/min.	$220	$2.20	negligible

Pressure Box Design

The design of the pressure box and the boiler pod is based on the analysis described earlier. Design aspects of the seals, valves, burst disks, and heat exchangers are discussed below. Sealing the pressure box is performed by two seals: a finger seal, and a C-seal. A tension rod seal is required for test panels with ring frames.

Seals

Three types of seals are used to seal the pressure box. One is a C-seal, which connects the panel to the transition channel. The second seal is a finger seal which seals the leak paths between the fingers, and the third seal is a tension rod seal that seals the penetration for the tension rod. The tension rod seal is not discussed here. These seals are shown schematically in Figure 27. Each of the different seals uses the same Gore-tex® fabric.

C-Seal

The C-seal must contain the pressure of the box as well a remain flexible down to 20K. The seal material that has been chosen for the C-seal is a Gore-tex fabric radome laminate, RA7943. The material is 100% fluoropolymer and is composed of 4 layers laminated together resulting in a total thickness of 0.014 in. Each layer of the laminate is made of different forms of the PTFE material (Teflon). The fibers are woven in a 2 x 2 basketweave. The typical Mullen burst strength (ASTM D-3786) is 800 psi. The typical breaking load (ASTM D-1682) in the cross machine direction is 300 lb/in. and in the machine direction is 350 lb/in. The manufacturer states that there is zero air permeability through the laminate. The material is capable of withstanding temperature up to 550°F. Water entry pressure is stated to be > 30 psi. More detail concerning the C-seal development effort and mechanical properties can be found in references 4 and 5.

Finger Seal

The finger seal must seal the leak paths that exist between the fingers and through the bolt holes in the fingers. The finger seal, unlike the C-seal, will not be required to contain the internal box pressure. The finger seal will consist of the same gray radome material used for the C-seal. Since the panel cannot be bolted tightly between the fingers, and the seal must be bolted tightly to the fingers, the finger seal cannot be bolted to the fingers with the bolts through the panel. The finger seal will be bonded to the test panel in front of the fingers. The finger seal will then drape around the fingers and be attached with a screw into a bearing bar.

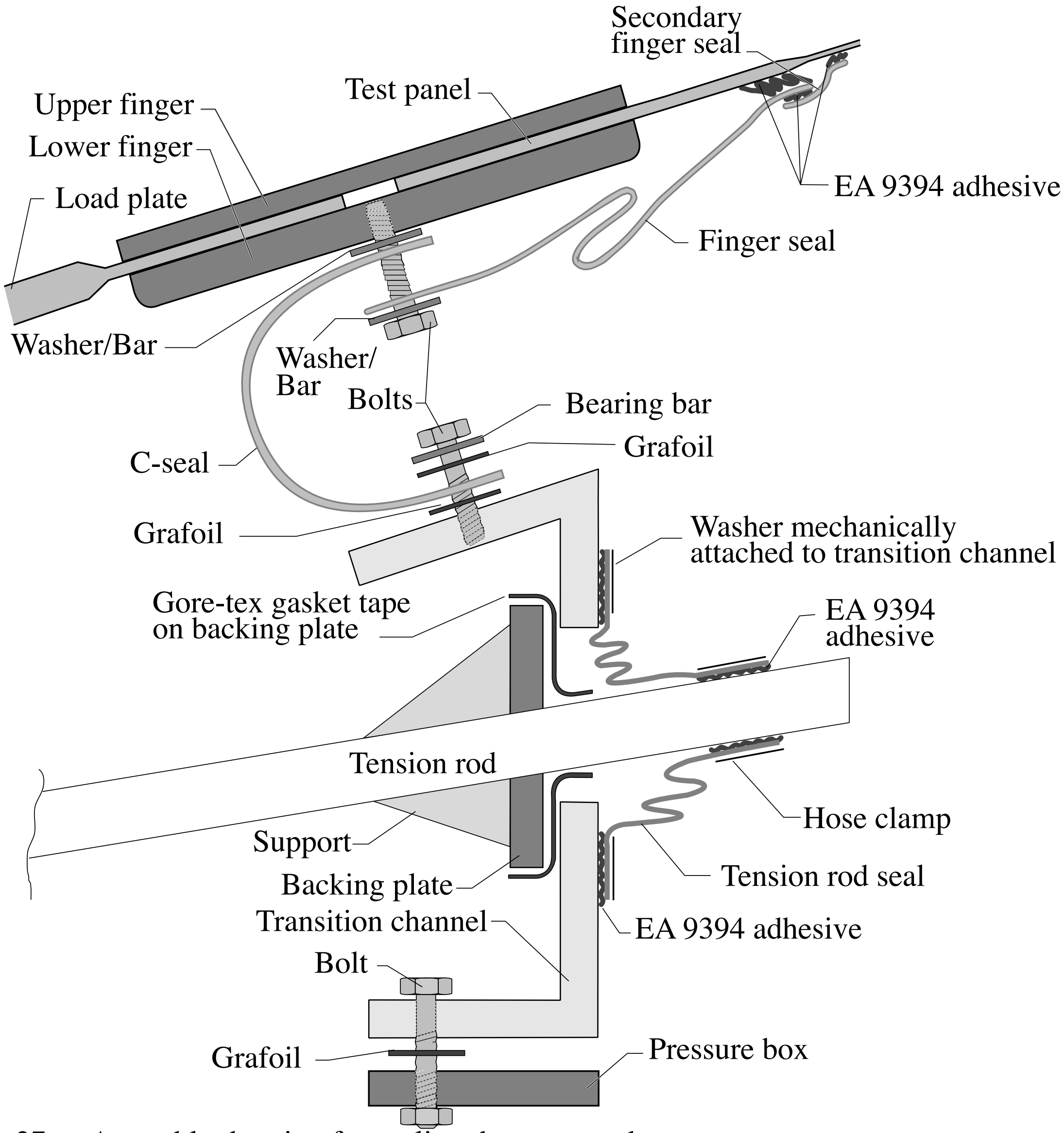

Figure 27: Assembly drawing for sealing the pressure box.

Several types of bonds will be required to attach the seals in each location. To obtain initial screening information, tests were performed to determine the feasibility of bonding Gore-tex gasket tape and teflon sheets to Gr/Ep. (Though teflon sheets will not be in the sealing, the teflon material will be used.) Three different room temperature cure adhesives were evaluated. Only room temperature adhesives were evaluated due to the fabrication difficulties involved with elevated temperature cure adhesives on a large test panel. The adhesives evaluated were Crest 3170®, Hysol EA 9394®, and PR 1664®. A strip of Gore-tex gasket tape was bonded between the Gr/Ep and a strip of teflon. A vacuum bag was used to apply 14.7 psi to the bonds. After the bonding was complete, the specimens were cycled between room temperature and 250°F twenty times, with a 20 min. hold at 250°F. After all the heating was complete, the specimens were dunked in LHe four times and held for 5 min. each cycle. In all cases, the bonded areas remained bonded and no negative effects could be observed. In prior tests, where the pressure was applied with a press rather than a vacuum bag, the specimens bonded with PR 1664 and Crest 3170 experienced cracking of the teflon that was bonded to the Gore-tex gasket tape after dunking in LHe. Portions of the teflon not bonded to the Gore-tex gasket tape did not crack.

The next cycle of bonding evaluation consisted of bonding the gray radome material to Gr/Ep, stainless steel, and aluminum to simulate bonding the finger seals to the test panel.

Pieces of the gray radome material that were etched and not etched were bonded. A vacuum bag was used to apply the pressure loads for bonding. After the bonding was complete, the Gr/Ep, stainless steel, and aluminum pieces were thermally cycled ten times between room temperature and 250°F. Both before and after the heating, the peel strength of the etched material was significantly higher than the unetched material. The etched material bonded with Crest 3170 adhesive experienced a material failure rather than a bondline failure when peeled, indicating a strong bondline. The specimens were then heated and the peel strength was evaluated (qualitatively) at 200°F, 250°F, 300°F, and 350°F. At 200°F, all three adhesives appeared to be nearly the same. At 250°F, the PR 1664 began to get weaker, and the EA 9394 appeared to be slightly stronger than the Crest 3170. This same trend held at 300°F and 350°F. The specimens were then dunked in LN2, and all the adhesives retained their strength. Finally, the Gr/Ep specimen was heated at 250°F for 24 hours. After the 24 hour heating, the radome material bonded with the EA 9394 was bonded better than the specimen with the Crest 3170. The Crest 3170 bondline was relatively strong, but could be peeled off, while the EA 9394 bondline was extremely difficult to peel off. As a result of these tests, the EA 9394 adhesive should be used when bonding the radome seal material.

Small test specimens were also prepared where the radome material was bonded to itself and to the Gore-tex gasket tape. Here, the radome material was etched. The test specimens were cycled between room temperature and 250°F ten times and between room temperature and LHe five times. In all cases, the bondline between the gasket tape and the radome material was stronger than the gasket tape. In addition, the bondline between the two layers of radome material was stronger than the radome material, as evidenced by a separation of the radome material upon peeling the two layers apart.

Tension Rod Seal

A 1 7/8 diameter stainless steel tension rod will penetrate the transition channel and attach to the ring frame of the test panel. Due to the possibility of the test panel lifting up to 2 in. upon box pressurization, the hole where the tension rod penetrates must be able to allow for that vertical motion. A stainless steel bellows seal was initially considered. However, due to the magnitude of the required length (~36 in.) and diameter (~ 6 in.) of the bellows seal, a more compact sealing mechanism was desired. A tension rod seal was designed and fabricated. The seal was then tested successfully at room temperature for five 30 min. cycles at 60 psi.

Valves

Both solenoid and proportional valves are used to control the flow of the LHe, LN2, and GHe. All of the valves that are used in cryogenic environments are rated by the manufacturer for cryogenic use. In addition, all valves are rated for outdoor use. A list of the valves, including description and part number are given in Table 7. All of the relief valves are in line valves and are manifolded to a common line to dump the cryogens away from the box and boiler pod.

Table 7: Description of Valves Used for Flow Control

Valve No.	Valve Description	Part No.	Remarks
V1	Regulator	Grove 11568PO56A	150 atm - 14 atm
V2	Control valve	CPC Corp Style 5510	Air operated, fail closed
V3	Control w actuator	Sinclair Collins	Air operated, fail closed
V4	Control w actuator & positioner	CPC Corp Style 5510	Air operated, fail closed
V5	Control valve	Fisher Controls 32-24-588SEE	Air operated, fail closed
V6A	Solenoid	ASCO 8222G2LT	Normally closed
V6B	Solenoid	ASCO 8222G2LT	Normally closed
V7	Control w actuator	Sinclair Collins	Air operated, fail closed
V8	Solenoid	ASCO 8210G7	Normally closed
V9	Solenoid	ASCO 8210G7	Normally closed
V10	Extended stem	CPC Corp Style 5510	Air operated, fail closed
V11	Relief	Circle Seal 559B-2M-100	100 psi
V12	Solenoid	Atcomatic 15427-G-WP	Fail open
V12A	Solenoid	Atcomatic 15427-G-WP	Fail open
V13	Solenoid	ASCO 8222G2LT	Normally closed
V14	Solenoid	ASCO 8222G2LT	Normally closed
V15	Check	Circle Seal 220B-4PP-0.15	0.15 psi
V16	Check	Circle Seal 220B-4PP-0.15	0.15 psi
V17	Relief	5V3-088-5W2 Cryolab	part of V18
V18	Vacuum	5V3-088-5W2 Cryolab	part of V17
V19	Check	Circle Seal 220B-4PP-0.15	0.15 psi
V20	Relief	5V3-088-5W2 Cryolab	part of V21
V21	Vacuum	5V3-088-5W2 Cryolab	part of V20
V22	Check	Circle Seal 220B-4PP-0.15	0.5 psi
V23	Relief	Circle Seal 220B-4PP-0.15	0.5 psi, boiler vent
V24	Check	S-886-16BWS10	No spring
V25	Relief	Circle Seal 520B-4M-100	100 psi
V26	Relief	Circle Seal 5159B-6M-250	250 psi
V27	Relief	Circle Seal 5180B-4MP-100	100 psi
V28	Solenoid	ASCO 8222G2LT	Normally closed
V29	Relief	Circle Seal 5180B-4MP-100	100 psi
V30	Check	Circle Seal 280T1-4PP-0.15	0.15 psig
V31	Relief	Circle Seal 5180B-8MP-10	10 psi
V32	Relief	Circle Seal 5180B-6MP-4	4 psi
V33	Solenoid	ASCO 8222G2LT	Normally closed
V34	Solenoid	ASCO 8222G2LT	Normally closed

Heat Exchangers

This section describes the method of choosing the sizes and geometry of the process systems heat exchangers.

HX1 Design

HX1 is a helium economizer heat exchanger. It pre-cools the incoming pressurization gas using the exhaust stream from the fan heat exchanger. When in operation, HX1 receives the low pressure liquid helium boil-off at approximately 5K on one side and the high pressure gas at 50 - 80K from the other side. The low pressure gas cools the pressurization gas to approximately 20K to help relieve the load on the fans. The projected flow rate of the high pressure side is about 19 g/s. The low pressure side flow will ramp up from 0 to 50 g/s as the panel cools. HX1 consists of a set of three parallel counter flow heat exchangers mounted under the inner vessel of the pressurization box. Each heat exchanger is a cross flow helical fin tube design allowing for a minimum pressure drop on the low side to maintain a low liquid temperature in the cooling plate. Its specifications are given in Table 8.

Table 8: Specifications for Heat Exchanger HX1

Inside diameter	3 in.
Outside diameter	4.25 in.
Overall length	36 in.
Fin tube size	3/8 in. OD x 1/8 in. fin height
T_{in} low side	5K
Flow low side	0 - 50 g/s
T_{in} high side	50 - 110K
Flow high side	19 g/s
Pressure drop high side (max)	15 psi
Pressure drop low side (max)	0.5 psig
Effectiveness at equal flows	0.90

The maximum stress in the heat exchanger HX1 is calculated as follows, with an outer diameter, d_{out}, of 4.3 in., and inner diameter, d_{in}, of 2.875 in., and a wall thickness of 0.25 in. The pressure differential is

$$\Delta P = 15 \text{ psi} + 15 \text{ psi} = 30 \text{ psi}.$$

Then,

$$b_a = d_{in} / d_{out} = 0.669$$

$$M = K\ M\ r\ b_a\ \Delta P\ (d_{out}/r)^2 = 6.324$$

Then the maximum stress is

$$\sigma = 6\ M / t^2 = 607.062 \text{ psi}$$

which is well below the allowable stress of 18,000 psi.

HX2 Design

HX2 is a second stage helium economizer heat exchanger. It pre-cools the ambient temperature incoming pressurization gas using the exhaust stream from HX1. When in operation, HX2 receives the low pressure stream from HX1 at approximately 20 - 50K. The low pressure gas cools the pressurization gas to approximately 80K to help relieve the load on HX1 and the boiler pre-cooler. The projected flow rate of the high pressure side is about 19 g/s. The low pressure side flow will ramp up from 0 to 50 g/s as the panel cools. HX2 consists of a set of three parallel counter flow heat exchangers mounted above the boiler in the boiler pod. Each heat exchanger is a cross flow helical fin tube design allowing for a minimum of pressure drop on the low side to maintain a low liquid temperature in the cooling plate. The specifications for HX2 are given in Table 9.

The maximum stress in the heat exchanger HX1 is calculated as follows, with an outer diameter, d_{out}, of 7.03 in., and inner diameter, d_{in}, of 5.38 in., and a wall thickness of 0.25 in. The pressure differential is

$$\Delta P = 15 \text{ psi} + 20 \text{ psi} = 35 \text{ psi}.$$

Then,

$$b_a = d_{in} / d_{out} = 0.765$$

$$M = K\ M\ r\ b_a\ \Delta P\ (d_{out}/r)^2 = 19.719$$

Then the maximum stress is

$$\sigma = 6\ M / t^2 = 864.234 \text{ psi}$$

which is well below the allowable stress of 18,000 psi.

Table 9: Specifications for Heat Exchanger HX2

Inside diameter	5.5 in.
Outside diameter	7.03 in.
Overall length	24 in.
Fin tube size	1.2 in. OD x 1/8 in. fin height
T_{in} low side	30 - 50K
Flow low side	0 - 50 g/s
T_{in} high side	300K
Flow high side	19 g/s
Pressure drop high side (max)	15 psi
Pressure drop low side (max)	0.5 psig
Effectiveness at equal flows	0.90

Boiler Design

The boiler is a helium economizer heat exchanger. It pre-cools the incoming pressurization gas (He) from HXN to 80K. The projected flow rate of the high pressure side is about 19 g/s. The boil-off is expected to be approximately 160 liter/hr. The boiler consists of a liquid pot and a helical fin tube. The specifications for the boiler are given in Table 10.

Table 10: Specifications for Boiler

Outside diameter	20 in.
Overall length	16 in.
Fin tube size	1/2 in. OD x 1/8 in. fin height
T_{in} high side	150K
Flow high side	19 g/s
Pressure drop high side (max)	20 psi
Effectiveness at equal flows	0.90
Nitrogen consumption (max)	160 liters/hr

HXN Design

HXN is a nitrogen economizer heat exchanger. It pre-cools the incoming pressurization gas using the boil-off from the liquid nitrogen boiler. When in operation, HXN receives the low pressure nitrogen boil-off at approximately 80K on one side and the high pressure He at 300K from the other side. The low pressure N_2 cools the pressurization gas to approximately 150K to help relieve the load on the nitrogen boiler. The projected flow rate of the high pressure side is about 19 g/s. The low pressure side flow will be about 35 g/s of nitrogen gas. HXN is a counter flow heat exchanger above the boiler in the boiler pod. The HXN heat exchanger is a cross flow helical fin tube design allowing for a minimum pressure drop on the low side to maintain a low liquid temperature in the boiler. Its specifications are given in Table 11.

Table 11: Specifications for Heat Exchanger HXN

Inside diameter	5.5 in.
Outside diameter	7.03 in.
Overall length	24 in.
Fin tube size	1.2 in. OD x 1/8 in. fin height
T_{in} low side	150K
Flow low side	35 g/s
T_{in} high side	300K
Flow high side	19 g/s
Pressure drop high side (max)	15 psi
Pressure drop low side (max)	5 psig
Effectiveness at equal flows	0.70

The maximum stress in heat exchanger HX1 is calculated as follows, with an outer diameter, d_{out}, of 7.03 in., an inner diameter, d_{in}, of 5.37 in., and a wall thickness of 0.37 in. The pressure differential is

$$\Delta P = 15 \text{ psi} + 25 \text{ psi} = 40 \text{ psi.}$$

Then,

$$b_a = d_{in} / d_{out} = 0.764$$

$$M = K\ M\ r\ b_a\ \Delta P\ (d_{out}/r)^2 = 22.536$$

Then the maximum stress is

$$\sigma = 6\ M / t^2 = 987.696 \text{ psi}$$

which is well below the allowable stress of 18,000 psi.

Interface Between Pressure Box and Support Structure

This section describes the interfaces between the cryogenic pressure box and the support equipment and test equipment. A block diagram of the entire system is shown in Figure 4 and consists of two major subassemblies. The interconnections between the subassemblies are not covered here. The major interfaces are:

- Cryogens to the system
- Pressure box to the test panel
- Support equipment
- Mounting configuration
- Electrical interface

Pressure Box

There are five major interfaces between the pressure box and the outside world. They are:

- Pressure box to test panel
- Evacuation system
- Cryogen supply
- Electrical
- Pressure box mounting

Pressure Box to Test Panel

The test panel is attached to the pressure box through a flexible seal which allows the test panel to move relative to the pressure box as the loads are applied. The seal attaches to the fingers which are bolted to the test panel, the details of this attachment are described in a prior section. The other end of the seal attaches to the transition channel through a bolt pattern. The details of this bolt pattern are shown on:

Test Panel	AET DWG # DA-1141 Rev A
Checkout Panel	AET DWG # DA-1136 Rev A

Evacuation System

Prior to operation, the pressure box must be evacuated to a pressure of less than 1×10^{-4} torr to ensure proper insulating vacuum. It is recommended that a pump with a pumping capability of 30 CFM be used to allow for pumpdown in a reasonable time. The pumping connection on the pressure box mates to a separate supplied operator which is connected via a standard KF-40 vacuum connection. The location of the pumping port on the pressure box is shown in Drawing A1222 Rev A.

Cryogen Supply

The pressure box is supplied with cryogens from three sources, a 1000 gallon rental storage dewar, a site installed liquid nitrogen storage dewar, and the transfer system/boiler pod. There are two interfaces covered by this document. The first is the 1000 gallon storage dewar to the pressure box. The system provided will interface to the commercial 1000 gallon storage dewar as currently defined by NASA.

The second cryogen interface is between the pressure box transfer system and the liquid nitrogen storage system. The details of this interface are defined in drawing A 1222 Rev A.

Electrical

The electrical interfaces to the pressure box are through a vacuum tight connector to the control system. The connector is to be specified and will carry the motor control power and the temperature signals from the silicone diodes used to monitor the temperature. Wiring information is shown in AET drawings # A1216 to A1220.

Pressure Box Mounting

The mounting of the pressure box to the support I-beams is through 4 welded tabs.

Boiler Pod

The boiler pod contains heat exchangers and vessels necessary to service the pressure box and for proper operation. It is connected via transfer lines to the following:
- Pressure box
- Storage dewar
- Liquid nitrogen storage dewar

The location of all of the interface points is shown in AET DWG # A1214. An additional connection is necessary to the high pressure gas storage as well as a service pumping connection. The details of the connections not covered here.

High Pressure Supply Gas

The boiler pod will contain a 0.75 in. swagelock connection for connecting to the gas supply system. The gas is to be 99.995% pure helium or better at a pressure of 250 psig max. The interconnecting piping is to be designed to carry a flowrate of 50 g/s at ambient temperature.

Liquid Nitrogen System

The interface between the boiler pod box transfer system and the liquid nitrogen storage system are shown in AET drawing A-1214.

Evacuation System

Prior to operation, the boiler pod must be evacuated to a pressure of less than 1 x 10^{-4} torr to ensure proper insulating vacuum. It is recommended that a pump with a pumping capability of 20 CFM be used to allow for pumpdown in a reasonable time. The pumping connection on the pressure box mates to a separate operator which is connected via standard KF-40 Vacuum connection. The location of the pumping port is shown on drawing A 1214. The same pump can be used for both the pressure box and the boiler pod, so we have chosen to make the interfaces identical. We have also provided a single operator to open both pumping ports.

Mounting

The boiler pod is designed to be free standing. If desired, holes may be added through the frame for lagging to the concrete.

Load Introduction Structure

The load introduction structure is used to apply mechanical loads to the edges of the test panels. The goal is to design and build a pressure box, load introduction structure, and test panel transition region that will accurately simulate the structural response of an actual, operational tank structure. The purpose of this section is to document the structural analysis and design of the load introduction structure for a specific Gr/Ep test panel. Other panels with larger radii and larger loads will be tested in the facility, but are not discussed here. The design here is for only the load introduction structure, and does not include the support structure and reacting members.

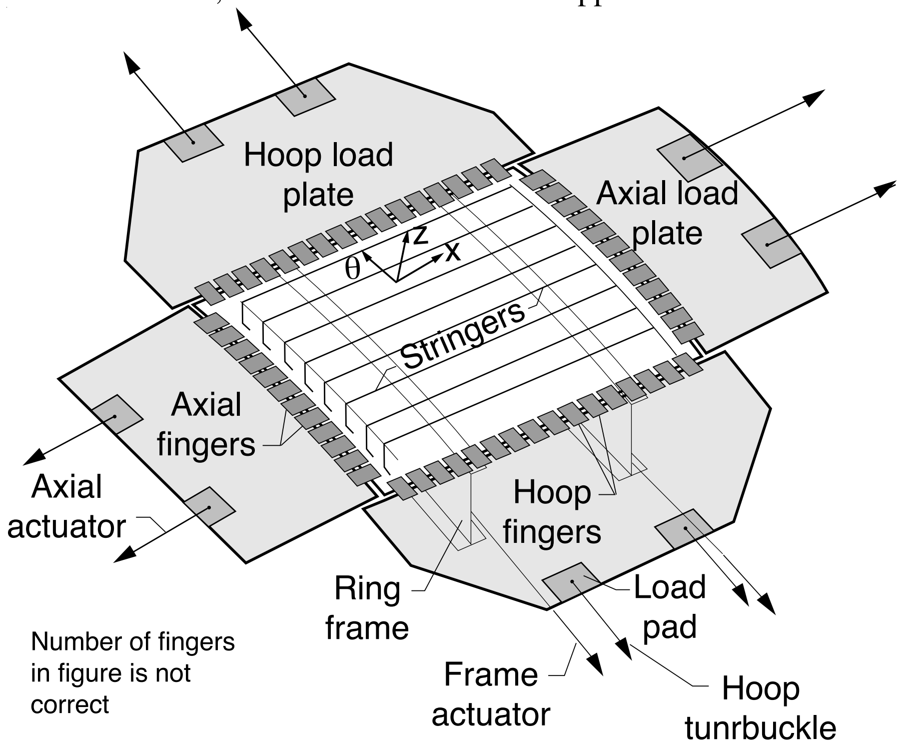

Figure 28: Schematic diagram of the LH2 tank panel with the load introduction structure.

The design of the pressure box, load introduction structure, and test panel must be closely integrated. Changes in one component design influence the other component designs. The test panel can be modified as required to redistribute the internal loads in the load introduction structure. The test panel and load introduction structure are shown in Figure 28. The test panel is composed of internal stringers and two ring frames. Two axial load plates and two hoop load plates are also shown in the figure. Load pads are located on the load plates where the loads are applied or reacted. In addition to the hoop and axial load plates, which apply load to the skin, turnbuckles are used to apply loads to the ring frame. Hoop and axial fingers, which transfer the load from the load plates to the test panel, are also shown in Figure 28.

Unlike the pressure box and control system, the load introduction structure was designed for a specific test panel. As shown in Table 1, the internal pressure for the test panel is 35 psig. Though this pressure is lower than the system capability of 52 psig, the load introduction structure was designed for the specific test conditions, and not the system capability. Subsequent test panels will have to be evaluated for changes in geometry, materials, load neutral axis, etc., and may require design modifications and/or a new load introduction structure prior to testing.

Manual calculation were used to estimate preliminary sizes of fingers, plates, bolts, and pads. Average loads were used for this early design phase. The load center for the axial edge of the curved panel was also estimated to obtain the correct datum for the axial actuators. The design follows the basic guidelines of Mil-Handbook 5. Weld allowable strengths were based on specifications from the AISC Steel Construction Manual. Section VIII of the ASME Code was used to obtain guidance on the combination of mechanical and thermal loads.

The approach taken for the design of the load introduction structure was to first generate a finite element model (FEM) cell model from which the stresses in a section of a full tank were obtained. A second FEM is then created with the load introduction structure as well as the test panel. The load introduction structure and transition region of the test panel were then modified until the stresses in the test panel closely match those of the cell model. Both linear and non-linear analyses were performed and compared to evaluate the effect of non-linearities. Several thermal analyses were also performed to evaluate the effect of thermal gradients on the stresses in the load plates.

Cell Model Finite Element Analysis

The cell model for the test panel is detailed in Figure 29. The cell model, which included 3 stringers and one ring frame, represented a repeatable unit of a LH2 tank structure which is subjected to uniform pressure and uniform axial load at room temperature. The model also included tension clips and shear webs to transfer forces between components. The axial load is the longitudinal load of 3360 lb/in. due to an internal pressure of 35 psig. Symmetric boundary conditions were used on the edges. With these conditions, a small unit of structure can be used to determine stresses due to design loads and estimate the load distribution between the stiffeners and skin. The location of this cell model with respect to the load introduction structure and test panel is shown in Figure 30. Figure 30 shows only 4.5 stringers since it is only half of the cell model.

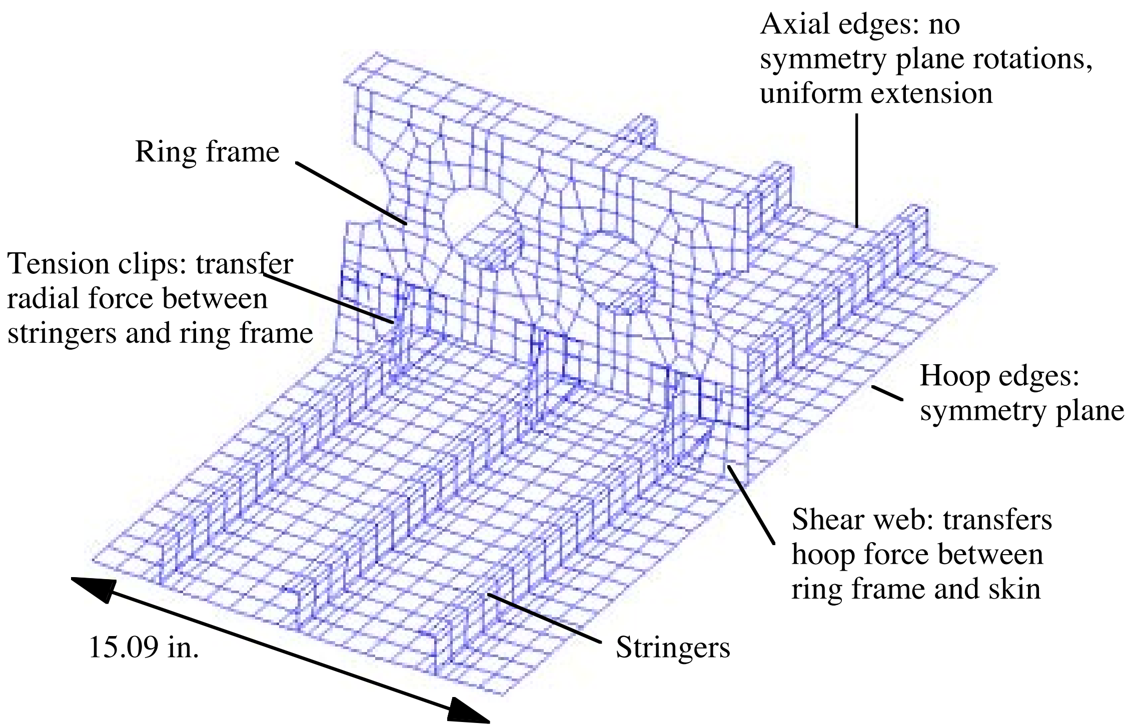

Figure 29: Cell model of the test panel showing the different components.

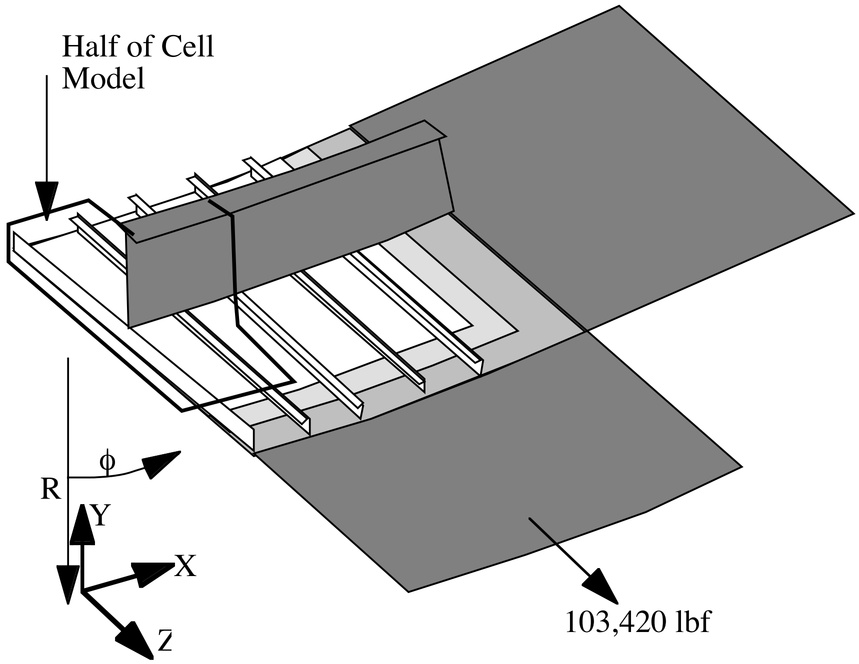

Figure 30: Schematic diagram of the FEM showing the location of the cell model relative to the load introduction structure and test panel.

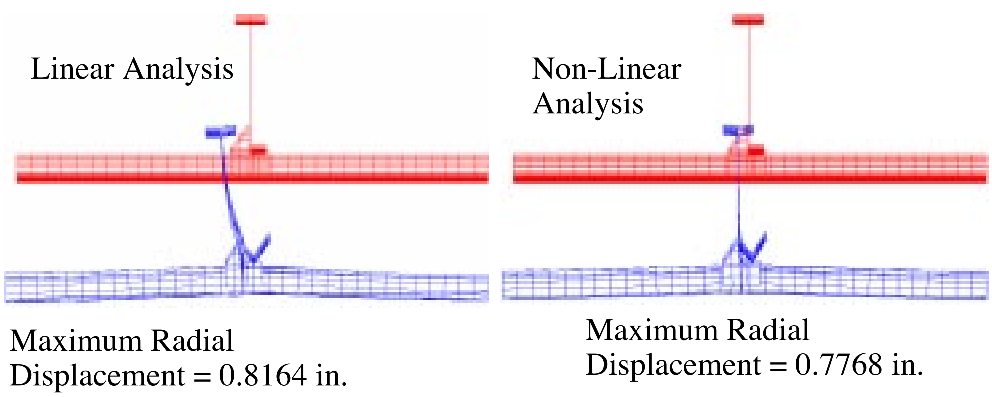

Figure 31: Comparison of linear and non-linear analysis of deformed shapes for the cell model with a 3360 lb/in. axial load and 35 psig internal pressure at room temperature.

Linear and non-linear finite element analyses were conducted on both the cell model and the pressure box test panel model to evaluate the capability of the cryogenic pressure box in simulating the loads due to actual flight conditions. Comparisons of the linear and non-linear results for the cell model are presented in Figure 31 through Figure 34. Deformed plots of the cell model and the test panel/load introduction structure model are shown in Figure 31. There is some twisting of the frame due to its unsymmetrical cross-section and this may be magnified in the test panel due to the "weak axis" bending induced by the frame restraint. There has been some attempt to offset this twisting of the ring frame by shifting the turnbuckle's line of action. The maximum radial displacement is shown for both the linear and non-linear cases. The non-linear case results in slightly lower displacements of 0.7768 in. compared to 0.8164 in. for the linear case, indicating little difference between the linear and non-linear cases.

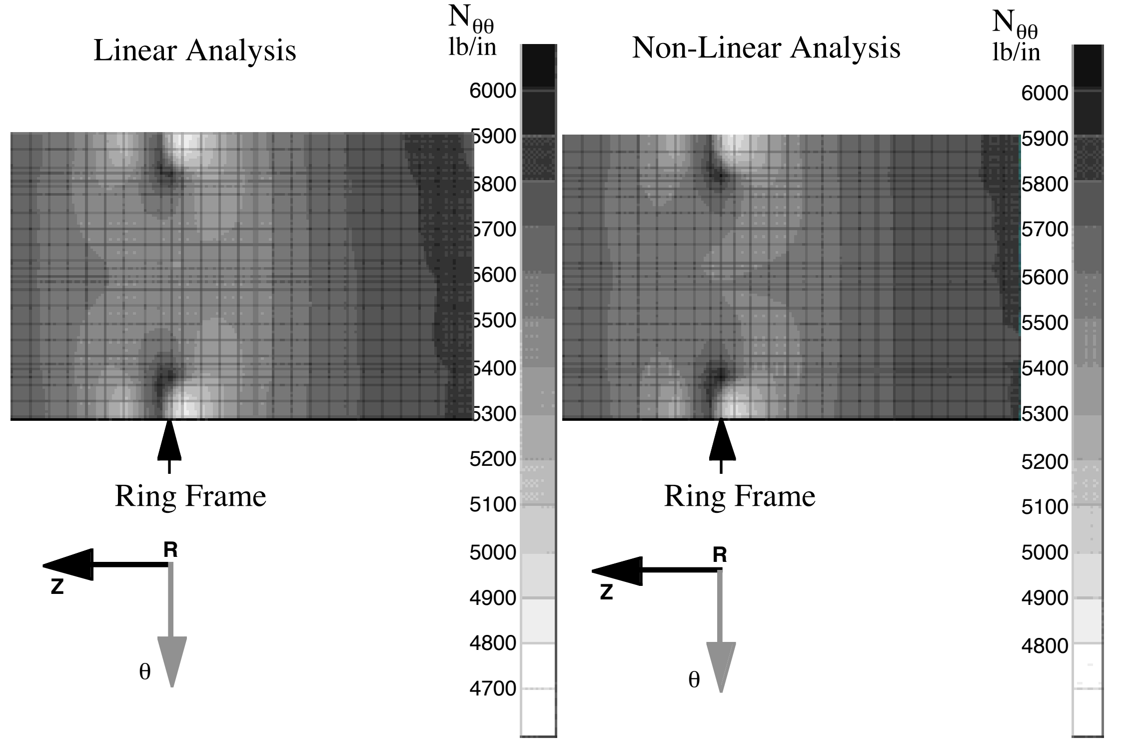

Figure 32: Comparison of linear and non-linear analysis of hoop load distributions for the cell model with 103,420 lb axial load and 35 psig internal pressure at room temperature.

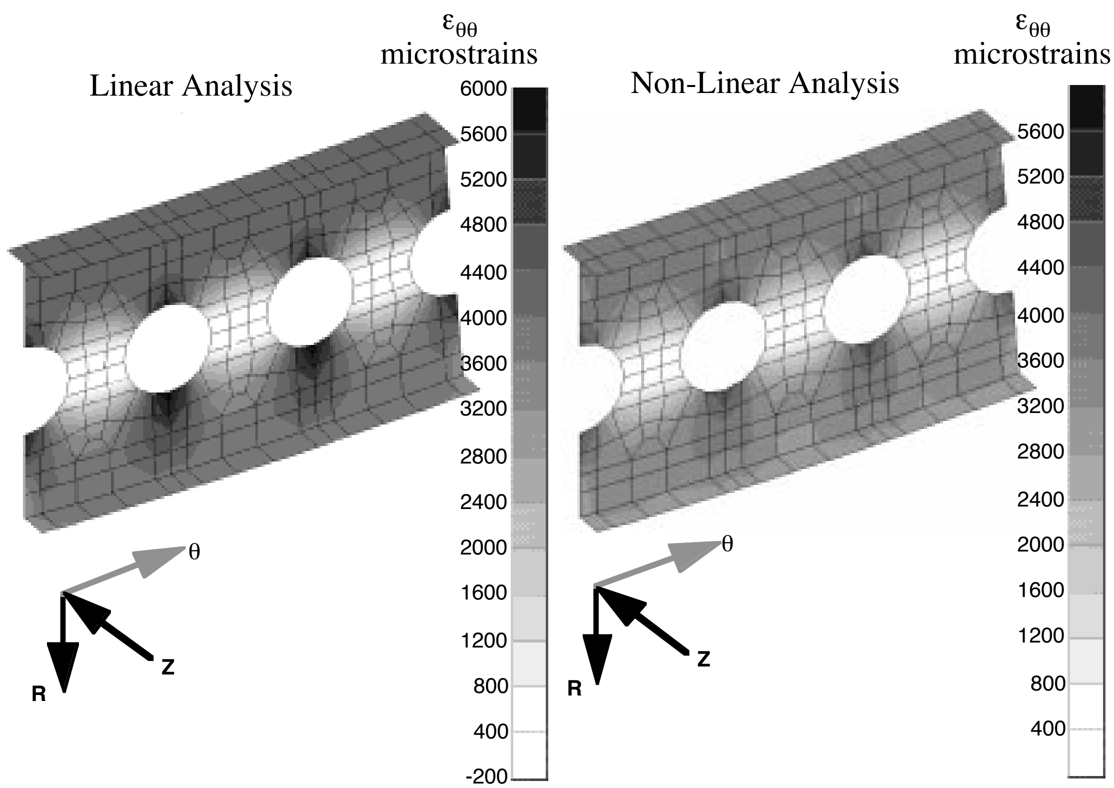

Figure 33: Comparison of linear and non-linear analysis of hoop strains in the frames for the cell model with 3360 lb/in. axial load and 35 psig internal pressure at room temperature.

Figure 32 shows a comparison of hoop load distributions ($N_{\theta\theta}$) for the cell model with 103,420 lb axial load and 35 psig internal pressure at room temperature. Both linear and non-linear distributions are shown. The location of the ring frames are shown for reference. Non-linear effects on the cell model hoop stresses is negligible.

Figure 33 shows a comparison of hoop strains in the ring frames for the cell model with 103,420 lb axial load and 35 psig internal pressure at room temperature. Both linear and non-linear cases are shown, and the non-linear analysis provides only minor differences.

Figure 34 shows a comparison of axial load distributions (N_{zz}) for the cell model with 3360 lb/in. axial load and 35 psig internal pressure at room temperature. Both linear and non-linear distributions are shown. The location of the ring frames are shown for reference. Again, the non-linearity only provided minor differences in the magnitude and distribution.

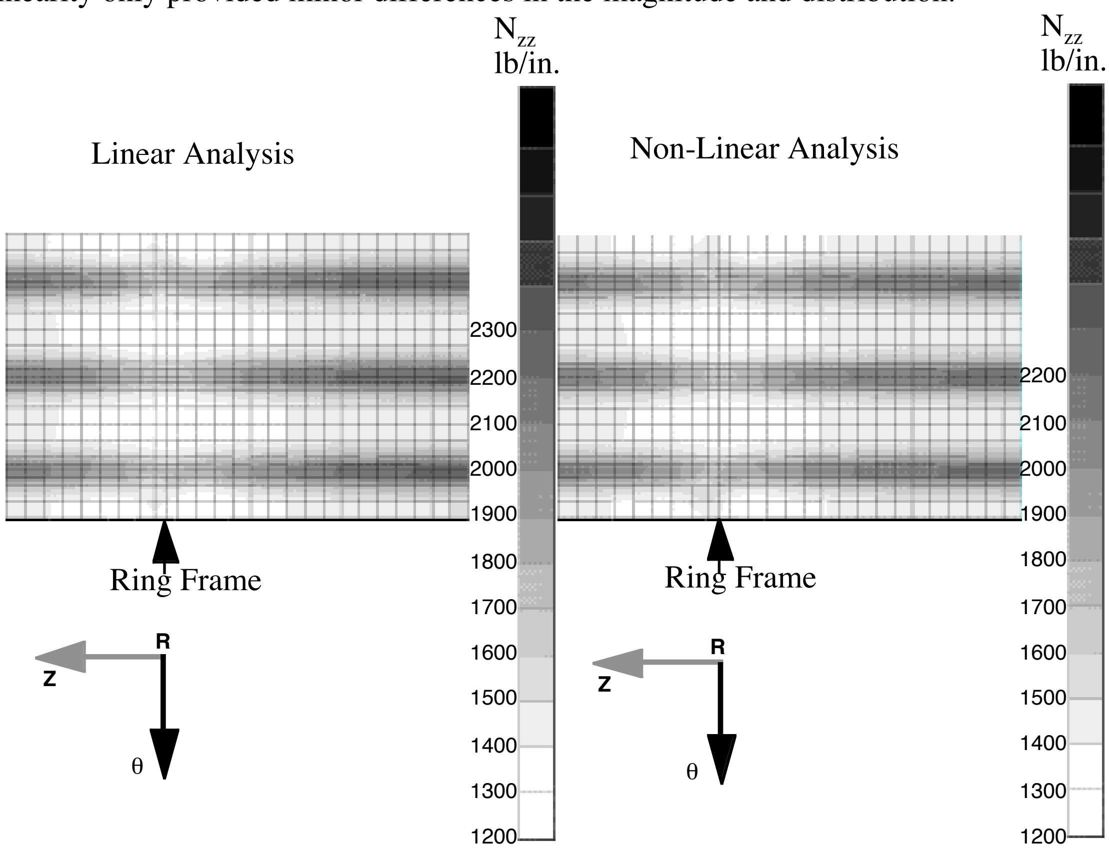

Figure 34: Comparison of linear and non-linear analysis of axial load distributions for the cell model with 3360 lb/in. axial load and 35 psig internal pressure at room temperature.

Finite Element Model

A symmetrical quarter of the finite element test panel model is shown on Figure 35. The ring frame, stringers, test panel, and load introduction plates are all shown on the figure. The test panel dimensions and spacing, including the stringers and ring frames, are shown in Figure 36. Figure 37 schematically illustrates the geometry of the stringers used in the finite element model and Figure 38 schematically illustrates the geometry of the ring frames used in the model.

The initial sizing of the individual components of the load introduction structure were based on the simplifying assumptions of a rigid test panel. This model contained 6674 nodes and was modeled with shell finite elements except for the fingers, actuators, and restraints (turnbuckles) which used beam elements. All bolted joints permitted rotation about the rigid bolt's longitudinal axis and in-plane translation was permitted for the in between finger bolts as required.

The mechanical and thermal properties used in the analysis were for SA 240 Type 304 stainless steel. The allowable values for normal stress, shear stress, and bearing stress for SA 240 Type 304 stainless steel are tabulated in Table 12.

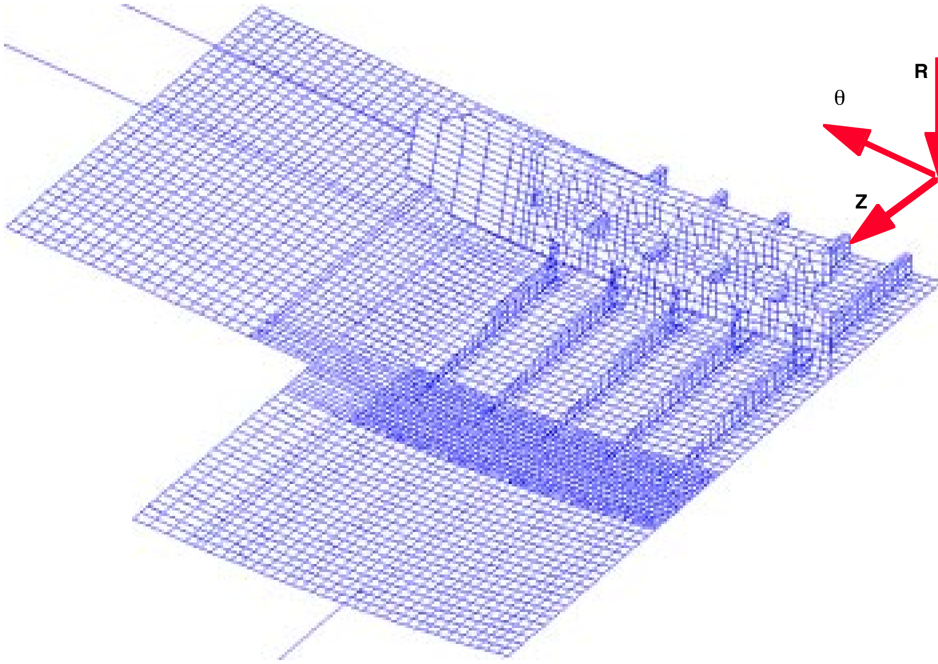

Figure 35: Symmetrical quarter model of the test panel used for the cell analysis.

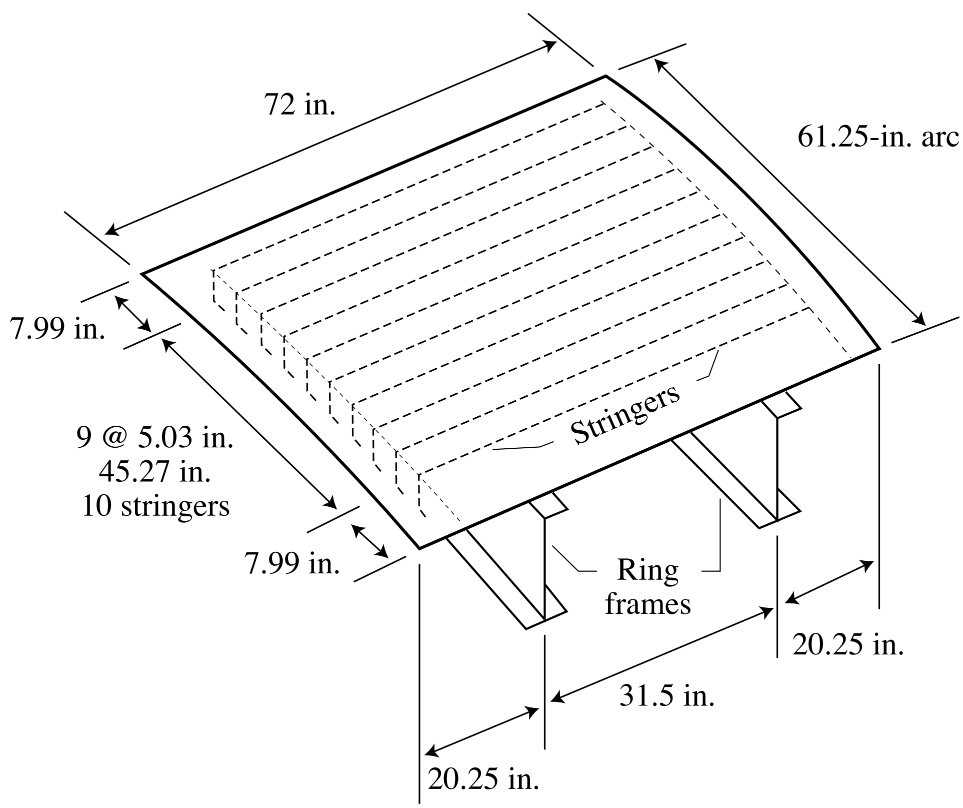

Figure 36: Schematic diagram of the LH2 tank panel with ten stringers and two ring frames.

Table 12: Loading Conditions and Design Data

Mechanical Loads	Pressure Differential of 35 psi Axial Force of 103,420 lbs
Thermal Loads	Test Panel at -423°F Load Introduction Plates at -300°F
Design Specifications	Mil-Handbook 5, ASME Code, AISC Steel Construction Manual National Aerospace Standard - NAS 6703 through 6720
Materials	SA 240 Type 304 Stainless Steel Plates A-286 Bolts
Material Strengths	<u>Plate</u> Minimum Yield (S_y or F_{ty}) = 30 ksi Maximum Tensile Strength (S_u or F_{tu}) = 75 ksi <u>Bolts</u> Maximum Ultimate Tensile Strength (S_u) = 160 ksi Minimum Ultimate Shear Strength (S_{su}) = 95 ksi
Design Allowables	<u>Plate</u> Normal Stress (S_t) = 18 ksi Shear Stress (S_s) = 12 ksi Bearing Stress (S_b) = 36 ksi <u>Bolts</u> Shear Stress (S_s) = 47.5 ksi <u>Pins</u> Shear Stress (S_s) = 12 ksi

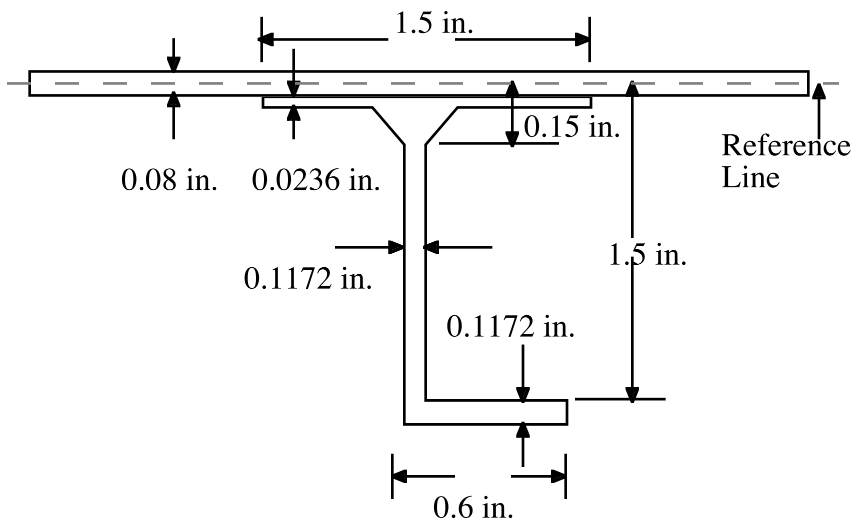

Figure 37: Schematic drawing of the stringer used in the finite element model.

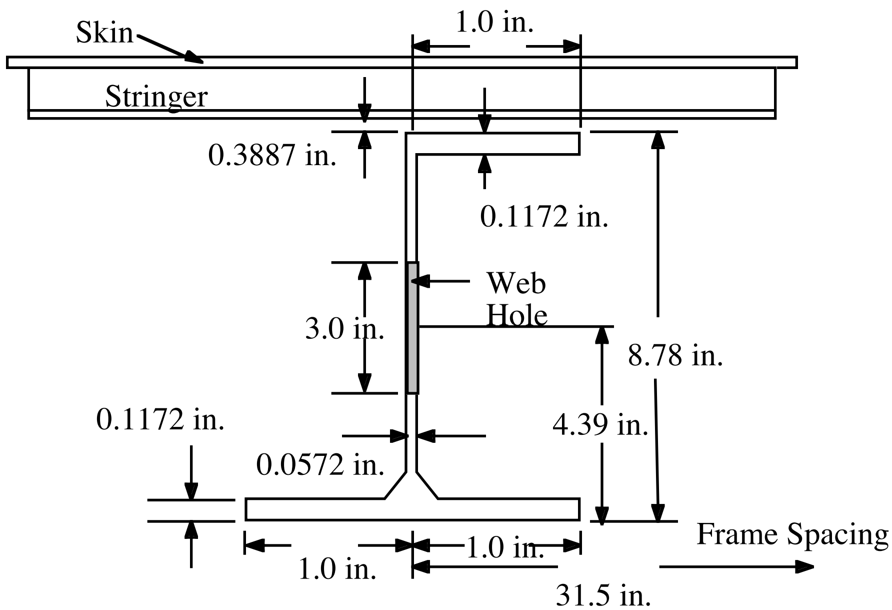

Figure 38: Schematic diagram of the ring frame.

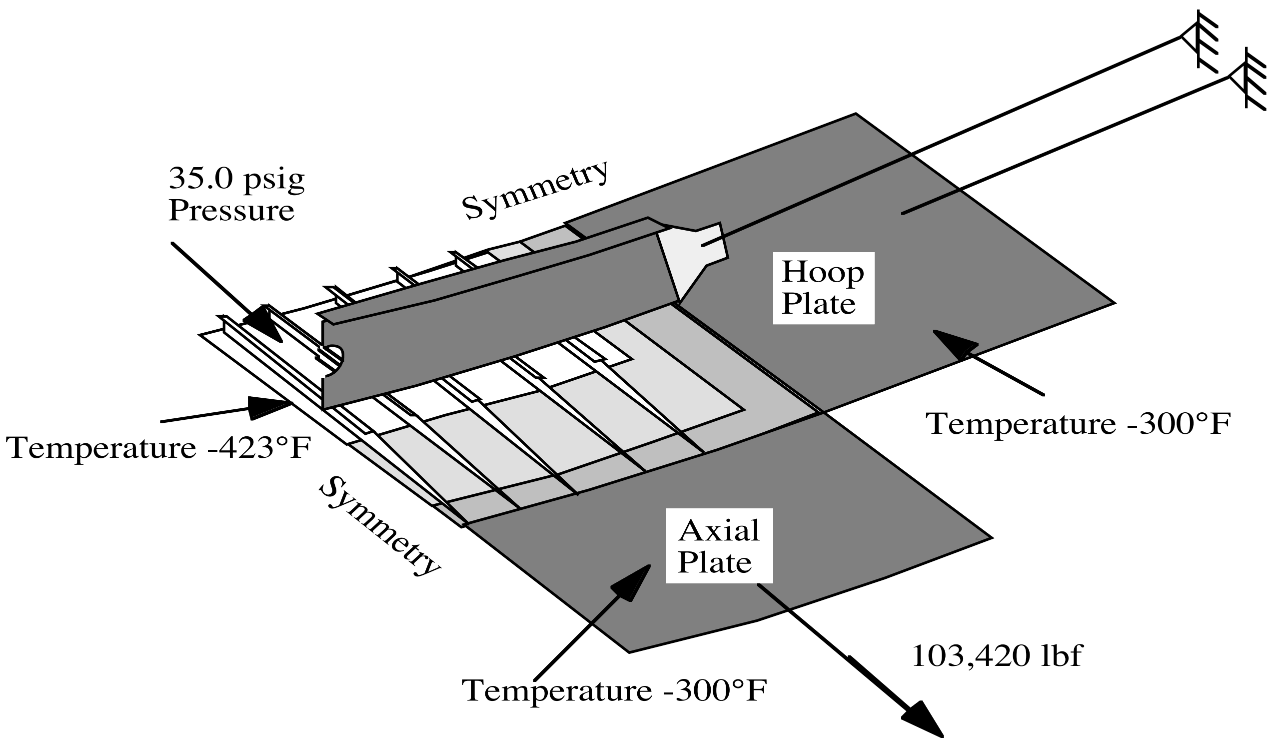

Figure 39: Schematic diagram of FEM model showing the boundary conditions.

Pressure, axial load, and temperature requirements are shown in Table 12. The design allowables taken from Mil-Handbook 5 are the smaller of F_{ty} or $F_{tu}/1.5$ and a joint factor of 1.15. For this analysis, it was assumed that the panel and load plates were held at a constant temperature of -423°F and -300°F, respectively. To avoid induced thermal stresses, it was assumed that the restraints and actuators will be free during the "cool-down" and the lateral slots in the fingers will significantly decrease the load transfer between panel and load plates due to binding of the fingers. The only significant thermal stresses observed were between the bolts where the stainless steel fingers are attached to the composite panel. The CTE mismatch between these materials resulted in a finger tensile stress of about 8 ksi.

The boundary conditions and applied thermal and mechanical loads are shown in Figure 39. The inside surface of the test panel experienced a pressure of 35 psig and temperature of -423°F. The load plates were assumed to be trace cooled and maintained at a uniform -300°F. For a linear static finite element analysis, the deformed shape of the entire load introduction/test panel model when subjected to Load Case 1 is shown on Figure 40.

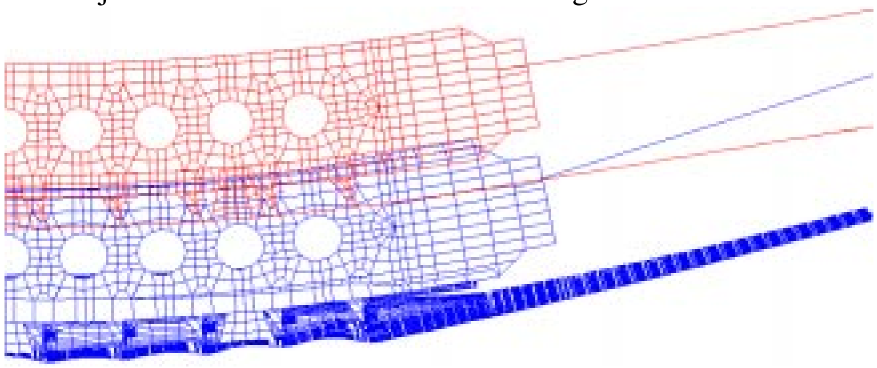

Figure 40: Deformed shape of the test panel.

Test Panel Finite Element Analysis

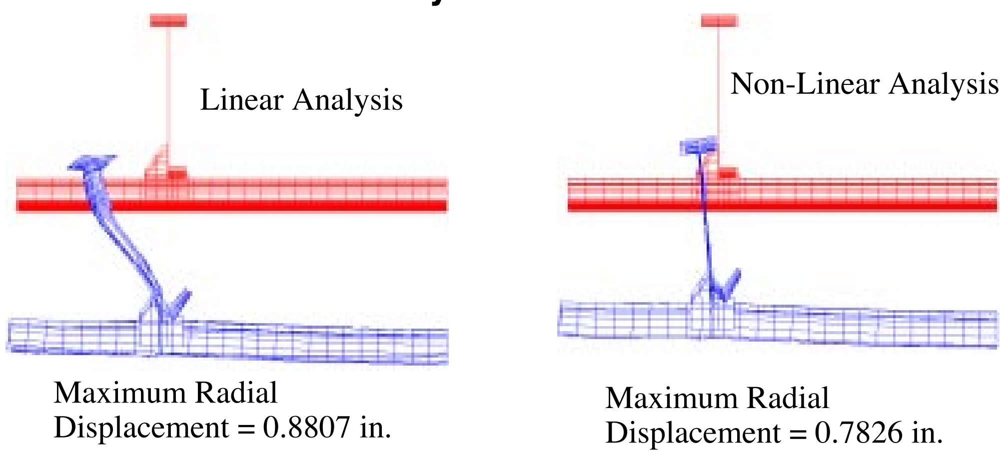

Figure 41: Comparison of linear and non-linear analysis of deformed shapes for the pressure box model with 103,420 lb axial load and 35 psig internal pressure at room temperature.

For comparison with the cell model, a linear and non-linear finite element analysis of the pressure box model was conducted. Although these results were based on the initial preliminary design of the load introduction structure (different stringer spacing), the effect of this non-linearity can be established. These results are shown in Figure 41 through Figure 44. As shown in Figure 42 through Figure 43, the hoop stresses and/or strains are reduced more than 15% due to the load redistributions due to lower stiffness associated with out of plane displacement. Good correlation is indicated by the linear analysis for the skin and stringers away from the boundary effects of the test panel/load introduction structure model. However, it appears that the non-linear effects should be accounted for in the pressure box analyses.

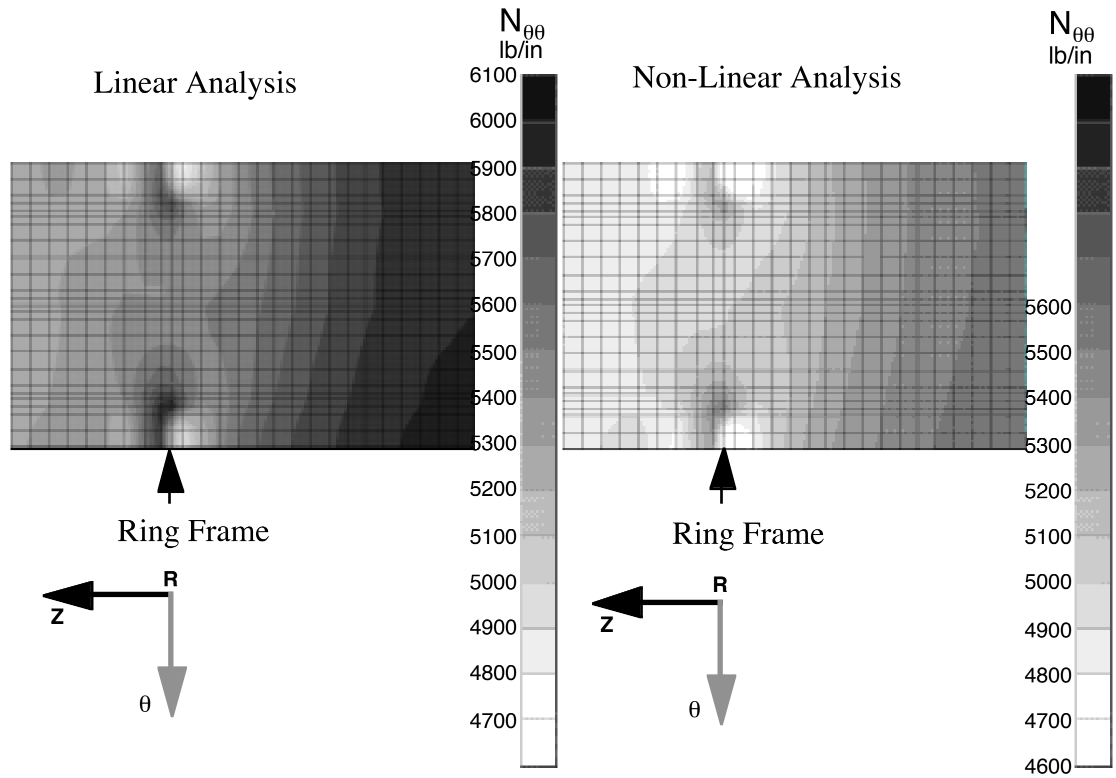

Figure 42: Comparison of linear and non-linear analysis of hoop load distributions for the pressure box test panel with 103,420 lb axial load and 35 psig internal pressure at room temperature.

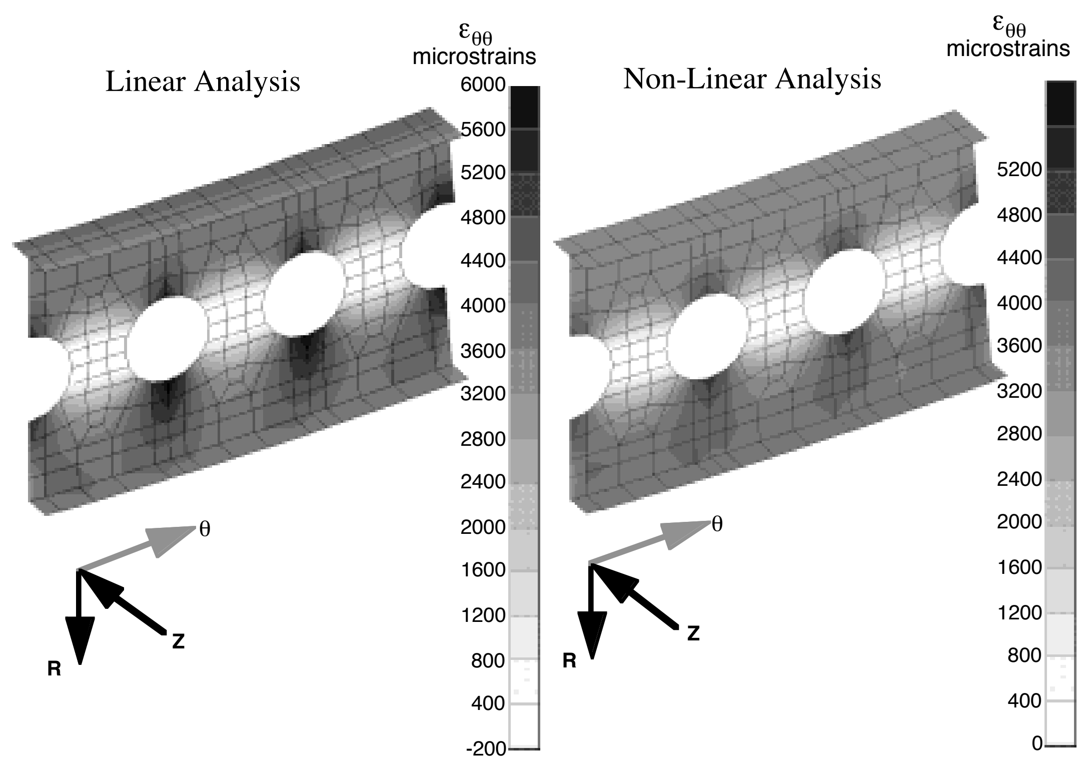

Figure 43: Comparison of linear and non-linear analysis of hoop strains in the frames for the pressure box model with 103,420 lb axial load and 35 psig internal pressure at room temperature.

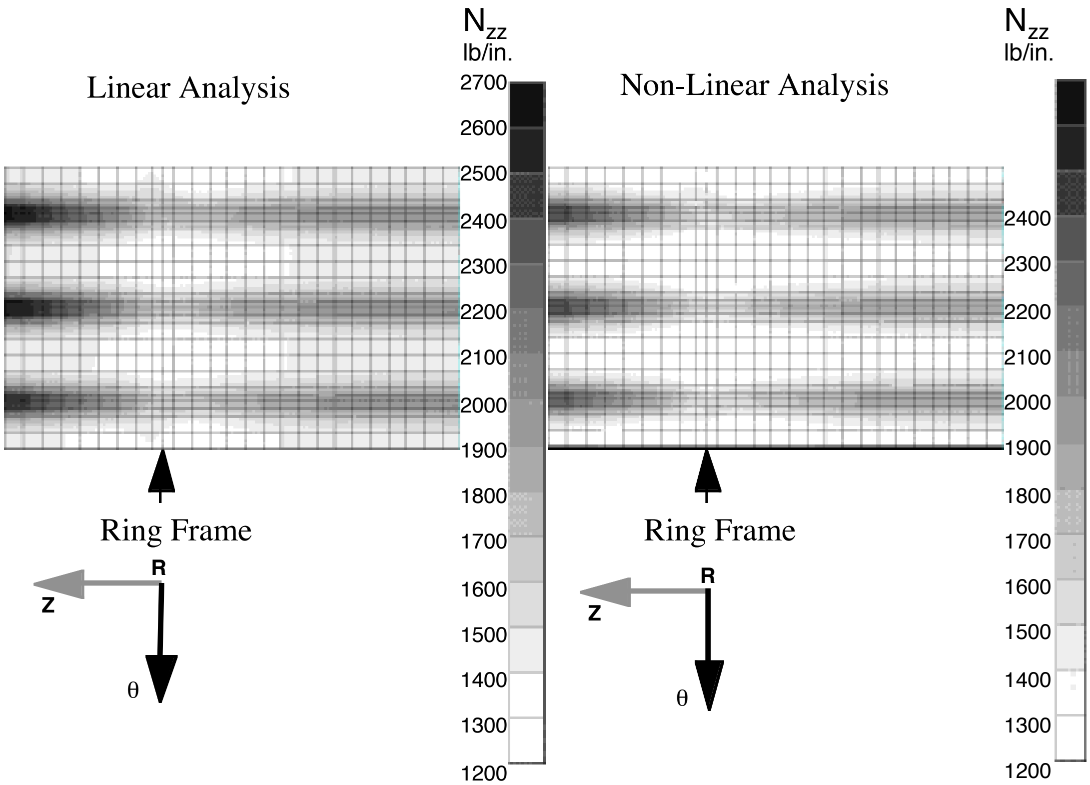

Figure 44: Comparison of linear and non-linear analysis of axial load distributions for the pressure box test panel with 103,420 lb axial load and 35 psig internal pressure at room temperature.

Axial Load Plate Analysis

A symmetrical half of the axial load plate finite element model, with fingers, is shown in Figure 45. The Von Mises stresses in the upper and lower surfaces of the load plate and the actuator load pad are shown in Figure 46 and Figure 47 for linear and non-linear analyses. The allowable stress of 18,000 psi is denoted on the scale. The variation in the stresses between the outer and inner surface is due to the small eccentricity of the neutral axes for the load plate and the stringer stiffened test panel. A schematic of the connections of the actuator and fingers to the load plate is shown on Figure 48. Calculations for weld loads and joint analyses for the actuator and fingers were performed. It was assumed that the outboard bolts on each finger reacted the entire finger load. These analyses indicated that 5 in. x 6 in. actuator plates, 0.5-in. thick, should be welded to both sides of the 1-in-thick axial load plate and contain a central hole to accommodate a 2.5-in-diameter pin. The minimum design factor, defined as the ratio of the allowable stress to the calculated stress, for the joints, weld and bolt/pin, was 1.19 and was with respect to the bearing of the 3/8-in. finger bolts on the axial load plate. A design factor of 0.85 was obtained for shear of the finger bolts but this is believed to be satisfactory based on the conservatism used to establish the allowable shear strength.

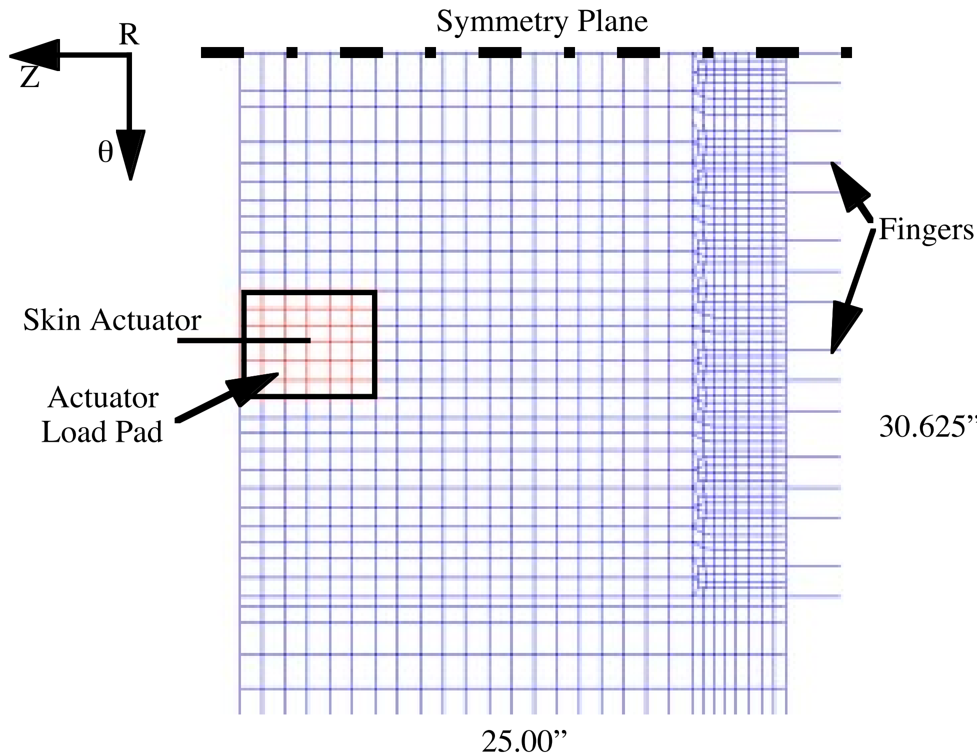

Figure 45: Axial load plate design model.

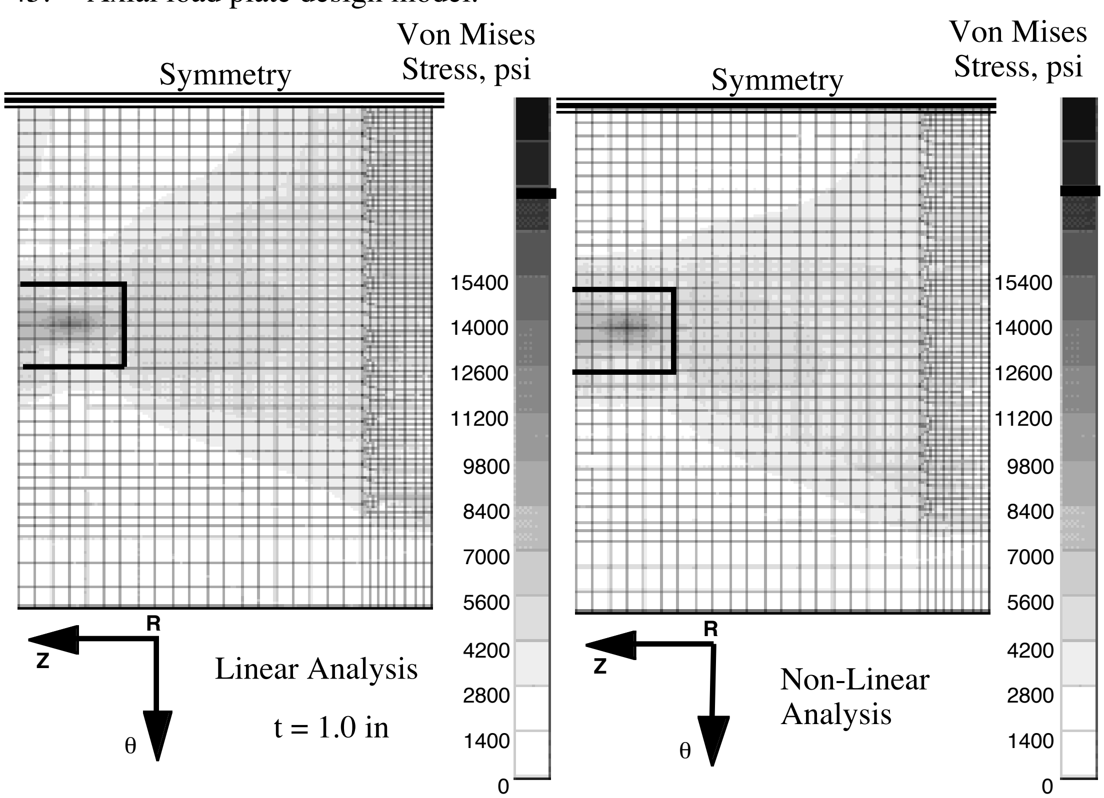

Figure 46: Comparison of linear and non-linear analysis of outer surface Von Mises stresses in axial load plate of pressure box with 103,420 lb load and 35 psig at room temperature.

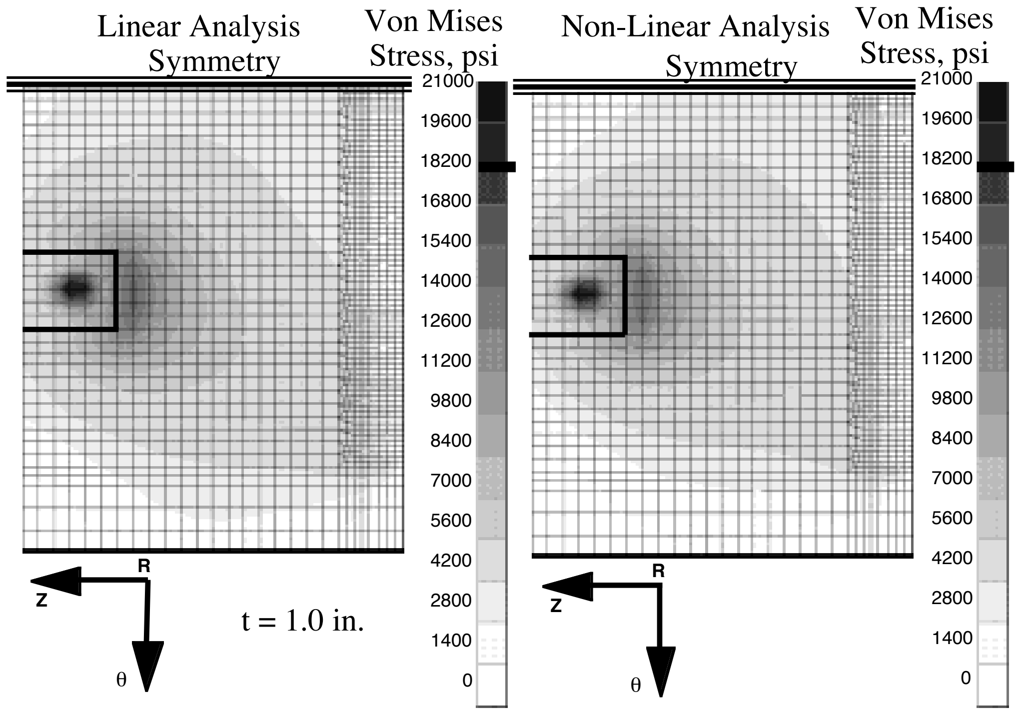

Figure 47: Comparison of linear and non-linear analysis of inner surface Von Mises stresses in axial load plate of pressure box with 103,420 lb load and 35 psig at room temperature.

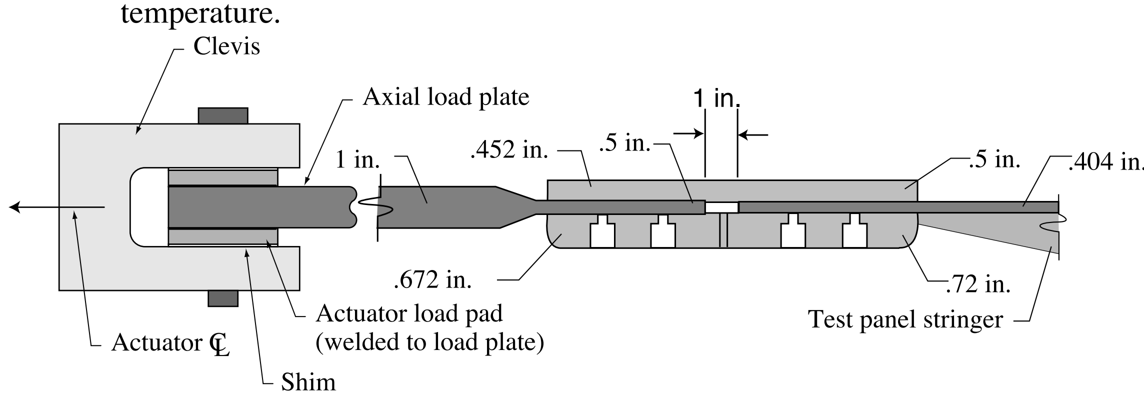

Figure 48: Schematic diagram of the connections on both sides of the axial load plate.

Hoop Load Plate and Ring Frame Restraint Analysis

A symmetrical half of the hoop load plate finite element model, with fingers, is shown in Figure 49. A portion of the structure showing the ring frame with the corresponding finite element model is shown in Figure 50. The axial stiffness for the beam elements representing turnbuckles attached to the load plate and the ring frame were adjusted to distribute the hoop load to the skin and frame at 85% and 15%, respectively[1]. Further, the line of action for the ring frame's restraint force was adjusted to minimize the twist and "weak-axis" bending in the frame and for this particular analysis, was located 0.13 in. from the web along the neutral axis. The Von Mises stresses in the upper and lower surface of the load plate and the actuator load pad are shown in Figure 51 and Figure 52 for linear and non-linear analyses. The allowable stress of 18,000 psi is denoted on the scale. There is very little evidence of bending in the hoop load plate. Although critical stresses are indicated in the turnbuckle area of the plate, it is believed

[1] Later analysis determined that 80%/20% was the proper load distribution.

they are due to the concentrated reaction at a single node and would be more accurately distributed (with lower stresses) if the actuator load pads were attached to each side of the plate using multi-point constraint (MPC's) equations along the edges which is consistent with the welded edges.

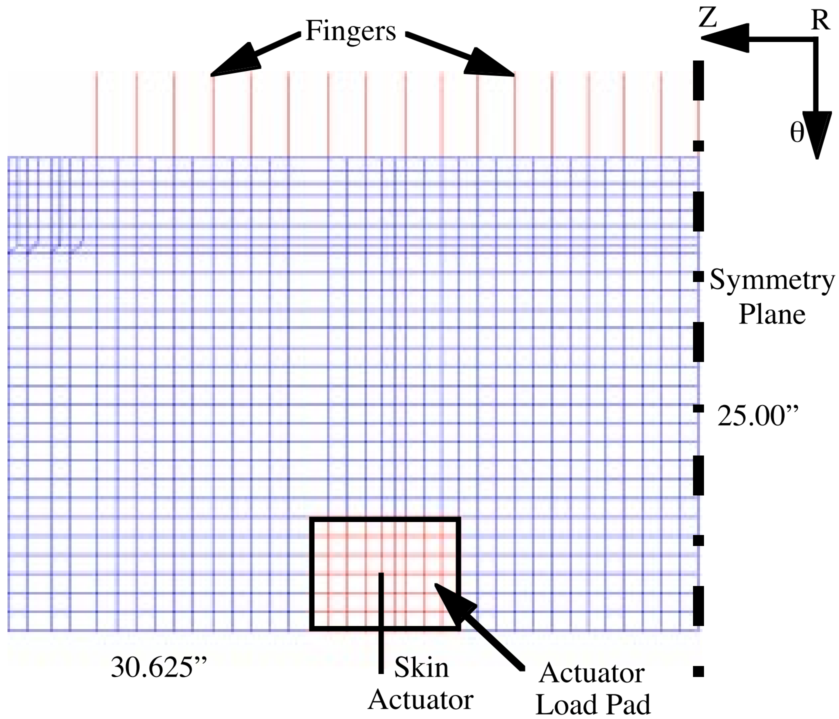

Figure 49: Hoop load plate design model.

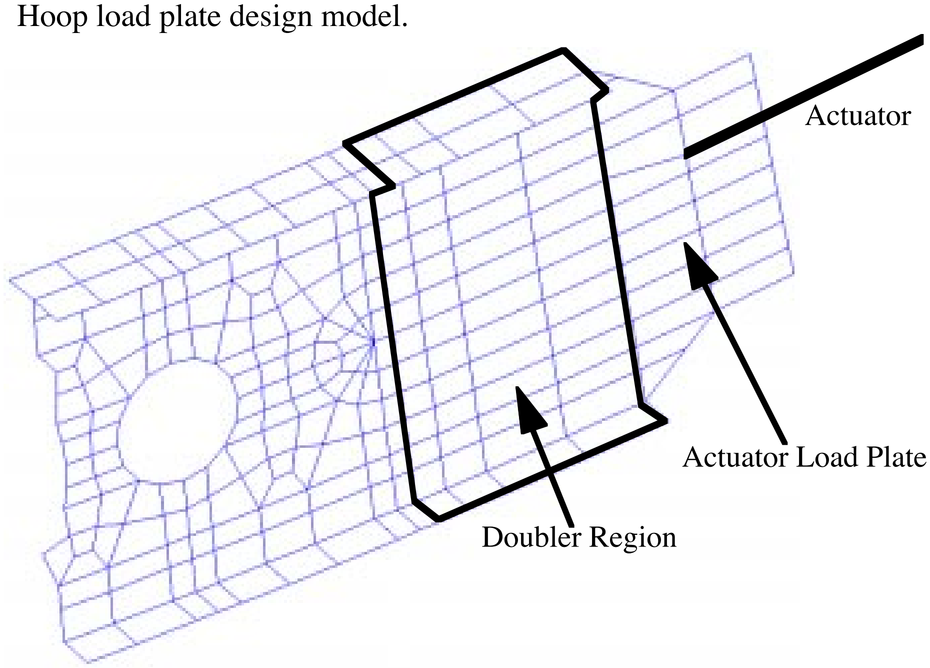

Figure 50: Finite element model of frame actuator attachment.

A section view of the connections of the actuator and fingers to the load plate is shown in Figure 53. Calculations for weld loads and joint analyses for the turnbuckles and fingers were also performed. An independent finite element analysis indicated the outboard, mid, and inboard bolts react 65%, 22%, and 13% of the total finger load, respectively. These analyses indicated that 8 in. x 8 in. actuator plates, 0.5-in. thick, should be welded to both sides of the 1-in-thick hoop load plate and contain a central hole to accommodate a 3.5-in-diameter pin. The minimum design factor for all joints, weld and bolt/pin, was 1.02 and was due to the tensile stress on the net finger area (3/8 in. finger bolts also used on the hoop load plates). As previously mentioned, a design factor of 0.89 was obtained for shear of the finger bolts but this is believed to be satisfactory based on the conservatism used to establish the allowable shear strength. For the ring-frame turnbuckle with a 1.5-in. pin, the minimum design factor was 1.33 and was with respect to the pull-out shear of the turnbuckle/frame attach pad.

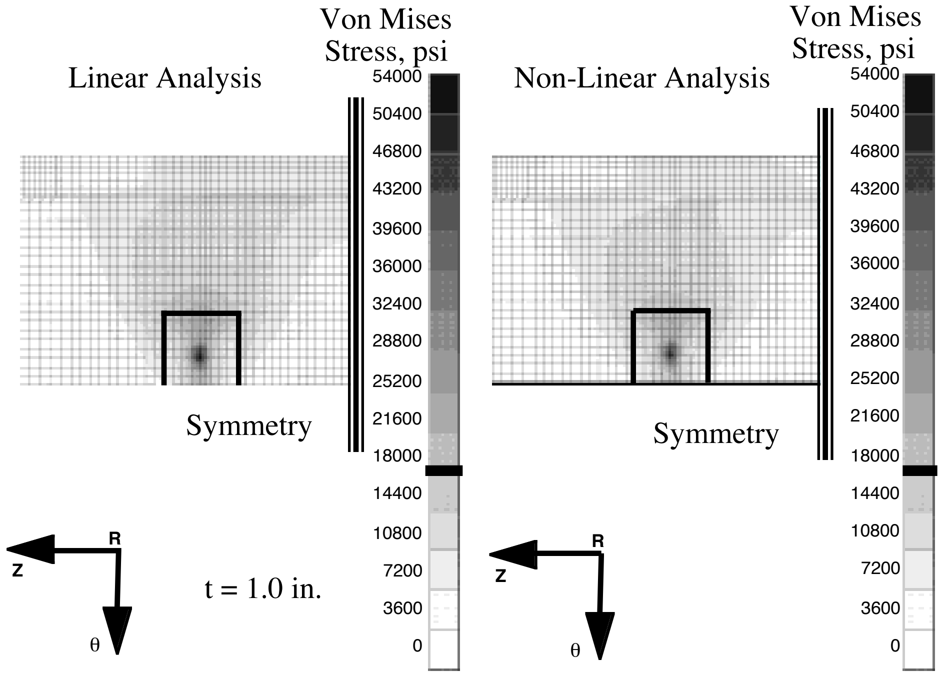

Figure 51: Comparison of linear and non-linear analysis of outer surface Von Mises stresses in hoop load plate of test panel with 103,420 lb axial load and 35 psig internal pressure at room temperature.

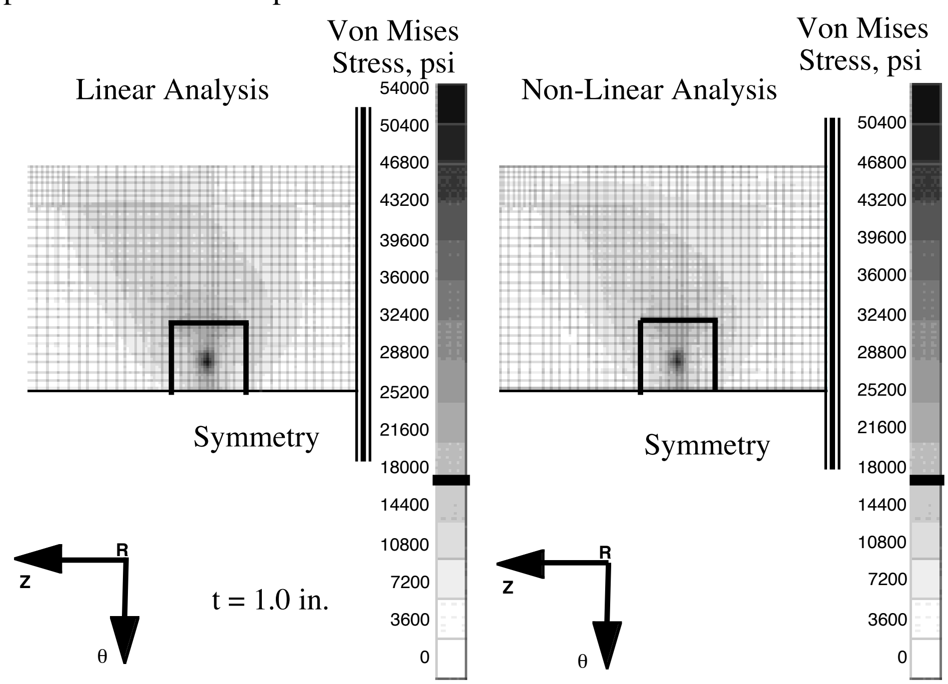

Figure 52: Comparison of linear and non-linear analysis of inner surface Von Mises stresses in hoop load plate of test panel with 103,420 lb axial load and 35 psig internal pressure at room temperature.

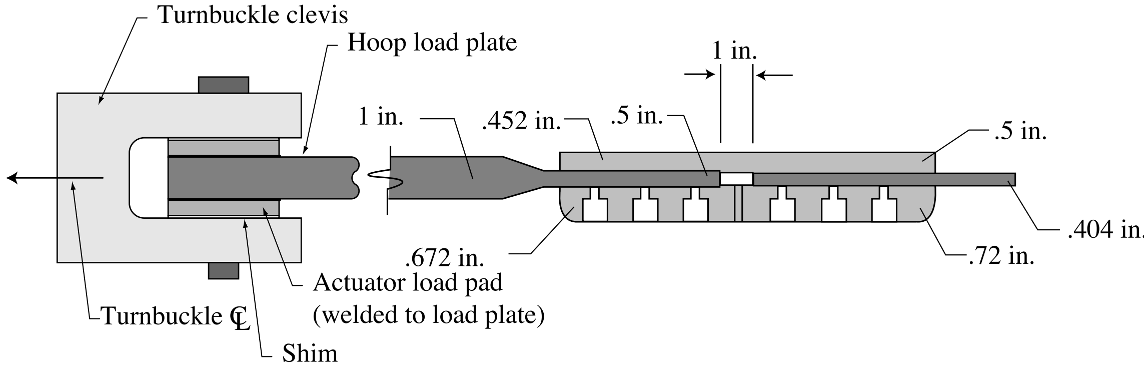

Figure 53: Schematic diagram of the connections on both sides of the hoop load plate.

Load Plates and Finger Design

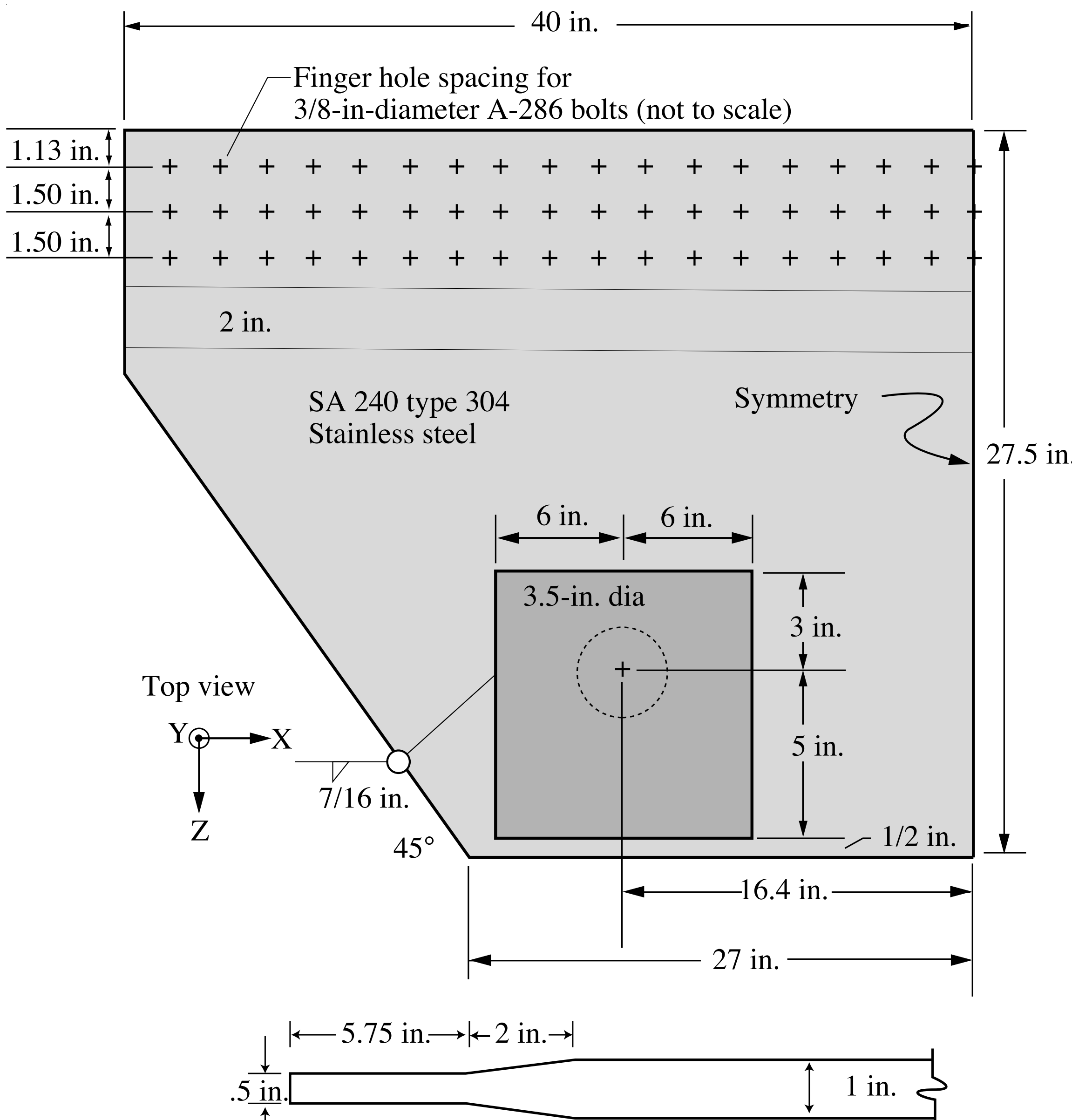

Figure 54: Schematic diagram of a symmetric half of the hoop load plate.

The dimensions for a symmetrical half of the hoop load plate, including the location of the actuator and restraint pads, is shown in Figure 54. The hoop load plate is 28-in. deep and 80-in. wide, with the corners of the load plate cut off at 45° angles. The corners are cut off since that region carries negligible load. Three rows of bolt holes are required in the hoop load plates, and the spacing is shown in Figure 54. The load plate material is SA 240 type 304 stainless steel.

The dimensions for a symmetrical half of the axial load plate including the location of the clevis pin and load pads is shown in Figure 55. The axial load plate is 25 in. deep and has an arc length of 61.25 in., with the corners of the load plate again cut off at 45° angles. The radius of the outer surface of the axial load plate is 193 in. Two rows of bolt holes are required in the axial load plates, and the spacing is shown in Figure 55. The load plate material is again SA 240 type 304 stainless steel.

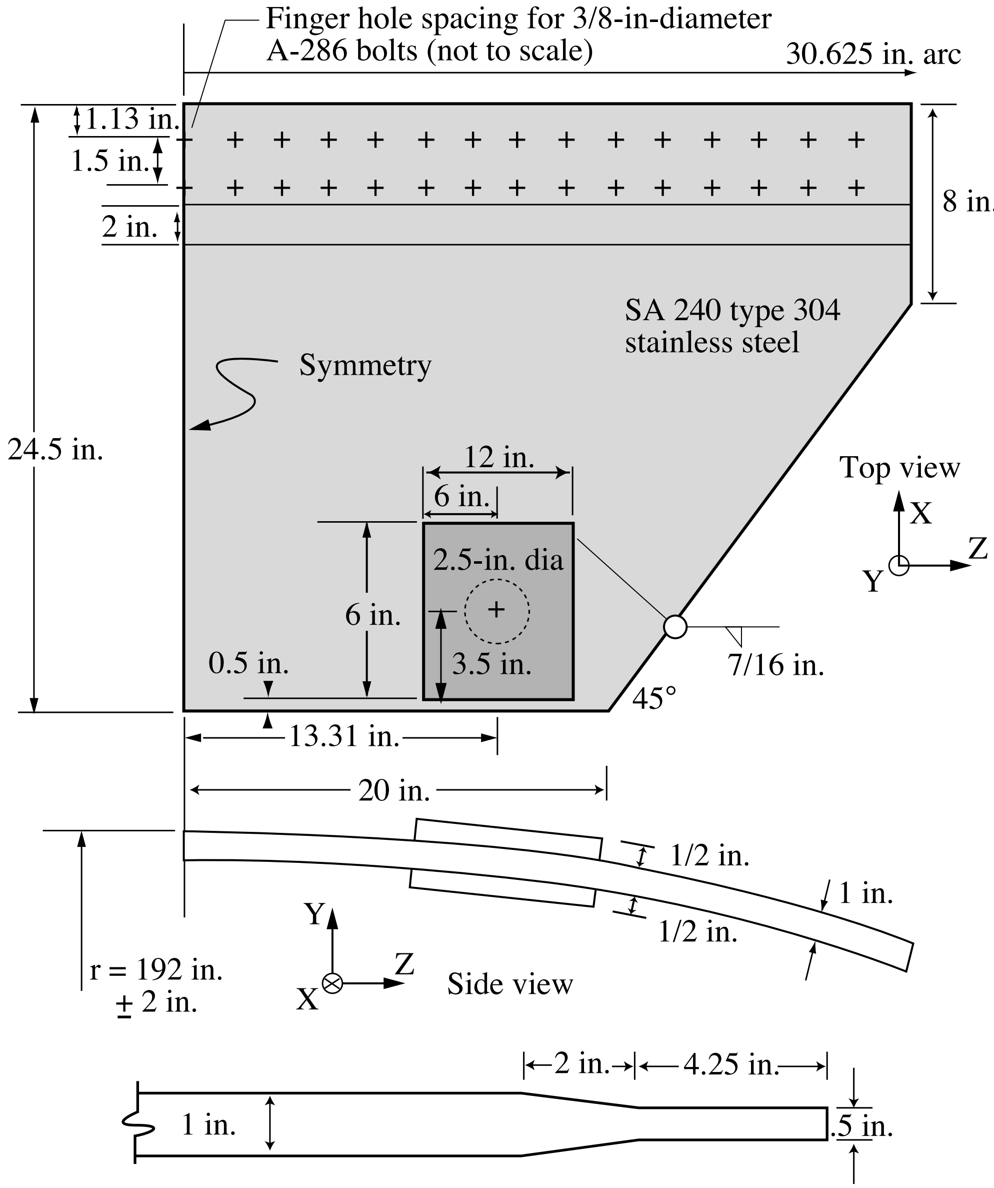

Figure 55: Schematic diagram of a symmetric half of the axial load plate.

During the cool-down process, the load plates will contract more than the test panel. Due to this contraction, the bolt holes in the fingers will be slotted to allow the contraction to occur stress free. The test panel was assumed to be cooled down from room temperature to -423°F (20K). With a CTE of 0.95×10^{-6} in/in-°F and a test panel length of 72 in., the test panel contraction is

$\delta = (0.95 \times 10^{-6}$ in/in-°F) (72°F - (-423°F)) (72 in.) = 0.0339 in.

For the load plate, the strain from 300K to 0K is 307 x 10^{-5} in/in., and the strain in cooling from 90K to 0K is 25 x 10^{-5} in/in. The total contraction in cooling from 300K to 90K is thus

$\delta = (307 \times 10^{-5}$ in/in - 25 x 10^{-5} in/in) (72 in.) = 0.203 in.

The maximum differential in contraction between the panel and the load plates is thus

$\delta = 0.203$ in. - 0.0339 in. = 0.169 in.

The above differential contraction is based on a load plate temperature of 90 K (approximately -300°F). In reality, the load plates may only be cooled to -260°F. At -260°F, the differential contraction is approximately 0.2 in. versus 0.169 in. for a -300°F load plate temperature. The fingers bolt holes must be slotted 0.169 in. to allow for the differential contraction due to temperature.

Figure 56 schematically shows the slotting required to allow the load plates to contract stress free when subjected to the mechanical loads due to an internal pressure.

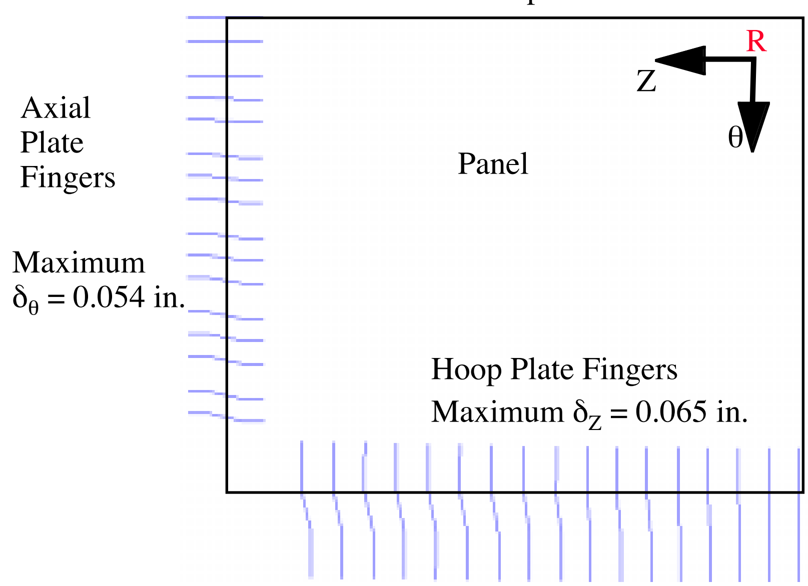

Figure 56: Schematic diagram of the slotting required to account for the contraction of the load plates relative to the test panel.

A schematic diagram of the lower hoop plate fingers, indicating dimensions and bolt hole spacing, is shown in Figure 57 All dimensions are in inches, but are not shown on the figure for clarity. Also shown in Figure 57 is the amount of slotting for the inner bolt holes to prevent the transfer of loads between the load plates. Though slotting is shown in the figure by ellipses, the actual slots are circular holes elongated in the middle. These slot dimensions represent the structural and thermal distortions in the lateral directions. The lower fingers are thicker than required to carry the load so the finger can be counter bored for the bolts. The bolts are recessed in the finger to provide a smoother surface for the finger seal. In addition, the corners of the fingers are rounded to eliminate sharp edges for the finger seal. The reference surface for this model is at the mid-plane of the panel's skin and the eccentricities associated with the load introduction structure has been accounted for by offsetting a particular component or by the use of multi-point constraints (MPC's).

Figure 58 shows a schematic diagram of the upper hoop finger. The upper hoop finger differs from the lower finger in that there is no counter bore for the bolts, and the corners are not rounded off to protect the finger seal. Both the upper and lower fingers are stepped due to the different thicknesses of the load plate and the panel.

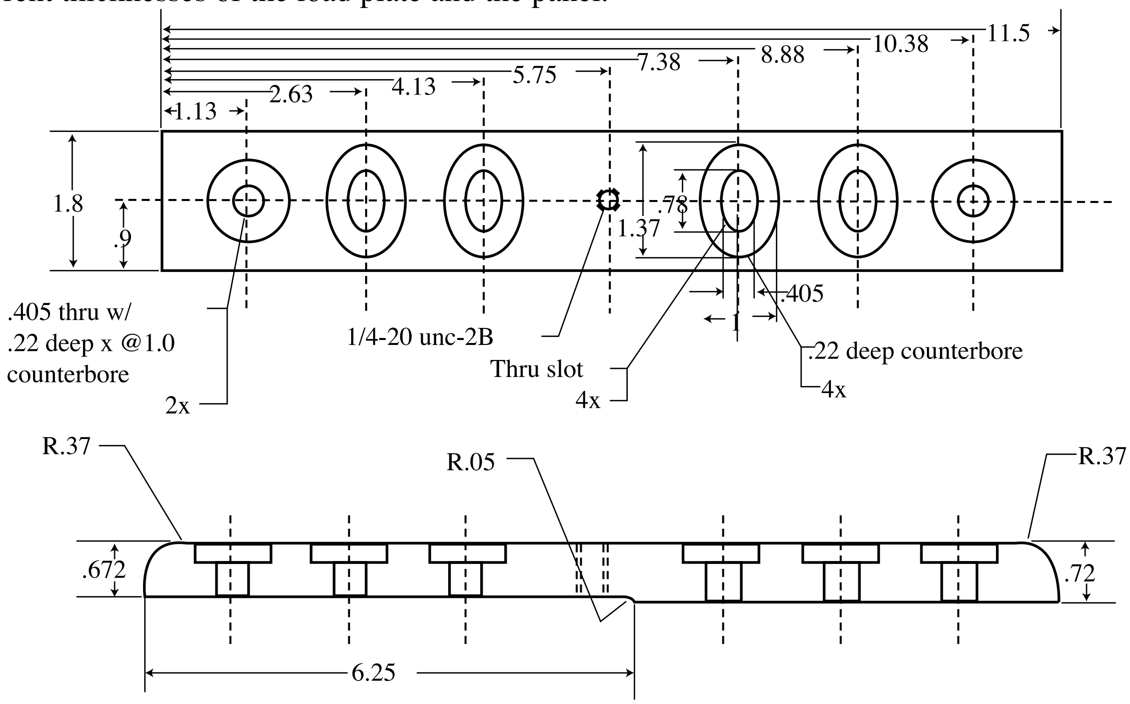

Figure 57: Schematic diagram of the lower hoop finger (all dimensions in inches). Actual holes are not ellipses.

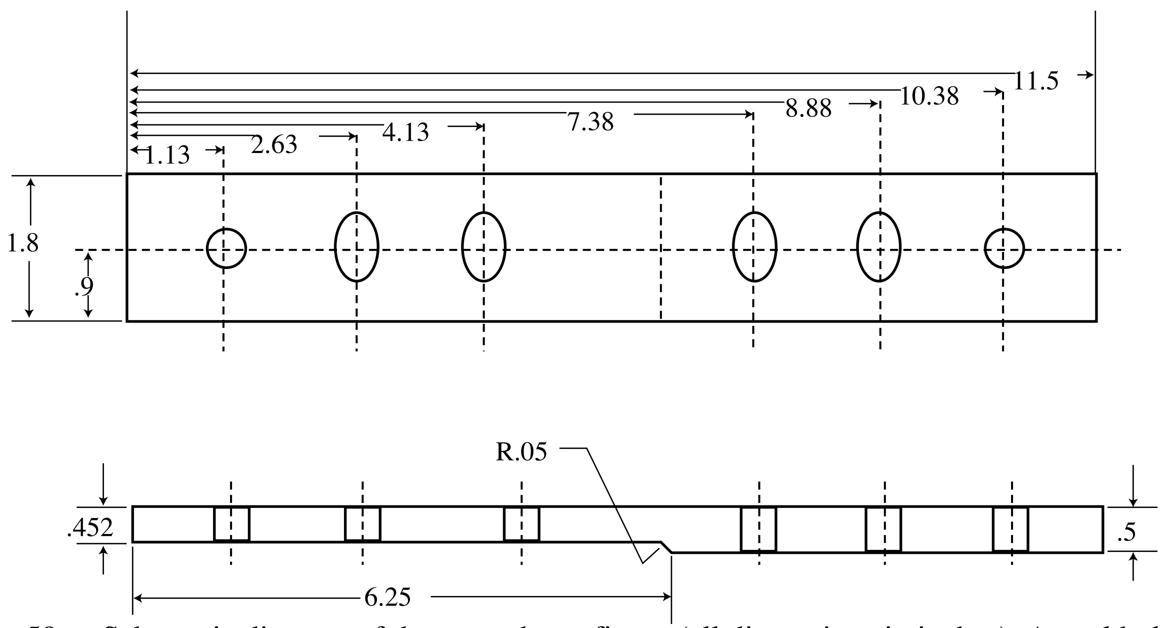

Figure 58: Schematic diagram of the upper hoop finger (all dimensions in inches). Actual holes are not ellipses.

Figure 59 and Figure 60 show schematic diagrams the lower and upper axial fingers. Due to the lower load on the axial load plates compared to the hoop plates, the axial fingers only have four bolt holes versus six on the hoop fingers. As with the hoop fingers, the lower finger contains counterbore holes for the bolts to provide a smooth seal surface. Also, the corners of the lower finger are rounded to eliminate sharp edges.

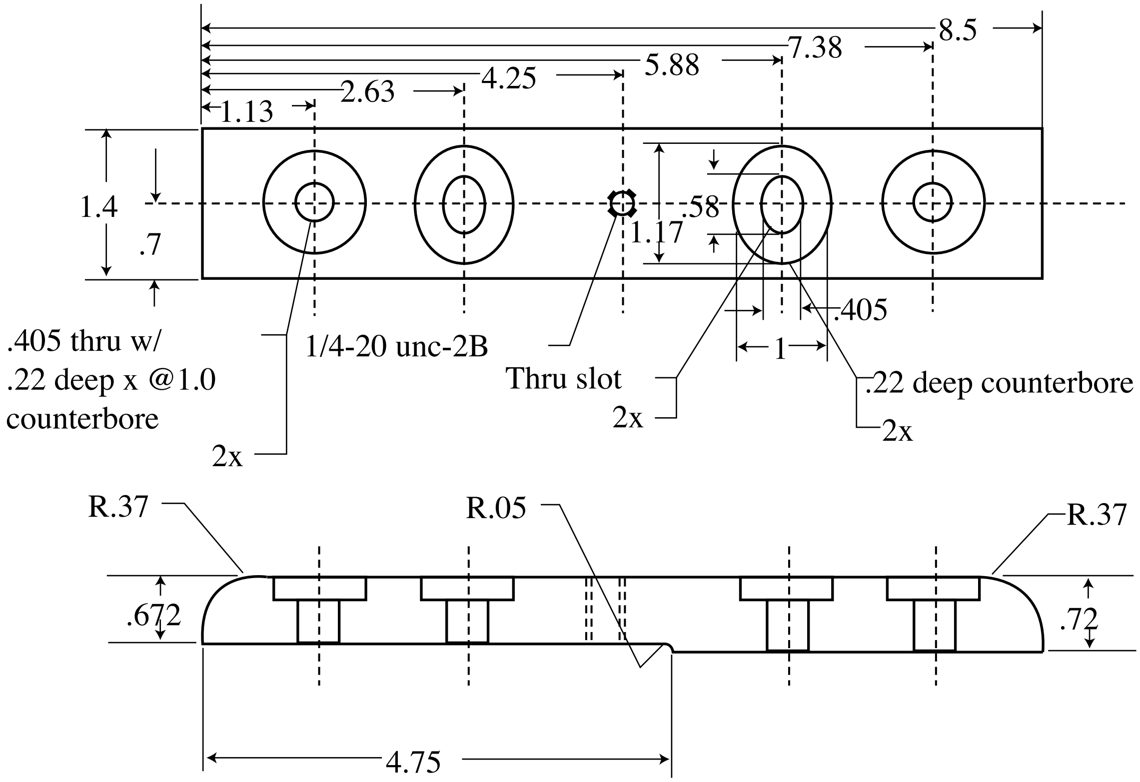

Figure 59: Schematic diagram of the lower axial finger (all dimensions in inches). Actual holes are not ellipses.

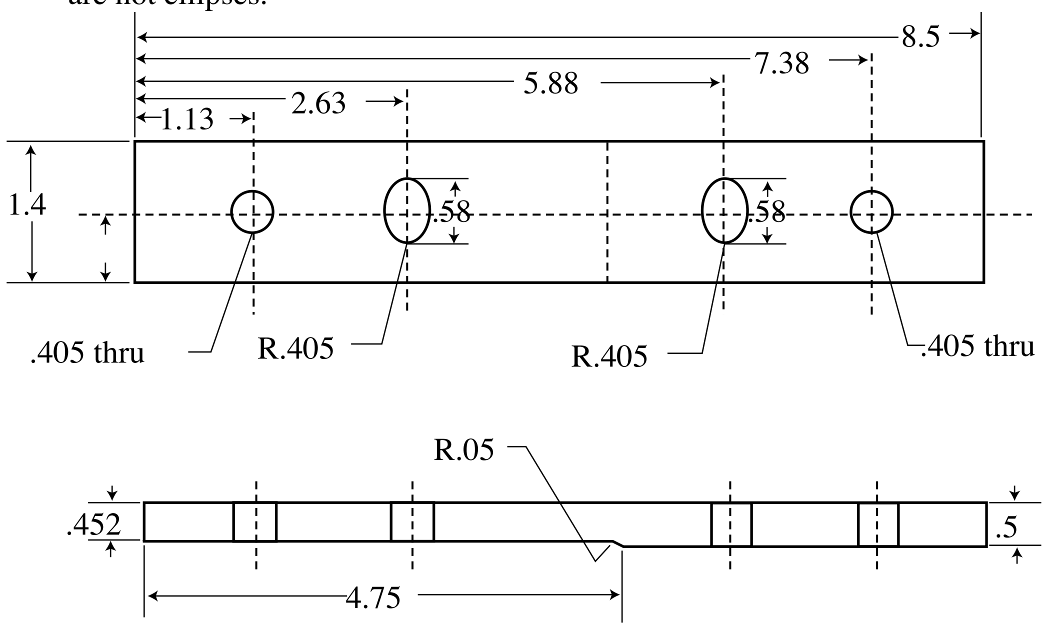

Figure 60: Schematic diagram of upper axial finger (all dimensions in inches). Actual holes are not ellipses.

Ring Frame Clevis Attachment

The finite element model of the ring frame is shown in Figure 61 with the stringers, tension clip, shear clip, skin, ring frame web, and edges of the ring frame shown. The coordinates are relative to the top center of the ring frame, which is (0 in., 192 in.). The "y" coordinate of 192 in. corresponds to a radius of 192 in. at 0° from vertical.

Figure 62 shows a schematic diagram of the clevis attachment to the ring frame. The upper drawing shows a top view of the clevis and ring frame, and the lower drawing shows the side view of the clevis and ring frame. The drawings are not to scale, and all dimensions are in inches. Half inch thick web plates will be bolted to each side of the flange region of the ring frame using a total of 8 bolts in 3/8-in-diameter holes. As shown in Figure 63, the web plates extend onto the “J” and “T” sections of the ring frame. Four bolts will be used on the “T” section and two bolts will be used on the “J” section. The web plates will extend past the flange region and into the region over the ring frame web, where the clevis pin will penetrate the ring frame in the web portion of the ring frame. A 2.25-in-diameter hole will be located in the ring frame web for the 1.5-in-diameter turnbuckle pin. With an oversize hole in the web, no bearing loads will be applied to the 2.25-in-diameter hole in the frame web.

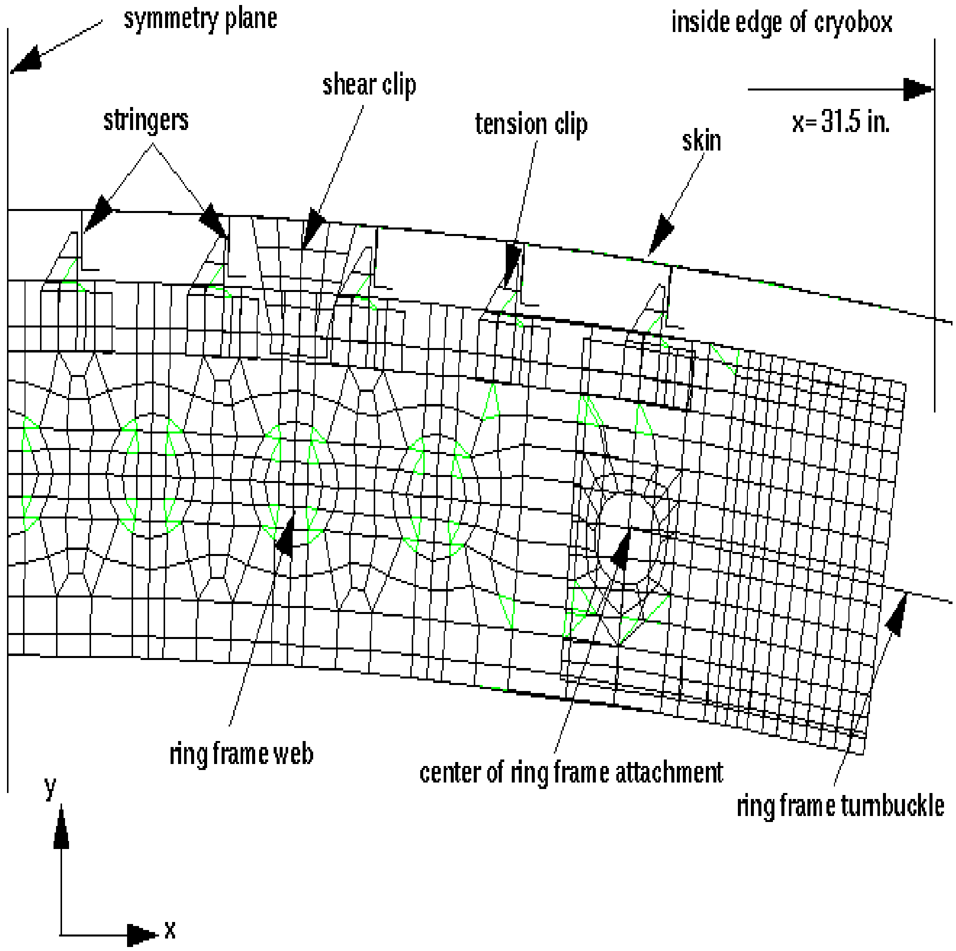

Figure 61: Finite element model of the ring frame showing coordinates necessary for locating the clevis attachment to the ring frame.

The frame turnbuckle load, P_f, is given as

$$P_f = \alpha \; P \; r \; l = 0.25 \; (0.035 \text{ ksi}) \; (192 \text{ in.}) \; (36 \text{ in.}) = 60.5 \text{ kips}$$

where the pressure loading P is 35 psi or 0.035 ksi, the percentage of the load to the frame, α is 25%, the radius of the test panel, r, is 192 in., and the hoop edge length per frame, l, is 36 in. The average bolt bearing load assuming 8 bolts is

$$P_b = P_f/n_b = 60.5 \text{ kips}/8 = 7.6 \text{ kips}$$

If 10 bolts are assumed, the average bolt load drops to 6.05 kips

The average bearing stress on the composite frame web is calculated next. The thickness of the web and the flange is 0.390 in. The ultimate bearing stress from the frame web, F_{bru}, is 67.3 ksi. The allowable bearing stress on the pad is then

$$F_{bf} = F_{bru}/1.5 = 44.8 \text{ ksi}$$

The bolt diameter, d, is 0.375 in., resulting in a bearing area, A_{bf}

$$A_{bf} = d\, t_p = 0.375 \text{ in. } (0.390 \text{ in.}) = 0.146 \text{ in}^2$$

Since the applied bearing stress on the pad can be no more than the allowable bearing stress on the pad, the allowable bolt load can be calculated as

$$P_b = f_{bf}\, A_{bf} = F_{bf}\, A_{bf} = 44.8 \text{ ksi } (0.146 \text{ in}^2) = 6.5 \text{ kips}$$

With an allowable bolt load of 6.5 kips, and a turnbuckle load of 60.5 kips, the number of bolts required is

$$n_b = P/P_b = 60.5 \text{ kips}/6.5 \text{ kips} \sim 10 \text{ bolts}$$

The composite web bearing stress, f_{bf}, in the flange is given as

$$f_{bf} = \frac{P_b}{t_w d} = \frac{6.5\text{kips}}{(0.39\text{in.})(0.375\text{in.})} = 44.4 \text{ ksi}$$

The web bearing stress is below the allowable bearing stress that was earlier calculated to be 44.8 ksi.

The allowable shear stress on the bolts, F_{sv}, assuming 0.375-in-diameter A-286 bolts, is 63 ksi. The applied shear stress for a single lap joint with an average bolt load of 6 kips is 54.5 ksi and for a double lap joint is 27.3 ksi.

The average web plate bearing load is 30 kips per plate (one plate on each side of the web). With a pin diameter of 1.5 in., and a steel web plate thickness of 0.5 in., the applied web bearing stress, f_{wb}, is 40 ksi. The allowable web bearing stress, F_{wb}, is 50 ksi for 304 stainless steel.

The bearing on the web plate at the bolts is next calculated. Assuming a bolt diameter of 0.375 in., an average bolt load of 6.5 kips, and a thickness of 0.5 in., the applied bearing stress at the bolts is 17.3 ksi, which is below the allowable bearing stress at the bolts of 50 ksi. If an average bolt load of 8 ksi is used, the applied bearing stress at the bolts is 42.7 ksi, still below the allowable of 50 ksi.

The applied shear stress on the 1.5-in-diameter pin is

$$f_{sp} = P_f/(2A_p)$$

With an allowable shear stress, F_{sp}, for 304 stainless steel of 17 ksi, and a frame turnbuckle force, P_f, of 60 kips, the pin cross sectional area A_p is

$$A_p = P_f/(2F_{sp}) = 1.76 \text{ in}^2$$

The minimum allowable pin diameter is then 1.5 in.

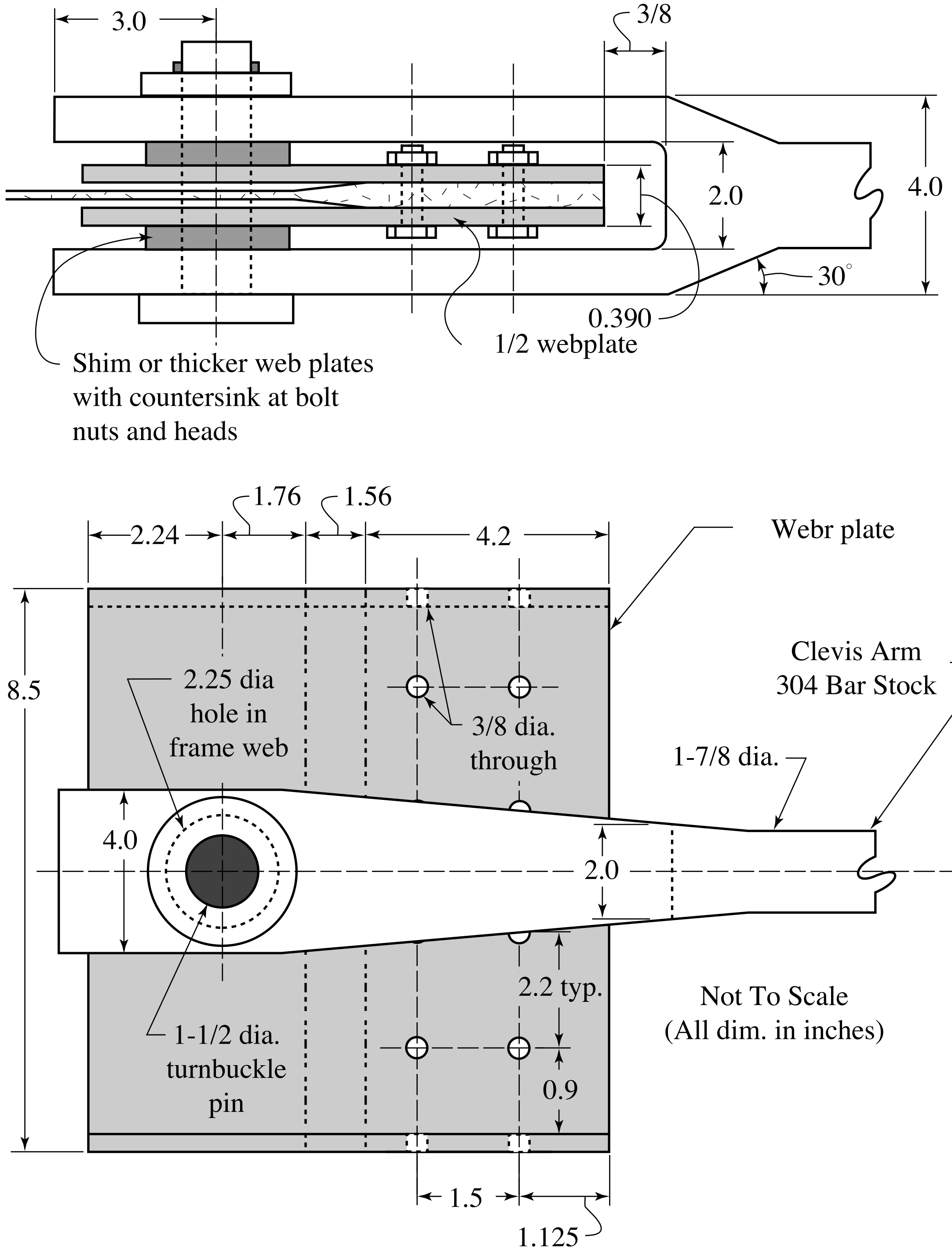

Figure 62: Schematic diagram of the clevis connection to the ring frame.

The allowable tensile stress at the net section of the stainless 304 clevis arm, F_{ts}, is 30 ksi. With a height of 4 in. and a thickness of 0.5 in., the applied tensile stress at the net section, f_{ta}, is

$$f_{ta} = P_a/t_a/(h-d_p) = 24 \text{ ksi}$$

The applied tensile stress of 24 ksi is below the allowable tensile stress of 30 ksi.

The shear tear out of the clevis arm must also be calculated. The clevis arm thickness is assumed to 0.75 in. The shear area, A_s, is

$$A_s = 2\, t_a\, (w - (d_p/2) \cos 40°) = 2\, t_a\, (w - 0.383\, d_p)$$

If w = 3 in., where w is the distance from the center of the hole for the pin to the back of the clevis arm, the applied shear stress, f_{tc}, is

$$f_{tc} = P_f/(2\, A_s) = 8.3 \text{ ksi}$$

which is well below the allowable shear stress of 17 ksi for 304 stainless steel.

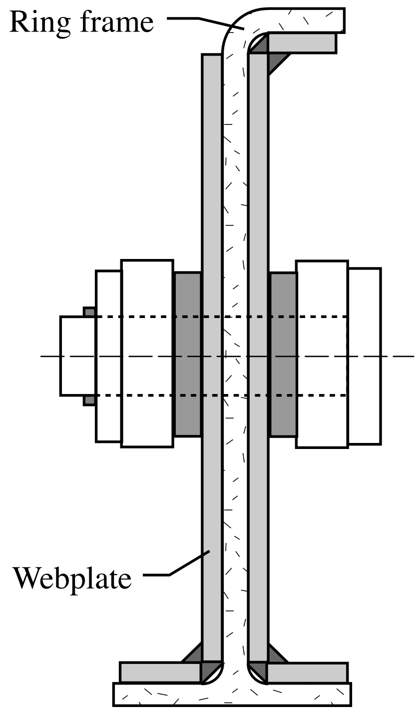

Figure 63: Schematic diagram of a cross-sectional view of the web plate and ring frame.

Design Factor Calculations

Hand calculations were used to calculate the design factors for the welds and finger joints, and stresses on the load pads for the test panel test. These design factors, and how they are obtained are detailed below.

Actuator Pad on Axial Load Plate

The pin size for the actuator, as shown in Figure 64, must be sized. Using an allowable shear stress of 34 ksi (60 ksi/√3 = 34 ksi) for the Nitronics N60 material, the area A_v is

$$A_v = \frac{120 \text{ kips}}{2(34 \text{ ksi})} = 1.76 \text{ in}^2$$

where the axial load of 240 kips (120 kips/actuator) is based on the internal pressure. The radius is thus

$$r = \sqrt{\frac{1.76\text{in}^2}{\pi}} = 0.75 \text{ in.}$$

A diameter of 2.5 in. will be used for the actuator pin. Using a 2.5-in. diameter pin and an allowable bearing stress of 50 ksi, the bearing stress of the pin on the load plate actuator pad is

$$\sigma_B = \frac{120}{2\,(2.5\text{ in.})} = 24\text{ ksi}$$

The bearing stress of 24 ksi is less than the allowable of 50 ksi, with a design factor of 2.

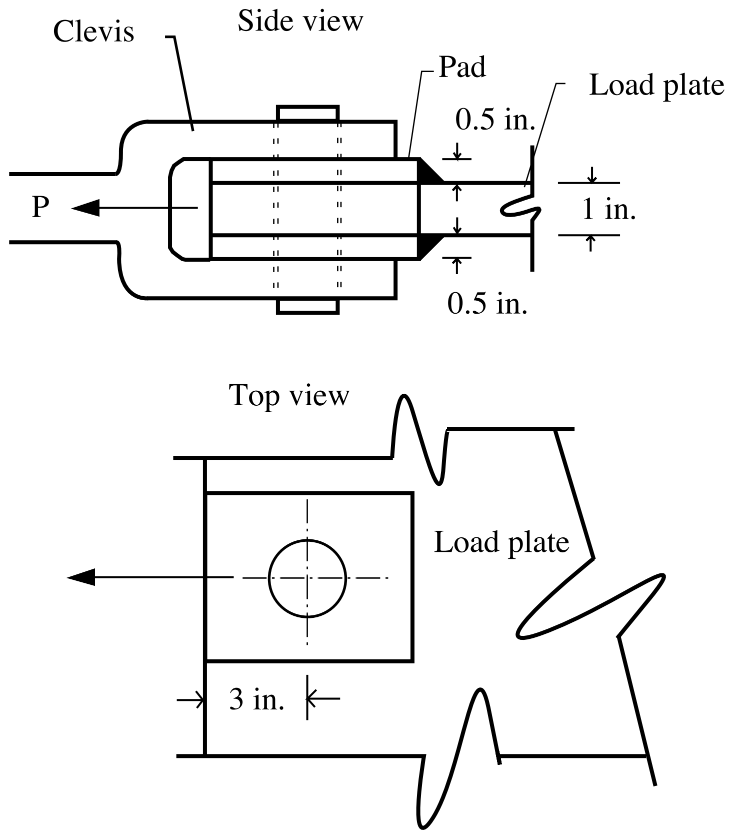

Figure 64: Schematic diagram of the actuator pad on the axial load plates.

Weld Estimate for Load Pad

The load plates will have a 12 in. x 6 in. 304 stainless steel pad that is 0.5-in. thick welded to each side of the load plate where the pin is located, as shown in Figure 65. With a load to each pad of 30 kips (with 60 kips to the plate), and a perimeter of 22 in., the fillet weld capacity is

$$\frac{30{,}000\text{ lb}}{22\text{ in.}} = 1.36\text{ k/in.}$$

The allowable stress is the minimum of

0.3 (weld metal yield) = 0.3 (60 ksi) = 18 ksi0.4 (base metal yield) = 0.4 (30 ksi) = 12 ksi

For a 7/16 in. fillet, the weld capacity is

$$\frac{7/16in.}{\sqrt{2}}\ (12\ \text{ksi}) = 3712\ \text{lb/in.}$$

The applied load (1.36 k/in.) is approximately 36% of the allowable load (3.7 k/in.).

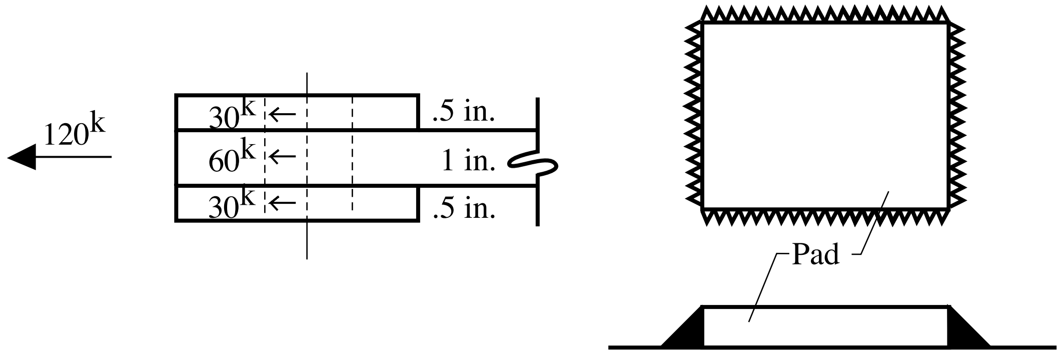

Figure 65: Schematic diagram of the load pad weld.

Actuator Pad on Axial Load Plate

The actuator pad on the axial load plate has an allowable shear stress of 17 ksi and a shear tear-out area of 2(2 in.)(3 in.) = 12 in^2. The shear stress due to the pin acting on the pads and plate is

$$\tau = \frac{120\ \text{kips}}{2\ (2\ \text{in.})(3\ \text{in.})} = 10\ \text{ksi}$$

The applied load is 59% of the allowable load.

Axial Finger Joint Analysis

The calculated stresses for the axial finger joints, as shown in Figure 66, are based on the maximum finger load obtained from the finite element analysis being applied at a single bolt, and are thus conservative. Since the finite element analysis has two fingers, upper and lower, at each finger position, the axial finger load is

$$F_{max} = \frac{1}{2}\ (12{,}324\ \text{lb}) = 6{,}162\ \text{lb}$$

The bolts that will be used will have a diameter of 0.375 in. with the threads out of the shear plane. The hole size is 0.405-in. diameter for the round holes with 0.58 in. for the slots. The tension on the net area is

$$\sigma_t = \frac{6.162\ \text{kips}}{(1.4\ \text{in.}\ -\ 0.58\ \text{in.})(0.5\ \text{in.})} = 15.0\ \text{ksi}$$

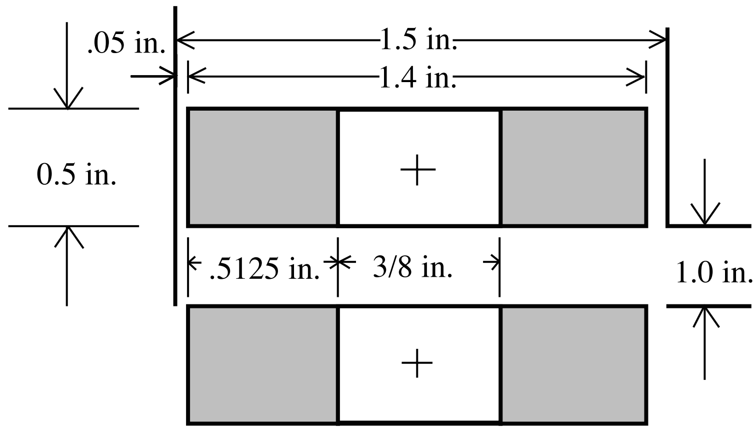

Figure 66: Schematic diagram of the axial finger joint.

Since the allowable tension stress for stainless 304 is 30 ksi. The shear stress on the finger bolts is

$$\tau_B = \frac{12.324 \text{ kips}}{2(\pi/4)(0.375 \text{ in.})^2} = 55.8 \text{ ksi}$$

The value of 55.8 ksi is greater than the allowable of 47.5 ksi. The shear stress assumes all the load is carried by a single bolt and is thus conservative. The design factor is thus 0.85. However, since the allowable shear strength for the fingers is conservatively taken to be 0.5 of the minimum ultimate shear strength, the design factor is conservative. The bearing stress on the axial load plate is

$$\sigma_B = \frac{12.324 \text{ kips}}{(0.375 \text{ in.})(1.0 \text{ in.})} = 32.9 \text{ ksi}$$

The bearing stress is less than the allowable stress of 50 ksi, resulting in a design factor of 1.09. The shear on the load plate is

$$\tau_P = \frac{12.324 \text{ ksi}}{2(1.0 \text{ in.})(1.0 \text{ in.})} = 6.2 \text{ ksi}$$

With an allowable stress of 12 ksi, the design factor is 1.95.

Actuator or Turnbuckle Pad on Hoop Load Plate

The pin size for the actuator pad or turnbuckle pad on the hoop load plate, as shown in Figure 67, can be estimated based on the shear allowable of 35 ksi for the Nitronics N60 material. Thus,

$$A = \frac{275 \text{ kips}}{2(35 \text{ ksi})} = 3.9 \text{ in}^2$$

where the total hoop load of 550 kips is based on the internal pressure. This area results in a radius of 1.11 in. A pin diameter of 3.5 in. will be used. The bearing stress is

$$\sigma_B = \frac{275 \text{ kips}}{(3.5 \text{ in.})(2 \text{ in.})} = 39.3 \text{ ksi}$$

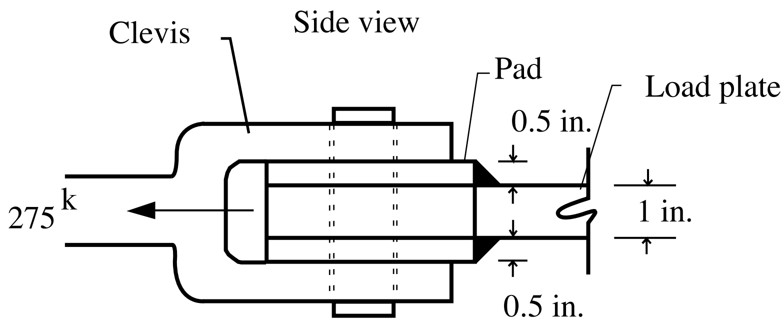

Figure 67: Schematic diagram of the hoop load plate and clevis.

The bearing stress is less than the allowable bearing stress of 36 ksi, and results in a design factor of 1.22. The allowable stress around the weld on the load pad (shown in Figure 68) was earlier calculated to be 12 ksi. With a perimeter of 32 in., and a load of 68.75 kips in the load pads, the required capacity is

$$\frac{68.75 \text{ kips}}{32 \text{ in.}} = 2.15 \text{ kips/in.}$$

giving an applied allowable ratio of 2.15/3.71 = 0.58

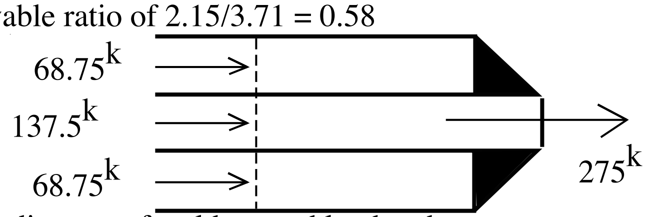

Figure 68: Schematic diagram of weld around load pad.

For a 7/16 in. weld

$$\frac{7/16 \text{ in.}}{\sqrt{2}} (12 \text{ ksi}) = 3.71 \text{ kips}$$

The 4.24 kips is greater than the required capacity of 1.62 kips, resulting in a design factor of 2.62. The pullout shear behind the bolt, as shown in Figure 69, is

$$\tau = \frac{275 \text{ kips}}{2(2 \text{ in.})(5 \text{ in.})} = 13.75 \text{ ksi}$$

The applied/allowable ratio is thus 13.75/17 = 0.80.

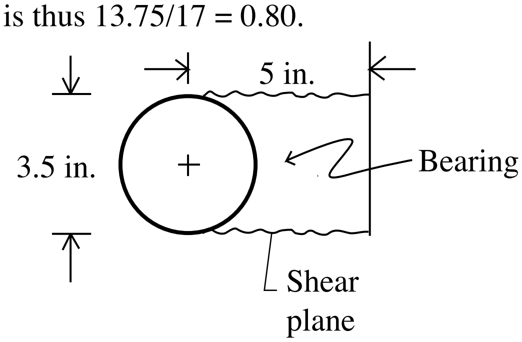

Figure 69: Schematic diagram of pull-out shear behind bolt.

Hoop Finger Load Analysis

On the hoop fingers, there are three rows of bolts through both the panel and the load plate. A schematic diagram of the hoop finger is shown in Figure 70, showing both the dimensions of the finger and the percentage of load in each bolt hole.

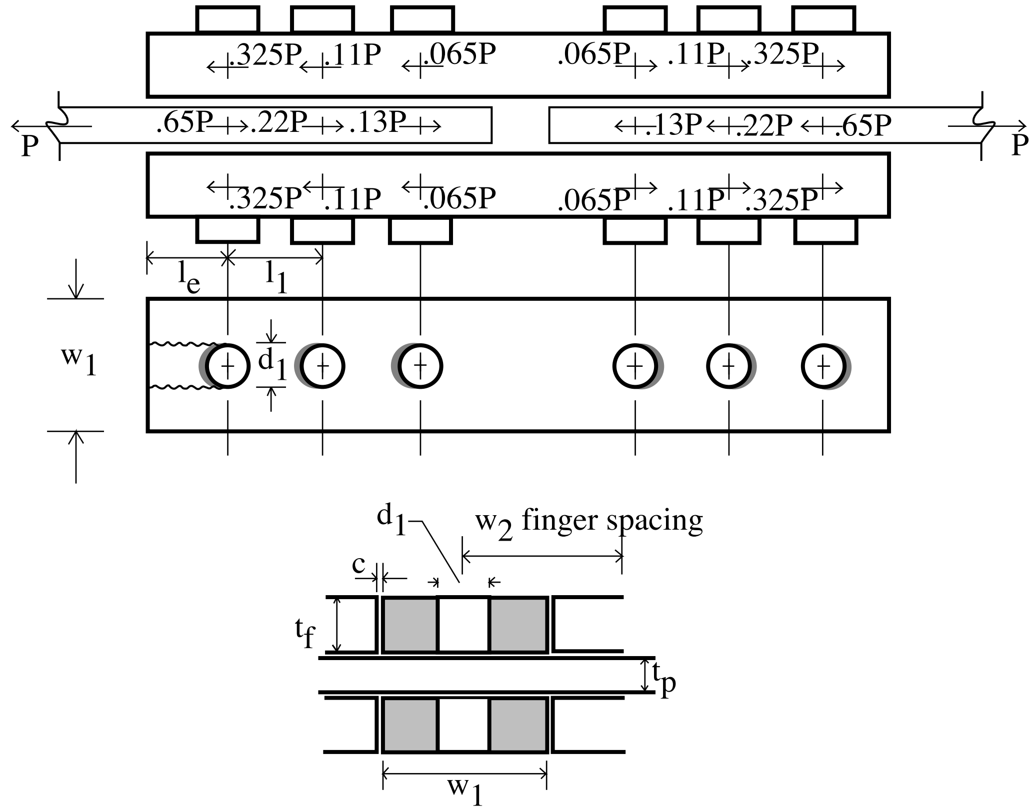

Figure 70: Schematic diagram of the hoop finger showing both the dimensions of the finger and the percentage of load in each bolt hole.

The hoop finger joint analysis assumes that the finger load is distributed to the bolts (and hence the finger segments) at 65%, 22%, and 13% from the outermost bolt to the bolt near the center line. Based on the assumed load distribution, a spreadsheet was used to calculate the needed values using a 0.375-in-diameter bolt. The tension on the net finger area was calculated to be 19.5 ksi, which is less than the allowable of 30 ksi and results in a design factor greater than 1.0. The shear on the bolts was calculated to be 53.3 ksi, which is greater than the allowable of 47.5 ksi. However, due to the conservative allowable value, the design factor of 0.89 is not of major concern. The bearing on the plate is 31.4 ksi, which results in a design factor of 1.15 based on the allowable value of 36.0 ksi.

Turnbuckle Joint at Ring Frame

Based on an allowable shear stress of 12 ksi, the pin size can be calculated. With a load of 34,993 lb (based on finite element analysis), and a shear allowable of 23 ksi for the Nitronics N40 material, the area can be calculated as

$$A_p = \frac{60{,}500 \text{ lb}}{2(23 \text{ ksi})} = 1.31 \text{ in}^2$$

An area of 1.31 in^2 results in a radius of r = 0.65 in. The diameter of the pin will be chosen to be 1.5 in. The bearing stress is

$$\sigma_B = \frac{34{,}993 \text{ lb}}{(1.5 \text{ in.})(1.0 \text{ in.})} = 23.3 \text{ ksi}$$

With an allowable bearing stress of 36 ksi, the design factor is 1.55. The shear behind the bolt is

$$\tau = \frac{34{,}993 \text{ lb}}{2(1.0 \text{ in.})(1.9347 \text{ in.})} = 9.0 \text{ ksi}$$

The applied/allowable ratio is 20.167/23.2 = 0.86.

Control System

The cryogenic pressure box temperature and pressure control system pressurizes the box and cools and heats the surfaces of the test panel. There is no connection to either the data acquisition system or to the load control system. This separation was established at the beginning of the design process to simplify the design and function of each system.

The box is pressurized with gaseous helium (GHe), since this is the only substance besides hydrogen which is still a gas at the desired operating temperatures. Liquid nitrogen (LN2) is used to precool the inside of the box, the radiation shield, and the inside of the panel to roughly –300°F. Liquid helium (LHe) is required to cool the inside of the box and panel to its coldest operating temperatures. The panel is cooled by blowing GHe past heat exchanger coils with a series of 12 fans located inside the pressure box. Internal heaters at each fan heat exchanger allow the control system to heat the box back to ambient temperature rapidly, and allow the inside of the panel to be heated to 300°F. The load introduction structure causes a potential heat leak problem and its temperature must also be controlled. LN2 coils and strip heaters fastened to the surfaces of the load plates perform this function. The exterior surface of the panel may be heated with a quartz radiant heater up to 1000°F. All these functions are controlled by the temperature and pressure control system.

The control system consists of a combination of custom-designed and off-the-shelf components which are integrated into a seamless control structure. A PC-compatible computer running Labview 4.1 provides synchronization of the various elements and performs the sequencing necessary for a test cycle. Most functional operations performed by the PC may also be performed manually by means of front-panel controls. Certain fail-safes are provided to mitigate the consequences of a control system device failure. An emergency stop (E-Stop) button allows the operator to immediately drop power to all control elements. Both the hardware and software operating the control system are discussed in this section.

Hardware

The elements of the control system are located in several areas at the pressure box site. The control room houses two full-height 19-in. racks which contain the PC and, in several rack-mount modular units, the device controllers. Rack-mounted components are mounted in clear anodized aluminum chassis; the heavier units are mounted on slides for easy access to internal components. Front and rear panel labels are screen-printed with a durable enamel.

Transducer signal and output signal conditioners are contained in the Remote Signal Conditioning Panel, which is located, together with the data acquisition isolation units, in a metal building just outside the control room. The Valve Power Control Panel uses solid-state relays to control all solenoid valves and also contains the emergency stop logic. The Internal Heater Control Panel contains solid-state power controllers for the internal heaters and for the load plate heaters; it also contains limit controllers and limit control relays for the internal heaters. These two panels are located in the same metal building that houses the SCR power controllers for the quartz radiant heater.

Field elements consist of transducers, actuators (valves), fans, and heaters. Since the working temperature range extends down to the liquid helium temperature range, it is necessary to use temperature sensors which can accurately measure cryogenic temperatures. DT-471 silicon diode temperature sensors manufactured by Lakeshore Cryotronics are used for all temperature sensors except for the load plates, which use RTD temperature sensors. Although it is possible to obtain pressure transducers which are rated down to liquid helium temperatures, the output of these devices is a complicated function of both pressure and temperature. Standard pressure transducers manufactured by Pressure Systems have been used and are plumbed in to the system at a distance from the cold gases.

Two basic types of valves are used: solenoid valves and proportional valves. The solenoid valves may be only fully closed or fully open. Both fail-closed and fail-open solenoid valves are used. All solenoid valves are powered by standard 115 VAC current. Proportional valves may be opened at any position from 0% to 100% and are actuated by compressed air. Each air-actuated proportional valve is equipped with a three-way solenoid dump valve to force the valve closed when power is lost. The three-way valve is controlled through the emergency stop system.

Fans are used to circulate GHe inside the pressure box. The 12 fan motors are located outside the cold area of the box, but are still in a helium atmosphere. Fans are driven by 0-130 VDC Bodine 1/8 Hp brush motors. Bodine motor speed controls are driven by a 4-20 mA signal produced by the temperature controllers.

There are three groups of heaters used in the pressure box: the internal heaters, the load plate heaters, and the quartz radiant heater. Four 250 W cartridge heaters are fastened to each fan heat exchanger for a total of 1 kW per fan. These heaters are controlled together as a single 12 kW internal heater; the fans are used to modulate the panel temperature. However, individual limit controllers are provided for each fan heat exchanger. The load plate heaters consist of strip heaters totaling 4 kW per load plate. Each load plate heater is controlled individually. The quartz heater is suspended over the panel and heats the outer (warm) side of the panel. The quartz heater may be controlled in up to 8 separate zones.

Principal Control Loops

All closed-loop control functions are performed by stand-alone Watlow Series 988 PID controllers except for the quartz radiant heater. All Watlow controllers may communicate with the computer via a multidrop serial RS-485 line. Alarms have been implemented which allow the controllers to constantly monitor process values and inform the computer of error conditions. This use of stand-alone controllers off loads the real-time task of computing the control signal from the computer, which can then be used for Supervisory Control and Data Acquisition (SCADA). In addition, it provides a measure of redundancy. If the computer fails, the controllers will maintain control of the system, allowing the system operator to manually shut down the system in an orderly fashion. Alternately, the failure of one controller will only affect the device which it controls. Other control loops will remain functional. Most of the Watlow controllers operate proportional output devices such as proportional valves or heaters, but several control solenoid valves. The quartz radiant heater is controlled by an 8-channel Dimension 8725 controller which communicates with the computer over an RS-232 serial line. The quartz radiant heater functions as a separate subsystem of the control system.

The PC has complete control over all controllers, and controller settings should be changed through the PC interface. Note that the controller front panels may be locked out through software, preventing unauthorized access to critical control parameters. Critical setup parameters are protected by software passwords.

V2

The pressure of the helium in the box is controlled from 0 psi to 53 psi by valve V2 (V2 BOX PRESSURE). V2 is an air-actuated proportional valve with a 4-20 mA process input which is controlled by a PID controller in cascade mode. This control scheme stabilizes the loop by providing local feedback of disturbances and effectively reduces the lag time of the process. The box pressure transducer PT3 (BOX PRESSURE) provides feedback for the master (outer) control loop and pressure transducer PT6 (V2 LINE PRESSURE) ported into the valve output line provides feedback for the slave (inner) loop. Alternate box pressure transducer PT3a may be switched into the master loop in case PT3 fails or freezes. Standard 4-20 mA process output pressure transducers are used. The pressure transducers are powered and isolated by isolation boards in the Remote Signal Conditioner Unit. V2 is equipped with a 3-way dump valve which is controlled by the emergency stop logic. Valve V2 works in conjunction with V12 to control box pressure.

V12

Valve V12 (BOX PURGE) is a solenoid valve which is opened when the atmosphere in the box is being purged. In addition, V12 is controlled by an on-off controller. In order to reduce the pressure of the box interior in the absence of a substantial leak through the seals it is necessary to vent the box when lowering pressure. V2 and V12 are sequenced by the computer so that when V2 is controlling pressure in automatic mode, V12 is programmed with a setpoint that is never greater than 1 psi above the setpoint of V2. V12 will also relieve box pressure during warm-up, when the cold gas in the box expands, and operates as a limit controller which will release box pressure if V2 should fail. Valve V12a is involved in a completely independent on-off control loop which also provides overpressure control should V12 fail or freeze. It is controlled directly by a Barksdale pressure switch and has no interface to the control system except for an indicator light on the Power Control and E-Stop unit front panel. Both V12 and V12a are fail-open valves; a power failure or E-Stop will cause the box to depressurize.

V3, V7

Valves V3 (V3 EXHAUST PRECOOL) and V7 (V7 LN2 PRECOOL) operate together to form a precooling system for the GHe used to pressurize the box. Two types of precooling are possible: liquid nitrogen (LN2) cooling or exhaust helium precooling. When a cooling cycle is started from ambient temperature, a liquid nitrogen boiler and heat exchanger precools the GHe supplied to pressurize the box and the LHe dewar. When liquid helium is being used to cool the panel (during the later stages of the cooldown process), the helium gas at the exit side of the cooling coils will still possess some cooling ability. Since liquid helium is expensive, it is desirable to use it as efficiently as possible. V7 directs the flow of ambient temperature helium through heat exchanger HXN and the boiler, which precools using LN2. V3 directs flow through economizer heat exchanger HX2 which precools with exhaust from the LHe coils in the box. Both are air-actuated proportional valves with 4-20 mA process inputs which are controlled by individual PID controllers. Feedback for both controllers is provided by temperature sensor TT2 (EXHAUST TEMP), located in the boiler pod. Alternate exhaust temperature sensor TT2a may be switched into the loop in case TT2 fails. V7 is cascade controlled using pressure sensor PT10 (V7 LINE PRESSURE) for the slave (inner) loop.

V4

Liquid helium is supplied to the cooling coils surrounding the fans by pressurizing a dewar with 0-10 psi helium gas which has been precooled by the economizer flow paths. V4 (V4 LP He PRESSURE) controls the dewar pressurization gas based on the temperature of the liquid helium as it exits the coils in the pressure box. V4 is an air-actuated proportional valve with a 4-20 mA process input which is controlled in cascade mode by a PID controller. Temperature sensor TT11 (EXIT TEMP), located in the pressure box vacuum jacket, provides feedback for the master (outer) control loop and pressure transducer PT4 (V4 LINE PRESSURE) located at the dewar provides feedback for the slave (inner) loop. Alternate exit temperature sensor TT11a may be switched into the loop in case TT11 fails. The pressure transducer is powered and isolated by an isolation board in the Remote Signal Conditioner Unit. V4 is equipped with a 3-way dump valve which is controlled by the emergency stop logic. In addition, the PID controller monitors the pressure at PT4, and will close valve V4 by means of the 3-way dump valve if the dewar pressure rises above 10 psi.

V5

Valve V5 (V5 BOX PRECOOL) controls the flow of LN2 used to precool the box and the panel. V5 is an air-actuated proportional valve with a 4-20 mA process input which is controlled by a

PID controller. Temperature sensor TT9 (LN2 COIL TEMP), located in the pressure box vacuum jacket in the LN2 exit line before the radiation shield, provides feedback for the controller. Sensor TT10, located in the same line but after the radiation shield, may be used as a backup sensor in case TT9 fails. V5 is equipped with a 3-way dump valve which is controlled by the emergency stop logic.

Internal Heaters

Internal heaters are mounted on the fan heat exchangers inside the pressure box. These heaters are controlled as a group by a PID controller through a Watlow QPAC power controller. Temperature sensor TT6 (HEATER TEMP), mounted on the test panel, provides feedback for the controller. There is no installed backup temperature sensor for the heater; in case of TT6 failure the controller must be operated in manual (percent power) mode. Although the heaters are controlled as a group, each fan heat exchanger is equipped with a silicon diode temperature sensor (labeled TT8-1 through TT8-12) and a limit controller which will turn off a heater if its temperature rises above 300°F. The limit controller setpoint is preset on the limit controller PC boards and is not accessible to the operator.

Fans

Panel temperature is controlled by varying the speed of 12 fans mounted through the bottom surface of the pressure box in a 4 x 3 array. Each fan has its own PID controller and motor speed controller. Temperature sensors TT12-1 through TT12-12, mounted on the test panel directly above the fans, provide feedback for the controllers. These sensors are cemented directly to the surface of the panel. Although backup sensors are not provided, a backup multiplexing system allows the operator to switch to an adjacent panel temperature sensor should a fan's primary temperature sensor fail.

Load Plates (V35-x)

The temperature of each load plate is controlled independently. Both heating and cooling functions are performed by a single PID controller for each load plate. Valves V35-1 through V35-4 are fail-closed solenoid valves which are operated by an on-off control output. These valves route LN2 through cooling traces on the load plate surface. Valves V28 and V36 are also involved in the load plate temperature control system. Each of the four 4 kW load plate heaters is controlled through a Watlow DIN-a-mite power controller by a proportional 4-20 mA control output from the PID controller for the respective load plate. RTD temperature sensors TT7-1 through TT7-4 provide feedback signals to the controllers. There are no backup sensors for the load plate temperature control system.

Radiant Heater

Panel warm side heating is performed by a large quartz radiant heater. This heater is controlled by a Dimension 8725 controller through SCR power controllers. Up to eight heating zones are provided. Feedback is provided by 8 thermocouples mounted on the warm side of the panel. The entire radiant heater control system acts as an independent part of the control system; its only interface is through the RS-232 serial interface to the control computer.

Other Control Systems

Additional input devices and valves which are not involved in closed control loops also exist. Solenoid valves are used during purging and to switch between various modes of operation. These valves may be controlled through the computer or by means of front-panel switches. Additional temperature sensors, pressure transducers, and level transducers allow the operator to monitor system performance and provide troubleshooting information. Their input data is read by the computer through an A/D card. These devices are described below.

V6

The liquid nitrogen boiler requires that the level of LN2 remain nearly uniform. This function is provided by a standalone LN2 level controller. Two thermistors are mounted at different levels in the LN2 boiler. When the LN2 level drops below the lower thermistor, solenoid valve V6 is opened by the LN2 level controller. When the level rises to the upper thermistor, valve V6 is closed. The spacing between the two sensors provides a measure of hysteresis to prevent the valve from continual actuation. The entire LN2 boiler system may be enabled or disabled through software or by means of front panel toggle switch V6 LN2 BOILER.

V8, V9

To prevent freezing of higher boiling-point compounds in the cryogen lines and to prevent the expansion of trapped cryogens, it is necessary to purge all lines with GHe before cooling the box and when changing over from LN2 cooling to LHe cooling. Opening solenoid valve V8 causes LHe to flow through the LN2 box precool lines including the LN2 fan heat exchangers and the LN2-cooled radiation shield. Opening solenoid valve V9 purges the LHe cooling lines. These valves may be controlled through software or with front panel toggle switches labeled V8 BOX PURGE and V9 He PURGE respectively.

V10

When LHe is not being used, solenoid valve V10 is used to shut off the LHe dewar output line. This valve must always be open when V4 is active. It may be controlled through software or with the front panel toggle switch labeled V10 LHe SHUTOFF

V13

During LN2 precooling or purging operations, solenoid valve V13 allows flow through the LN2 box precool lines to be vented through a check valve. Closing V13 seals off the LN2 lines. Cooling the box with LHe causes a slight negative pressure in the LN2 lines; without V13 warm air at atmospheric pressure could be drawn past the check valve into the cryogenic lines. V13 must always be open when V5 is open or V8 is open. It may be controlled through software or with the front panel toggle switch labeled V13 LN2 VENT.

V14

Solenoid valve V14 allows the LHe fan heat exchangers to be purged directly to the outside without passing the purge flow through heat exchangers HX1, HX2, and HXN. This prevents the heat exchanger coil sealing materials from absorbing moisture and other contaminants. This valve may be controlled through software or by the front panel switch labeled V14 He DUMP.

V28, V36

Solenoid valves V28 and V36 operate together to allow either LN2 or 100 psi compressed air to flow through the load plate cooling traces. Opening V28 and closing V36 allows the load plate cooling traces to receive LN2 through cryogenic control valves V35-x and cool the plates. Closing V28 and opening V36 supplies the load plates with air to purge the N2 from the coils and facilitate the warm-up process. V28 and V36 should never be open simultaneously. These switches may be controlled through software or with a 3-position front panel switch labeled V36 HEAT/V28 COOL.

V33, V34, AUX 1, AUX 2

Solenoid valves V33 and V34 were originally intended to support helium purity monitors (not installed) to determine purge completion. Two additional unused output lines, AUX 1 and AUX 2, have also been provided for future addition of ON-OFF devices. All these controls may be operated through software or through front panel switches.

Consumables

Digital process meters (Newport Infinity series) are provided to display the LHe dewar level, the LN2 dewar level, and the GHe supply pressure. Currently, the dewar level sensors are not installed. These values are read through separate channels on the PC A-to-D interface board.

Pressure Transducers

Besides those used by the closed loop controllers (PT3, PT3a, PT4, PT6, PT10), several additional pressure transducers have been instrumented for diagnostic purposes. PT2 monitors the preregulated GHe system supply pressure at manual regulator V1. PT5 monitors the He cooling exhaust line pressure between the fan heat exchangers and economizer heat exchangers HX1 and HX2. PT7 monitors the LN2 boiler exhaust pressure. PT8 monitors the He cooling system exhaust pressure. PT9 monitors the LN2 cooling system exhaust pressure. PT11 monitors the GHe supply pressure entering the economizer heat exchangers HX1 and HX2. One possible use for these transducers is to determine the pressure drop across a flow path. For example, the pressure drop across the LHe fan heat exchangers may be determined from the difference of PT4 and PT5. These process values are multiplexed together with the temperature sensors listed below and read through a single channel on the PC A-to-D interface board.

Temperature Sensors

As with the above pressure transducers, additional temperature sensors are installed besides those used by the closed loop controllers (TT2, TT2a, TT6, TT7-1 through TT7-4, TT8-1 through TT8-12, TT9, TT11, TT11a, TT12-1 through TT12-2, and eight panel warm side thermocouples). TT1, located in the boiler pod, indicates the temperature of precooled GHe which has passed through either the LN2 boiler system or heat exchanger HX2. TT3 provides the temperature of the LN2 precool line between the LN2 fan heat exchangers and the radiation shield traces. The temperature of the LHe fan heat exchanger inlet is given by TT4. TT5 indicates the temperature of the precooled GHe used to pressurize the box. TT10 provides the temperature of the LN2 exit line. As with the pressure transducers, these sensors may be used for diagnostic purposes such as determining ΔT across a heat exchanger.

Main Control Unit

The Cryogenic Pressure Box Main Control Unit handles the closed-loop control functions for all proportional valves and for the twelve internal heaters. It also controls most solenoid valves not involved in closed-loop control. In addition, this unit serves as the interface between the supervisory control functions provided by the PC through the RS-485 interface and the A-to-D converter and all other rack-mounted control units. This unit is a vital link in the control system.

Front Panel

The front panel contains six Watlow Series 988 controllers for closed-loop PID control of proportional valves V2 BOX PRESSURE, V3 EXHAUST PRECOOL, V4 LP He PRESSURE, V5 BOX PRECOOL, V7 LN2 PRECOOL and for the INTERNAL HEATERS. These controllers communicate with the PC through an RS-485 multidrop network.

Controllers may be operated in one of two modes: manual or automatic. In manual mode, the controller simply relays a user command to the output device. For example, a proportional valve may be commanded to be open 75%, or a heater may be commanded to operate at 5% power. In automatic mode, a setpoint is provided and the controller does everything it can to maintain the input transducer at that setpoint by controlling the output device. Automatic mode will be the most common mode of operation, but some devices will probably be operated in manual mode (e. g. the internal heaters).

Toggle switches allow control of solenoid valves and backup functions, and LEDs provide indication of system status. All toggle switches used require the operator to pull the switch lever out in order to actuate the switch. This prevents inadvertent actuation of a switch by bumping or brushing it.

Each closed-loop controller is augmented by a backup switching function. This function, which may be accessed through software or by manually actuating a front panel control, allows the user to switch from a primary (default) control sensor to a backup sensor should the primary sensor fail. The input signal to the controller is remotely switched by a solid-state CMOS switch located on the Backup Input Multiplexer PC board located inside the Main Control Unit. When in backup mode, a yellow LED is lighted to indicate that an abnormal condition exists. A SENSOR BACKUP switch transfers control of this function from the front panel switches (MANUAL) to the PC (AUTO). Note that although the backup switching function is provided for each controller, backup sensors may not be present for all controllers. The backup control switch for V2 also controls the sensor input for V12's controller, located on the Auxiliary Functions Control Unit.

The following solenoid valves are controlled through the Main Control Unit: AUX 1, AUX 2, V6 LN2 BOILER, V8 BOX PURGE, V9 He PURGE, V10 LHe SHUTOFF, V13 LN2 VENT, V14 He DUMP, V33, AND V34. These valves may be controlled by software or by manually actuating the front panel switch. A green COMMAND LED is lit when a control signal is present for a valve. This LED does *not* indicate the actual position of the valve, and will not indicate a physical valve failure. The switch labeled LOCKOUT transfers control of these valves (and two controlled from the Auxiliary Functions Unit, V28 and V36) from the front panel switches (MANUAL) to the PC (AUTO). A green LED is lit when in MANUAL mode. The computer monitors the status of this switch, and if it is switched to MANUAL during a test, an alarm condition is generated. The VALVE MASTER switch closes all solenoid valves not involved in closed-loop control when in the CLOSE position. The computer also monitors the status of this switch, and will generate an alarm condition if it is switched to CLOSE during a test.

Provision was made to display feedback from the valves. The FAULT indicators are yellow LEDs which are lit whenever the actual position of a valve differs from the commanded position of a valve. Since the actual solenoid valves used do not permit addition of a position sensor, these indicators have been internally disconnected. Proportional valve feedback is displayed by green LEDs for the 100% open condition and red LEDs for the 0% open (closed) position. However, the valve limit switches are not installed, so these indicators have also been disconnected.

Red LEDs indicate alarm conditions generated by the Series 988 controllers. A separate LED is provided for the Main Control Unit, the Auxiliary Functions Control Unit, the Fan A Control Unit, and the Fan B Control Unit. An alarm condition will also be generated if the connections from the Main Control Unit to the Auxiliary Functions Control Unit or to the Fan A/B Control Units become disconnected. These alarm signals are OR'd together and monitored by the computer.

A red neon lamp indicates the presence of 115 V power for internal functions, and a red LED indicates the presence of the logic power supply output.

Circuit Description

The Main Control Unit may be divided into 4 sections: PID controllers, backup input multiplexer, power supply, and the Logic Control board.

There are two basic types of Watlow Series 988 PID controllers used in the Main Control Unit. Type 988A controllers allow for basic PID control functions with one input sensor. Type 988B controllers allow more advanced functions with two input sensors and are here used for cascade control of valves V2, V4, and V7. All controllers are configured for a main input signal type of 0-5V which is fed from the Backup Input Multiplexer discussed below. Secondary inputs used by cascade controllers do not pass through the Backup Signal Multiplexer and are configured as 4-20 mA process inputs. All inputs are scaled in engineering units for the specific input sensor type and range used.

Each Series 988 controller is equipped with several outputs. Output 1, configured for 4-20 mA current loop operation, is the control signal output and is routed directly to the rear panel output connector. Output 2 is normally not used, except for valve V4, which is configured with output 2 as an alarm which is triggered when process input 2 rises above 10 psi. This signal is routed through the control signal output connector for V4 and used to immediately close V4. Output 3 is reserved for alarm conditions. This alarm output is configured as a normally closed mechanical relay, and all outputs from the controllers on the Main Control Unit are daisy-chained together. The alarm conditions are internally programmed; all controllers are configured to alarm on a process value range error on input 1. An alarm condition raised by any controller will open the loop and signal an alarm. Alarms are presented to the PC through the Logic Control board. Output 4 is configured for RS-485 multidrop communications. The multidrop RS-485 loop extends beyond the Main Control Unit to service other control units. A loop termination resistor is installed in the Fan B Control Unit, the last unit on the RS-485 loop.

Controller event inputs are not used. Controllers are powered by 115VAC power and are externally fused. A faulty controller may be removed and replaced without opening the chassis or disturbing any wiring. Note that controller inputs and outputs depend on installed options, internally settable DIP switches, and software configuration parameters.

The backup input multiplexer allows the system to select between a primary input device and a backup input device. Channels 3 and 4, which drive the controllers for valves V3 and V7, share the same input sensor loop (TT2 and TT2a). Front-panel switches allow manual control of the backup function, and indicators display the current input status. Power and signals for computer control of the backup function are supplied by the Logic Control board.

Correct low-frequency shielding procedure requires a single-point ground for the shield over the entire length of the cable. All analog signal connectors contain a dedicated terminal which allows the shield current to pass through the enclosure.

Power for the Logic Control board, solid state relays located in the field, and all backup signal multiplexer boards is provided by a linear power supply. All power supply inputs and outputs are fused.

Logic Control Board

The Logic Control board handles the interface between the PC, front panel switches, all on-off controllers, and all on-off type field devices. Sequencing and operational procedure logic is performed entirely by the PC under software control; the Logic Control board handles mundane tasks such as decoding, signal OR'ing, etc. The Logic Control board is a 4-layer epoxy-glass PC board. Power entry is through a pair of screw-type terminals. All signals enter and exit through headers which are mated with applied-wire type housings. No ribbon cable is used. 74HC logic is used throughout for low power consumption, reliability, minimization of noise, and availability. Positive logic is used to permit normal operation of the front panel switches whether the computer is on, off or disconnected.

Inputs are provided for valve position limit switches. These inputs are designed to be conditioned by standard solid-state input modules which produce an isolated 0-5VDC negative logic output from either an AC or DC input. Buffers invert the signals to provide positive logic signals. Each solenoid valve limit switch input is X-OR compared with the associated valve command to determine whether or not the valve is in the position commanded. A yellow FAULT LED is lit on the front panel whenever a valve is in the wrong position. Because there is a delay between the time a command is issued by the logic board and the time the valve actually moves, the fault signal is delayed to prevent the LED from flashing during the time a valve is changing states. The proportional valves do not use this system; a separate limit switch input is provided for both the fully open (100%) and fully closed (0%) positions. Since no limit switches have been installed, none of the features are actually used by the control system.

Solenoid valve outputs are conditioned by relay drivers. The positive-logic signal is inverted once by these drivers and once by the standard solid-state output modules which actually drive the valves.

For those solenoid valves not involved in a closed-loop control, control signals can come from one of two sources: the computer or the front panel switches. In order to avoid conflict, a front-panel LOCKOUT switch selects either manual (switched) or automatic (computer-controlled) operation through a bank of multiplexers. Multiplexer inputs come directly from the switches and the computer. A master control function is provided for these valves which causes them to go to their powered-down state. For closed-loop controlled solenoid valves, switches are provided for each valve which either enables automatic operation by the controller or closes the valve. Both classes of valves are subject to a power-up reset signal which ensures that no valve is inadvertently powered within the first few seconds of power-up. The master switch state is routed to the computer for monitoring purposes and also to the solenoid drivers to allow a field-mounted relay to drop power to all valves.

The Logic Control board also provides the interface for the alarm inputs, +5V power, and the backup signal multiplexers in the Main Control Unit, the Auxiliary Functions Control Unit, and the Fan A/B Control Units. Each alarm input has a pull-up resistor which causes the signal to go high when one relay contact in the daisy-chain opens. The alarms are OR'd together and routed to the computer. Power for the multiplexers and for the solenoid valve output drivers is brought on-board and filtered separately from the main board logic power supply to minimize voltage drops and noise.

Fan A/B Control Units

The Cryogenic Pressure Box Fan A/B Control Units handle all closed-loop control functions for the 12 fans. Fan A Control Unit controls fans 1 through 6, and Fan B Control Unit controls fans 7 through 12. The fan motors are powered through SCR motor speed controls which receive speed commands from closed-loop controllers.

Front Panel

The front panels each contain six Watlow Series 988A controllers for closed-loop PID control of six fans. These controllers communicate with the PC through the RS-485 multidrop network. Controllers may be operated in one of two modes: manual or automatic. In manual mode, the controller simply relays a user command to the output device. For example, a fan motor may be commanded to run at 75% of the maximum speed. In automatic mode, a setpoint is provided and the controller does everything it can to maintain the panel temperature zone at that setpoint by varying fan speed. Automatic mode will be the most common mode of operation, but the fans will be operated in manual mode during purging operations. Fans may be operated as a group or individually.

Each fan is provided with a FAN MOTOR toggle switch. This switch has two positions: RUN and OFF. In the RUN position, the fan power controller is enabled and the fan speed is controlled via the PID controller; in the OFF position, the fan power controller is disabled and the fan is off. The switches used are immune to accidental activation. The E-Stop system also has control over the fan motors.

Each controller is augmented by a backup switching function. This function, which may be accessed through software or by manually actuating a front panel control, allows the user to switch from a primary (default) control sensor to a backup sensor should the primary sensor fail. The input signal to the controller is remotely switched by a solid-state CMOS switch located on the Backup Input Multiplexer PC board located inside each Control Unit. When in backup mode, a yellow LED is lighted to indicate that an abnormal condition exists. A SENSOR BACKUP switch transfers control of this function from the front panel switch (MANUAL) to the PC (AUTO). For the Fan A/B Control Units additional backups sensors are not used due to cost considerations. Instead, switching to a backup channel will switch to the temperature sensor of an adjacent control zone. This allows closed-loop control to continue although with reduced accuracy and control ability. The process control system will be unable to determine the exact temperature at the inner surface of the panel in the failed zone.

Fan motor current may be monitored by means of a digital ammeter. A 6-position rotary switch allows the operator to check the current being supplied to each fan. This feature may be useful when trying to diagnose an apparent heat leak on the panel caused by a fan malfunction.

Unfiltered and unregulated AC power for the motor power controllers is provided separately from the filtered and regulated power for the Watlow controllers. A red neon lamp indicates the presence of 115 V power for the motor speed controllers.

Circuit Description

The Fan Control Units may be divided into four sections: PID controllers, backup input multiplexer, motor power controllers, and the motor current ammeter.

Each Watlow Series 988A PID controller allows for basic PID control functions with one input sensor. All controllers are configured for a 0-5 V input signal type which is fed from the Backup Input Multiplexer discussed below. All inputs are scaled in engineering units for the silicon diode sensors used (-457°F to 395°F). Each Series 988 controller is equipped with several outputs. Output 1, configured for 4-20 mA current loop operation, is the control signal output and is routed directly to the rear panel output connector. Output 2 is used to disable the motor power controller. Output 3 is reserved for alarm conditions. This alarm output is configured as a normally closed mechanical relay, and all outputs from the controllers on the Fan A/B Control Unit are daisy-chained together. The alarm conditions are internally programmed; all controllers are configured to alarm on a process value range error on input 1. An alarm condition raised by any controller will open the loop and signal an alarm. Alarms are presented to the PC through the Main Control Unit. Output 4 is configured for RS-485 multidrop communications. The multidrop RS-485 loop extends through each Control Unit with Watlow PID controllers. A loop termination resistor is installed in the Fan B Control Unit, the last unit on the RS-485 loop.

Controller event inputs are not used. Controllers are powered by 115 VAC power and are fused with externally accessible fuses. A faulty controller may be removed and replaced without opening the chassis or disturbing any wiring

The backup input multiplexer allows the system to select between a primary input device and a backup input device. The Fan A/B Control Unit multiplexers are configured to switch to a neighboring control zone for use as the backup input device. Independent backup sensor input channels are not provided as they are with the Main Control Unit. All inputs are 4-20 mA current loop; all outputs are 0-5VDC. 6 channels are used by the PID controllers. Front-panel switches allow manual control of the backup function, and indicators display the current input status. Power and signals for computer control of the backup function are supplied through a connector by the Logic Control board in the Main Control Unit.

Correct low-frequency shielding procedure requires a single-point ground for the shield over the entire length of the cable. All analog signal connectors contain a dedicated terminal which allows the shield current to pass through the enclosure.

Bodine 0830 open-loop SCR motor controls supply current to the brush DC motors which drive the fans. The 4-20 mA control output signal from the Watlow controllers is wired directly to the input of a Bodine 0880 analog isolation and interface card mounted on each motor controller. The enable function of these cards is driven both by the Watlow controller and by a front panel switch. Motor speed controller inputs and outputs are internally fused. Trimpot adjustments for maximum acceleration, maximum and minimum speed, and torque limiting are also provided on each motor control. The acceleration time may be increased up to 10 seconds to reduce the spin-up chatter which occurs because of the fan shaft mechanical configuration. Since these are open-loop motor speed controls, tight speed control is not to be expected. Braking and direction control are not implemented.

Motor supply current is measured across voltage-drop resistors. A break-before-make 6-position rotary switch selects the desired voltage drop and routes it to a Non-Linear Systems 3-1/2 digit panel meter. The entire ammeter system is floating; power is supplied by an isolated and fused switching +5 V power supply.

Auxiliary Functions Control Unit

The Cryogenic Pressure Box Auxiliary Functions Control Unit handles control of all load plate temperature control functions and for solenoid valve V12. Digital panel meters display the status of consumables.

Front Panel

The front panel contains five Watlow Series 988A controllers for closed-loop PID control of solenoid valves V35-1 HOOP 1, V35-2 HOOP 2, V35-3 AXIAL 1, V35-4 AXIAL 2, and V12 BOX PURGE. These controllers communicate with the PC through an RS-485 multidrop network. The PC has complete control over these controllers, and controller settings should be changed through the PC interface. The controllers for V35-1 through V35-4 also control the 4 kW heaters mounted on each load plate. These are the only controllers in the system to operate both direct-acting (valves) and indirect-acting (heaters) output devices. Controllers may be operated in one of two modes: manual or automatic. In manual mode, the controller simply relays a user command to the output device. For example, a solenoid valve may be commanded open or closed, or a heater may be commanded to operate at 5% power. In automatic mode, a setpoint is provided and the controller does everything it can to maintain the input transducer at that setpoint by controlling the output device.

Toggle switches allow control of solenoid valves and LEDs provide indication of system status. Solenoid valves V28 and V36 are controlled through the Auxiliary Functions Control Unit: These valves may be controlled by software or by manually actuating a 3-position front panel switch. Moving the switch handle up opens valve V36; moving it down opens valve V28. In the center position, neither valve is open. This switch configuration prevents the operator from opening both valves at the same time. These valves are subject to the actions of the VALVE MASTER and LOCKOUT switches located on the Main Control Unit.

Valves V35-1 through V35-4 and valve V12 are primarily controlled by the Watlow controllers. A switch is provided to allow the user to override the controller and close these valves. V12 is a fail-open valve; a power failure or E-Stop will open the V12. A green COMMAND LED is lit when a control signal is present for a valve. This LED does *not* indicate the actual position of the valve, and will not indicate a physical valve failure. However, provision was made to display feedback from the valves. The FAULT indicators are yellow LEDs which are lit whenever the actual position of a valve differs from the commanded position of a valve. Since the actual solenoid valves used do not permit addition of a position sensor, these indicators have been internally disconnected.

Three Newport Infinity series panel meters display the status of consumables: GHe supply pressure, LHe dewar level, and LN2 dewar level. The information displayed by the meters is also monitored by the computer. Currently, LHe and LN2 level sensors are not installed and so these meters are not used.

Circuit Description

Each Watlow Series 988A PID controller allows for basic PID control functions with one input sensor. The load plate controllers are configured for a main input signal type of 4-2 0mA. V12 has a 0-5 V main input signal which originates at the Backup Signal Multiplexer in the Main Control Unit and is routed to the Auxiliary Functions Control Unit. All inputs are scaled in engineering units for the sensor type used. Each Series 988 controller is equipped with several outputs. Output 1 is a mechanical relay which controls the valves. These valve control output signals are routed back to the Main Control Unit. Output 2 is configured for the load plate heater 4-20 mA control signal outputs; Output 2 is not used on V12's controller. Output 3 is reserved for alarm conditions. This alarm output is configured as a normally closed mechanical relay, and all outputs from the controllers on the unit are daisy-chained together. The alarm conditions are internally programmed; all controllers are configured to alarm on a process value range error on input 1. An alarm condition raised by any controller will open the loop and signal an alarm. Alarms are presented to the PC through the Main Control Unit. Output 4 is configured for RS-485 multidrop communications. The multidrop RS-485 loop extends through each Control Unit with Watlow PID controllers. Controller event inputs are not used. Controllers are powered by 115VAC power and are externally fused. A faulty controller may be removed and replaced without opening the chassis or disturbing any wiring.

Correct low-frequency shielding procedure requires a single-point ground for the shield over the entire length of the cable. All analog signal connectors contain a dedicated terminal which allows the shield current to pass through the enclosure.

The digital panel meters receive their 4-20 mA input signals directly from rear-panel connectors. They are configured with a retransmit function which outputs the input signal as a 0-5 V signal. This is routed to the A to D card in the PC. The meters are externally fused.

Power Distribution Unit

The Cryogenic Pressure Box Power Distribution Unit handles power distribution and conditioning for the control room rack-mounted units, the fans, and the Remote Signal Conditioner Unit. It does not supply power to the valves and heaters. The E-Stop system does not control the Power Distribution Unit; therefore, the control system remains on line and transducers may be monitored during and after an E-Stop event.

Front Panel

Momentary ON (green) and OFF (red) push buttons control power to the system. If power is lost while the control system is on, the control system will not restart until the ON button is pressed. A front-panel LOCKOUT key switch is provided which disables the action of the ON and OFF push buttons. When the key switch is in the LOCK position, the push buttons have no effect. This feature prevents an accidental power-down of the process control system when a test is in progress. It also prevents unauthorized personnel from powering up the process control system. Red neon lights indicate the presence of conditioned and unconditioned output power.

Circuit Description

Unconditioned 125 VAC power at up to 6500 VA enters the rack-mounted unit from an external disconnect switch. The unusually large 120 V current level is required by the twelve fan motor controllers. Power supplied to critical control units is conditioned by a 1500 VA ferroresonant regulating transformer which will maintain a sine wave output voltage to within 3% over an input voltage range of -20% to +10%. This transformer also provides isolation, harmonic rejection, surge suppression, and overload protection. All outputs are either fused or current-limited.

Remote Signal Conditioning Panel

The Cryogenic Pressure Box Remote Signal Conditioning Panel, mounted in the data acquisition system isolation shed, provides signal conditioning for the sensors, transducers, and control outputs. The circuitry for the Remote Signal Conditioner is mounted in a 30 in. x 36 in. x 8 in. NEMA 4 enclosure. All input and output control signals (except for the limit switch inputs) are accessible through 97-series crimp-type connectors mounted through the side walls of the box. Connector labels are printed directly on the box with a durable enamel. Signal conditioning circuit boards are mounted on custom-made card racks with insulated card guides and a card retaining system. Signal connections are clearly labeled.

A series of 28 CSC-100 boards provides sensor excitation, amplification, isolation, linearization, and conversion to 4-20 mA current loop for 24 silicon diode and four RTD sensors. The control system has been designed to accept pressure transducers with a 4-20 mA output and proportional valves with a 4-20 mA input. A series of 16 ISO-100 isolation boards is provided to isolate and power pressure these transducer inputs and proportional valve control outputs.

This unit provides the following sensor inputs which are conditioned to 4-20 mA outputs for use by the rest of the control system:

TT12-1 through TT12-12	Panel Temperature Input Diodes
TT1, TT1a, TT2, TT2a	Boiler Temperature Input Diodes
TT3	N2 Lower Plate Exhaust Diode
TT4	LP Helium Inlet Diode
TT5	HP Helium Inlet Diode
TT6	Internal Heater Temperature Diode
TT7-1	Hoop 1 Load Plate RTD
TT7-2	Hoop 2 Load Plate RTD
TT7-3	Axial 1 Load Plate RTD
TT7-4	Axial 2 Load Plate RTD
TT9	Fan Heat Exchanger N2 Exit Diode
TT10	Radiation Shield N2 Exit Diode
TT11	Exit Temperature Diode
TT12	Exit Temperature Diode Backup
PT1	GHe Supply Pressure
PT2	V1 Pressure

PT3a	Box Backup Pressure
PT3	Box Pressure
PT4	V4 Line Pressure
PT5	Fan HX LHe Exhaust Pressure
PT6	V2 Line Pressure
PT8	LHe Cooling Pressure
PT10	V7 Line Pressure
LN2	Dewar Level (not used)
LHe	Dewar Level (not used)

Circuit Description

Each silicon diode temperature sensor input is equipped with a 4-lead (Kelvin) connection which minimizes the effects of cable resistance. A separate twisted pair is provided for the 10 μA excitation current and for the diode voltage. The Panel Temperature inputs are grouped together into a single connector, as are the Boiler Temperature inputs. All other temperature inputs are provided with independent connectors. The RTD devices use a 3-lead interface with dual 100 μA current sources. This system provides performance equal to that of a 4-lead interface. All 4-20 mA conditioned temperature sensor outputs are provided with individual connectors.

The pressure transducers use a powered 2-wire 4-20 mA interface. Power for the pressure transducers is provided by the ISO-100 isolation boards. The ISO-100 boards used for valve control signal isolation and the dewar level inputs are not configured for a powered loop. A separate connector is provided for each channel to permit configuration flexibility.

A ±15 VDC, 8 A linear power supply powers all CSC-100 and ISO-100 circuit boards; all power supply inputs and outputs are fused. This power supply is supplied with conditioned power by the Power Distribution Unit mounted in the control system rack.

Cooling is provided by a heat pipe heat exchanger which prevents the interior of the unit from reaching excessive temperatures. Four DC fans circulate air across the circuit boards and a baffle system forces cool air from the heat exchanger to flow directly towards the signal conditioning circuit boards. Warmer return air flows across the linear power supply and back into the heat exchanger.

A 16 channel I/O module board provides inputs for proportional valve limit switches. A simple unregulated power supply powers the limit switches. Currently, none of these valve actuator limit switches are installed.

Correct low-frequency shielding procedure requires a single-point ground for the shield over the entire length of the cable. Connectors contain a dedicated terminal which allows the shield current to pass through the enclosure.

Valve Power Control Panel

The Cryogenic Pressure Box Valve Power Control Panel distributes power to all solenoid valves. It contains the control logic for the pressure switches, the revolving warning light, and much of the E-stop logic. All components are mounted in a 24 in. x 30 in. x 8 in. NEMA 4 enclosure. Control signal connections to the control room rack are made through Amphenol 97-series circular connectors; connections from fan controllers and to all field devices are made through knockouts. This panel is mounted in the SCR shed.

Pressure switches external to the panel provide panel overpressure protection and an indication to the operators through the revolving red warning light that the box is under pressure. Relays allow the E-Stop system to release power to all field control elements, including the fans and those devices controlled by other panels. Solid-state output modules convert low-level outputs generated by the control system to higher-power signals which control solenoid valves.

Circuit Description

All valves are powered by 120 VAC 60 Hz current. The panel is designed to control up to 7.8 KVA. Each subsystem is independently fused, and each output device is individually fused. A control transformer provides 24 VAC power for the E-stop logic.

The E-Stop logic is intimately connected with the Power Control Unit mounted in the control room rack. The E-Stop logic integrates an E-Stop button, master power control switches, and the panel protection and operator warning functions provided by the pressure switches. Pressure switch PS1 is intended as a secondary panel protection device. It is to be set (through the use of a calibrated pressure gauge) whenever a new panel is installed to that panel's pressure limit. If the box pressure exceeds this setting due to control system failure or freezing in the transducer lines or in valve V12, then box pressure is released through V12a. An indicator in the control room displays the status of this valve to the operator. V12 is opened and closed by a closed-loop controller; V12a is only controlled by PS2. This design protects V12a from conditions which might cause valve freezing and allows V12a to protect the panel.

Pressure switch PS2 is also ported to the box pressure and is set at 2 psi. When the box pressure exceeds this value, the switch closes and turns on the red revolving light. This light indicates to personnel working on or near the box that a hazardous condition may exist and that they should immediately leave the area. This information is also displayed in the control room.

The E-Stop system controls electromechanical relays which control power distribution to the field control elements. One relay controls the 3-way solenoid valves used to dump the air pressure for the valve pneumatic actuators, causing the proportional valves to close immediately. The LHe dewar requires overpressure protection. The controller for proportional valve V4 monitors dewar pressure and may control the 3-way solenoid valve for V4 independently through a solid-state output module.

Individual solenoid valves are powered by solid-state output modules; a contactor controlled by the VALVES switch in the E-Stop system and the VALVE MASTER switch on the Main Control Unit front panel provides power to all the output modules. Valves are switched on the hot side for safety, and each output module is individually fused. Power and control signals are provided through Amphenol 97-series connectors.

A relay under E-Stop control is intended to interface with the circuit breaker which feeds power to the radiant heater to cause it to drop power to the radiant heater. A bank of DC relays isolates the fan motors from the fan motor controllers during an E-Stop condition. This allows the E-Stop system to have ultimate control over power to the fan motors, and overrides the fan motor controllers.

Internal Heater Power Control Panel

The Cryogenic Pressure Box Internal Heater Power Control Panel distributes power to the internal heaters and to the load plate heaters. All components are mounted in a 30 in. x 36 in. x 8 in. NEMA 4 box. Control signal connections to the control room rack and to limit controller input sensors are through Amphenol 97-series circular connectors; connections to all field devices are made through knockouts. All connectors are labeled with screen-printed enamel. This panel is mounted in the SCR shed.

Circuit Description

All heaters are powered by 240 VAC 60 Hz single-phase power. The internal heaters and the load plate heaters have separate power entry points. The internal heaters require 12.5 KVA and the load plate heaters require 16 KVA. Fusing is provided for each output device and power controller. A Noren CC200 fan-cooled heat pipe heat exchanger cools the electronics without introducing airborne contaminants and humidity into the enclosure.

Each of the 12 fan heat exchangers mounted in the pressure box requires a 1 kW heater. A contactor disconnects the entire internal heater system and is controlled by a switch on the Power Control Unit and also by the E-Stop system. These heaters are controlled as a group by a Watlow QPAC power controller which receives its command from a PID controller, allowing both closed-loop and output power level control. The controller is protected by fast-acting fuses. Each internal heater is equipped with an independent LIM-100 limit controller which will prevent the fan heat exchanger from overheating in the event of a fan failure, heater failure, or other problem. The limit controllers are powered directly from the 240 VAC lines and fused as a group. These limit controllers are set at 300°F with a trimpot adjustment. Their set points cannot be controlled on-line by the control system. Silicon diode temperature sensors provides feedback input to the limit controllers. Electromechanical relays control power to the heaters. Since these heaters are 240 VAC devices, both poles are switched and fused.

There are four 4 kW load plate heaters. Another contactor disconnects all load plate heaters and is controlled through the same logic that controls the internal heater contactor. Each load plate heater is controlled independently by a Watlow DIN-a-mite power controller. Each controller is separately fused with fast-acting semiconductor protection fuses which also protect the heater circuits.

Power Control Unit

The Cryogenic Pressure Box Power Control Unit allows the operator to manually control the power for the Valve Power Control Panel and the Internal Heater Power Control Panel from the control room. It also contains the E-Stop button. This unit should not be confused with the Cryogenic Pressure Box Power Distribution Unit discussed above.

The front panel contains all indicators and switches used to control power to the control system field elements. This panel contains the following indicators and switches: BOX PRESS. > 2 PSIG, PANEL PRESS. LIMIT, VALVES, RADIANT HEATER, INTERNAL HEATERS/FANS, POWER, and EMERGENCY STOP. All switches are maintained-contact types, except for POWER. Red indicator BOX PRESS. > 2 PSIG is controlled by pressure switch PS1 and is lit whenever the pressure in the box exceeds 2 psi, indicating that access to the site is not permitted. The field-mounted revolving red light will also be lit under these conditions. Yellow indicator PANEL PRESS. LIMIT is controlled by pressure switch PS2 and indicates that PS2 has caused V12 and V12a to open due to unacceptably high pressure in the box.

Three 2-position maintained-contact rotary switches control power to the valves, the radiant heater, and the internal heaters and fans. Lights above each switch indicate that power is indeed present for these field devices. A green light is provided for the valves, and red lights for the heaters and fans. Turning the switch to the ENABLE position allows the control system to control the device. Note that the valve indicator will not be lit unless the VALVE MASTER switch on the Main Control Unit is in the AUTO position. All of these indicators and switches are subject to the actions of the POWER and EMERGENCY STOP switches discussed below.

The POWER switch powers up the field elements; the EMERGENCY STOP mushroom switch allows the operator to immediately drop power to all control elements. To prevent inadvertent initiation of an E-Stop event, this switch must be pulled out to cause an E-Stop. Pushing the EMERGENCY STOP mushroom switch in and pressing the green push button labeled POWER will enable the field elements. Note that the system may be in the powered-up state, but no elements will be powered because the three rotary switches mentioned above are in the OFF position. POWER and EMERGENCY STOP do *not* control power to the computer and the other units mounted in the control room rack; this allows continued monitoring of the state of the pressure box system during an E-Stop. The correct power-up sequence for the control system is as follows. First, power up the control room rack by pressing the green ON button on the Power Distribution Unit. Ascertain that the pressure box is in a state suitable for control by inspecting the values on the PC's screen Finally, push in the EMERGENCY STOP button, press POWER on the Power Control Unit, and place all rotary switches in the ENABLE position. The pressure box process control system is now fully on-line.

A terminal block labeled HYDRAULIC SYSTEM INTERLOCK allows an E-Stop event to signal the load control system. This is the only connection between the process control system and the load control system.

Multiplexer Unit

The Multiplexer Unit (not to be confused with the Backup Signal Multiplexer PC Board) is a rack-mounted device which allows the control system computer to address up to 16 additional input channels. Ten of these channels have 4-20 mA input modules and are currently in use; 6 are available for future expansion. Analog signals are conditioned, isolated, converted to 0-5 V range, and selected by the computer. Another 16-channel Multiplexer Unit could be built and addressed by simply daisy-chaining the connection to the Main Control Unit. No internal modifications to the control system would be necessary. The Multiplexer Unit is based on the Burr-Brown/Dataforth SCM series of analog input modules. The computer selects a channel by sending a 5-bit binary address, delaying 50 ms, and reading the analog input information back through the computer's A-to-D converter. Both digital address and analog output are routed to the computer through the Main Control Unit.

CSC-100 Cryogenic Signal Conditioner

The CSC-100 accepts inputs from silicon diode cryogenic temperature sensors and produces an amplified, isolated, and linearized 4-20 mA current loop output for use with standard temperature controllers, indicators, or data acquisition systems. It is intended to be used in industrial cryogenic temperature control applications. A standard Curve 10 diode should be used. RTDs may also be accommodated with certain modifications. Linearization is performed by a ROM look-up table, which may be modified for additional sensor types if necessary.

Circuit Description

The circuit consists of five basic sections: power distribution and conversion, input signal conditioning, digital control, digital conversion, and output signal conditioning. The input signal conditioning section is separated by a physical barrier from the rest of the board. This barrier is bridged only by a DC-to-DC converter and the signal isolation amplifier; this provides at least 500 VAC RMS isolation for the input circuitry. The signal is first scaled to a unipolar 0-10 V range and converted to a digital form. The digital signal is then used to index a look-up table. The output of the look-up table (the linearized digital signal) is converted back to analog (unipolar 0-10 V) and finally converted to a 4-20 mA output.

Regulated input power supplies of ±15 VDC are required. Filter and decoupling capacitors are liberally provided throughout the board. 5 V power for the digital logic devices is provided by an on-board linear regulator. Sensor input circuitry is completely isolated and powered by an isolated DC-DC converter. A single trimmable 10 μA constant current source or two fixed 100 μA constant current sinks are provided for sensor excitation.

Inputs are amplified by an instrumentation amplifier. Input protection and current limiting are provided. Amplifier gain is jumper-selectable over several ranges and may be trimpot-adjusted. An offset adjustment circuit provides a constant voltage which is summed by the second stage of the instrumentation amplifier. Suitable adjustment of the offset circuit will cause the output of the instrumentation amplifier to have a zero volt output when the input signal is equal to the low range input value.

A capacitively-coupled isolation amplifier provides signal isolation. The isolation amplifier adds small gain and offset errors which are trimmed by the input signal offset and gain adjustments. The isolation amplifier is the weakest link in the signal chain and limits output resolution to 12 bits. A 12-bit analog-to-digital converter (ADC) provides 0.12K resolution. The linearization tables are contained in an electrically-programmable read only memory (EPROM). Tables are provided for several different input device types and may be selected by jumper.

After linearization, a 12-bit digital-to-analog converter (DAC) returns the digital data back to analog form. In order to prevent DAC switching transients from appearing at the output, a sample-and-hold circuit (SHC) has been included which allows the output voltage generated by the previous cycle to be held for the duration of the settling time of the DAC.

All digital sequencing is based on a 64 KHz system clock which drives a modulo-16 counter. The counter states are decoded to produce the signals necessary for the ADC/DAC system. One conversion is performed every 16 counts. Digital sequence control lines which travel from the digital portion of the circuit to the analog portion are provided with guard loops to minimize radiated noise from the fast edge transitions typical of digital circuits.

Output signal conditioning is performed with a current-loop driver which performs all offsetting and scaling necessary to convert the analog signal to a 4-20 mA output. This driver is intended to operate with two-wire unpowered current loops.

ISO-100 4-20 mA Isolation

The ISO-100 accepts a 4-20 mA input and produces an isolated 4-20 mA current loop output for use with standard temperature controllers, indicators, or data acquisition systems. The card may be configured to operate with a powered two-wire input device or an unpowered two-wire input transducer which requires power from the loop.

Circuit Description

The circuit consists of four basic sections: power distribution and conversion, input signal conditioning, isolation, and output signal conditioning. Regulated input supplies of ±15 VDC are required to power the board. Filter and decoupling capacitors are provided throughout the board. The input signal conditioning section is located on the left side of the board and is separated by a physical barrier from the rest of the board which provides at least 500 VAC RMS isolation. This barrier is bridged only by a DC-to-DC converter and the signal isolation amplifier. The DC-to-DC converter, in addition to powering the input stage, may also be configured to power the input transducer by changing jumper settings.

The input device precisely converts the 4-20 mA input into a 0-5 V output. Its input is fused to protect against connection to a non-current limited source. The 0-5 VDC output drives the isolation amplifier. A current-loop driver converts the output of the isolation amplifier to a 4-20 mA current loop. This output driver is intended to operate with two-wire unpowered current loops.

LIM-100 Si Diode Limit Controller

The LIM-100 accepts inputs from silicon diode cryogenic temperature sensors, RTD's, or from voltage/current output devices. It produces two control outputs: an on-off (thermostatic) output with adjustable hysteresis and a limit control output. This device is intended to be used in industrial temperature applications in the 1.4 K to 475 K temperature range.

Circuit Description

The circuit consists of five basic sections: power supply, input signal conditioning, reference generation, level comparator, and output logic. An on-board fused linear power supply powers the circuitry directly from 115/230 VAC power. A power-on reset circuit keeps the outputs in a stable state until the power supply has settled. A single fixed 10μA constant current source or two fixed 100 μA constant current sinks are provided for sensor excitation. Inputs are amplified by an input-protected instrumentation amplifier. Amplifier gain range is jumper-selectable and may be trimmed.

The output of a precision 10 V voltage reference produces limit, setpoint, and deadband references. The setpoint reference is buffered to allow it to drive other boards in a master-slave configuration. The deadband reference tracks the setpoint.

A precision comparator and a set-reset flip-flop determines the output states based on the input temperature and the various set points. Both negative and positive temperature coefficient input sensor types and direct or indirect acting outputs are supported by the logic, which is jumper-configurable. LEDs indicate the actual output state of the flip-flop. The output devices are solid-state relays capable of driving up to a 3 A load over a voltage range of 24 to 280 VAC. Higher loads must be driven by a slaved relay.

Backup Sensor Multiplexer

The Backup Sensor Multiplexer allows a control system to switch between one of two input sensors in seven independent channels. It was specifically designed for use with standard PID controller modules and digital process meters to allow a system to automatically switch to a backup sensor if there is a failure of the primary input sensor. An unusual cyclical switching option allows switching to a neighboring sensor zone in non-critical cases where the cost of a duplicate input sensor for each channel would be excessive. Switching control may be initiated by front-panel switches or by computer control. All digital control signals are optically isolated from analog functions to prevent ground loops. LED indicator outputs allow front-panel switch state indication.

Circuit Description

The circuit consists of five basic sections: power supply, input signal conditioning, switch banks, interface logic, and control signal isolation. This device operates from a 5 VDC ±5% power supply. The analog circuit sections are powered by a DC-to-DC converter to provide isolation.

There are fourteen identical input stages which are grouped in seven channels, with each channel providing a default input and an alternate input. Each individually fused input stage converts a standard 4-20 mA current loop signal to a 0-5 VDC signal.

Solid-state CMOS switches which select between default and alternate inputs for each channel. It is not possible to switch between channels; it is only possible to switch between inputs in a channel. However, jumpers allow switching between the default input of channels 1-6 in a cyclical manner. For example, when these jumpers are in place, switching channel 4 from the default channel to a backup channel actually switches to the default input of channel 5. Channel 6 “wraps around” to channel 1 and channel 7 is independent. Digital logic interfaces front-panel switches, control lines, and switch state indicators to the CMOS switches. A power-up reset function resets all switches to the default state. In order to prevent ground loop noise, digital control signals are optically isolated.

Software

This section describes the various functions of the software encountered by the system operators. Supervisory control and data acquisition (SCADA) software for the cryogenic pressure box temperature and pressure control system is written completely in National Instruments' LabVIEW 4.1 graphical programming environment. The software runs on a PC-compatible industrial computer under Windows NT. To enhance the reliability of this configuration, the software acts as a setpoint generator only. The software performs all test sequencing functions, leaving the execution of all closed-loop control functions completely to standalone controllers. Failure of the computer, the software, or the operating system will not cause a catastrophic lack of control, since the standalone controllers will continue to maintain setpoints.

Software Organization

There are eight primary functional blocks of the software: the Process Control Panel, the Manual Operation functions, the Test Sequence Editor, the Sequencer, the Sequence State controller, the Process Value Monitor functions, the Alarm Monitor system, and System Setup functions. There is not necessarily a simple mapping between these functional blocks and the actual LabVIEW file names since many functions are heavily interrelated. The above description is useful, though, when trying to understand how the control system software works.

The control system software may operate output devices in one of two basic operational modes: manual operation and sequenced operation. Manual operations are initiated in several different ways depending on which device must be accessed. Manual operations may also be performed by using hardware switches on the control room panels or through the closed-loop controller front panels. Avoid confusion of the term “manual operations” as used here with the term “manual mode,” which refers to the operation of a (normally) closed-loop controller in an open-loop mode. The advantage to working through the computer is that the computer is immediately aware of all actions performed and will update all log files and state variables. The Message Board maintains a record of every operation performed for future analysis. Manual operations will be very useful when performing tests of the pressure box itself and whenever a problem arises in a panel test sequence. However, because of the complexity of the system it is recommended that all panel testing be performed under sequencer control.

When under sequencer control, the process control system steps through a set of procedures established previously and generates control outputs and controller setpoints automatically. The operator assembles a test sequence from a set of subsequences. Subsequences may query the operator for certain values such as setpoints or dwell times. This process of test assembly requires absolutely no knowledge of LabVIEW programming; however, a proficient LabVIEW programmer may augment the list of subsequences by following the instructions in the *Control System Software Functional Description* reference. A typical test sequence will set all control devices to some initial state, purge the pressure box and cooling lines, pressurize the box, generate setpoints to cool or heat the panel, delay while the operators perform turnbuckle adjustments, and return the system to room temperature. There is very little operator intervention required when under sequencer control. At any time the operator may initiate a **HOLD** or a **SHUTDOWN**. During **HOLD**, the operator may access any device manually, change setpoints, or even change the sequence.

The Process Control Panel is the main display and allows access to all other functions. This panel displays the current state of nearly every transducer and output device in the system in the form of a process schematic. Valve symbols are interconnected by stylized "pipes" and "pipe fittings." The valve state is represented by the color of the valve. A green-shaded valve is open, indicating that the valve may pass its working fluid; closed valves are shaded red. When a valve is opened, its interconnection pipes will change color from white. Various colors represent different working fluids: Helium is blue, liquid nitrogen is green, and service air is yellow. Note that the working fluids are assumed to flow based on the commanded valve states only. There is no feedback from the field that a specific fluid is actually flowing in a specific pipe.

To help protect the test article, the pressure box, and the control system from failures or operator errors, the alarm monitor continually checks the system state against a set of rules. When a rule is violated the alarm monitor will immediately take action to mitigate the problem, if possible, and will inform the user.

A significant segment of the software is devoted to communicating in various ways with the Watlow Series 988 PID controllers over the multidrop RS-485 network. The serial interface commands mimic the controller's front panel prompts, and therefore reading and writing to a controller involves accessing "prompts." The prompts actually available on a controller depend on the software type, the options installed in the controller, and the configuration of the controller as set by certain prompts. Attempting to access a controller prompt which is inactive will generate an error. In addition, not all active prompts may necessarily be accessed through software.

The following typefaces are used in the documentation:

Bold Italic	VI names
Arial	Control or indicator names; program labels, etc.
BOLD ARIAL	Sequencer states: **HOLD**, **RESUME**
<>	Keyboard keys are enclosed in angle brackets
" "	Messages generated by the computer are enclosed in quotation marks

Hardware issues

Although Windows NT is not known for its real-time capabilities, LabVIEW running under Windows is a highly reliable configuration. However, there are a few caveats. Because the control system and LabVIEW requires so much of the available system processing bandwidth, it is not possible to run other Windows applications while the control system is running. There are two reasons for this. First, the control system is a real-time program and requires regular access to process variables. Running another program will reduce the amount of time that Windows can allocate to LabVIEW. In addition, Windows becomes overwhelmed and will invariably crash. Therefore, observe the following warning:

WARNING:

DO NOT ATTEMPT TO START OTHER PROGRAMS WHILE THE CONTROL SYSTEM IS RUNNING.

The addition of a network card to the control system computer will also likely cause serious problems if the network is enabled while the control system is running.

MAIN.VI

This is the main program loop for the control system software. It initializes the system, interprets user selections, and shuts down the system at exit. Its front panel displays the system state in the form of a stylized flow diagram containing valves, interconnection piping, transducer inputs, and pressure vessels. This front panel always remains open; the operator is not permitted to resize or close it. Controls may be "grayed-out" and inaccessible in certain system states or at lower permission levels.

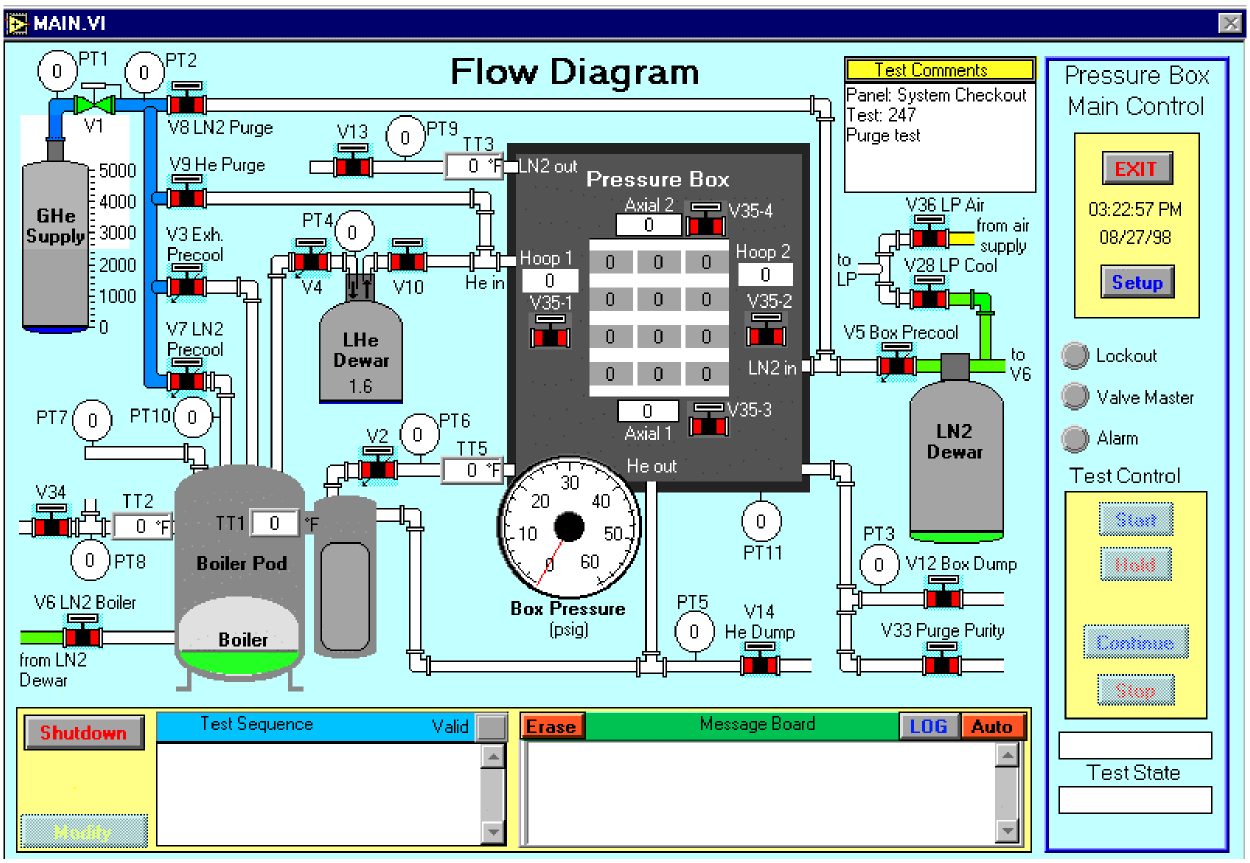

Figure 71: Main.vi front panel

Valve symbols are colored green when the valve is open and red when the valve is closed. The valve may not be operated by clicking on it with a mouse; the manual operations under Setup must be used to access a valve manually. A valve is considered open if it is in automatic mode or if it is in manual mode and not at 0%. Therefore, a valve symbol may be colored green even when the valve is off when a controller is in automatic mode. V1 is a manual valve and is always colored green for display purposes.

Flow paths are represented with stylized "pipes" and "fittings." Their color will change according to the state of the supply valves. Blue is used for helium, green for nitrogen, and yellow for service air. Pipes not containing any fluid are white. Note that the display represents the commanded valve and flow state and not the actual state. The display is intended to represent the flow logic of the current system configuration. Actual conditions must be verified through the temperature and pressure sensor displays. The pipe segments between the boiler pod and valves V3 and V7 and at the LHe dewar are exceptions. These pipes will be colored according to the valve state and the readings of PT10 and PT4, respectively, if the pressure of either reaches 3 psig.

Process values are displayed with digital displays placed on the process diagram in locations corresponding to the actual location of the transducer. Pressure transducer readings are displayed in small circles connected to the piping. Temperature sensor values appear in rectangular boxes. In addition, the GHe pressure and LN_2 and LHe dewar levels (if sensors are installed) are displayed in a tank-level format. The following process variables are displayed:

Table 13: Displayed Transducers

Designation	Range	Name	Location
PT1	0-5000 psig	GHe Supply Pressure	above GHe Supply
PT2	0-250 psig	V1 Pressure	above GHe Supply
PT3	0-100 psig	Box Pressure	below right side of Pressure Box (also in Box Pressure gauge)
PT4	0-100 psig	LP He Pressure	above LHe Dewar
PT5	0-100 psig	Fan HEX LHe Exhaust Press	below Pressure Box
PT6	0-250 psig	V2 Line Pressure	left of Pressure Box
PT7	0-100 psig	LN2 Boiler Pressure	above left side of Boiler Pod
PT8	0-100 psig	LHe Cooling Pressure	left of Boiler Pod
PT9	0-100 psig	Fan HEX LN2 Exhaust Press	left of Pressure Box
PT10	0-250 psig	V7 Line Pressure	above Boiler Pod
PT11	0-100 psig	Box Backup Pressure	below Pressure Box
TT1	-457 - 395°F	He Boiler Exh. Temp	in Boiler Pod
TT2	-457 - 395°F	LP He Vent	left of Boiler Pod
TT3	-457 - 395°F	N2 Lower Plate Temp	left of Pressure Box
TT5	-457 - 395°F	HP He Box Inlet Temp	left of Pressure Box
TT7-1-TT7-2	-328 - 395°F	Load Plate Hoop 1-2	in Pressure Box
TT7-3 - TT7-4	-328 - 395°F	Load Plate Axial 1-2	in Pressure Box
TT12-1 - TT12-12	-457 - 395°F	Fan 1 - 12 Temp	in Pressure Box:

Top row	TT10	TT11	TT12
	TT7	TT8	TT9
	TT4	TT5	TT6
Bottom row	TT1	TT2	TT3

For process values obtained from Watlow controllers, the default read interval is 1 second, although this minimum time may be stretched because of the readback loop speed. Box pressure and all other inputs are read more frequently.

Several text indicators provide status information to the operator. The Message Board contains a record of all actions performed by the software. Each message contains a time stamp which represents the time elapsed since program start or since the last test sequence was started. The user may scroll to view earlier messages by toggling the Auto control to Scroll. When this control is in Auto, the text will scroll automatically as new messages are produced. The contents of the board may be deleted with the Erase control, accessible for permission levels of 3 and above. A Test Comments textbox allows the user to enter brief notations. The Test Sequence box displays the subsequences which form a complete sequence; the Valid indicator will be colored green if the sequence has been applied and is valid. The test state and filename (if any) are displayed in the lower right-hand corner. Selecting the LOG control above the Message Board will open a file selection dialog box and write all these items to a file after the operator selects a filename. The status of the hardware alarms, the manual Lockout switch, and the manual Valve Master switch are displayed on the right side of the screen. These inputs are also monitored by the alarm monitor.

Selecting Exit will close down all systems and exit the control system. The operator must verify the exit operation before the system continues. If verified, all systems will be returned to a safe state immediately. The following valves are turned off (in this order): 2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 14, 28, 33, 34, 36, and 35-1 through 35-4. V12 is opened. The internal heaters, fans, and radiant heater are also turned off. Selecting Shutdown at the lower left-hand side of the screen will halt the sequencer, depressurize the box at the preset ramp rate, and return the system to ambient conditions using the temperature control systems to supply or remove heat from the system as necessary. This function may be used to terminate any test at any time, regardless of the test state. Although it may take some time, it should always be considered before a hard E-stop. If Shutdown is selected, the operator is asked "Do you really want to SHUTDOWN?" and must select "Yes - Shutdown" to continue. The Hold button may be used during the shutdown process. The sequence of operations performed is exactly the same as that of the ***ENDTEST.VI*** subsequence. The Setup control opens the Setup Menu, which allows the user to access test sequence setup, manual operations, the permission level panel, and configuration functions.

The sequencer controls are positioned at the right side of the screen. The system will at times "gray-out" these controls to protect the sequencer from prohibited operations. When a sequence has been created and applied, the Start control will be available. Selecting this control will cause the sequencer to begin stepping through the test sequence. After Start has been selected, it will be "grayed-out" and the Hold and Stop controls will be accessible. The time counter used by the message board will be reset to 0 so that all message times are from the beginning of the test. Selecting Hold will temporarily stop the sequencer, save all setpoints, and create new setpoints based on the current process values. In **HOLD** the Continue and Stop controls are available. Selecting Continue will reverse the process and allow the sequencer to continue executing test steps. Selecting Stop at any time will terminate the sequence, leaving the system in whatever state it was when the sequencer received the Stop command. The Modify control, located in the lower left-hand corner, may be used during a **HOLD** to modify setpoints. This control is only accessible for users with a permission level of 2 or greater.

The program start time is recorded for use by the data logging routines and the message board. All sequencer controls are disabled and "grayed-out" since no sequence can have been loaded yet.

ALARM.LLB

This library performs all hardware and software alarm functions.

AlarmMon.vi

The alarm monitor continually checks for alarm conditions caused by hardware alarms, sequencing errors, an incorrect system state, and limit conditions. In many cases the alarm monitor will take action to correct the problem. For example, the alarm monitor may close a valve or turn off heaters. In other cases the operator must take some action to correct the problem. In all cases the operator is notified that an alarm condition exists. All alarm conditions are also recorded on the message board.

The alarm monitor operates in conjunction with ***AlarmOpr.vi*** (see Figure 72) which performs the task of alerting the operator that an alarm condition has occurred. The operator must acknowledge the alarm through this panel and never encounters ***AlarmMon.vi*** directly.

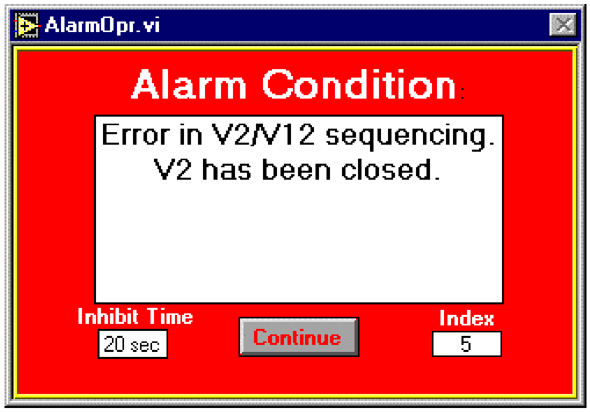

Figure 72: AlarmMon.vi front panel

The alarm monitor inhibits alarms from reoccurring within a certain time period. This time period varies among the alarm types. For example, alarms are provided for a panel temperature deviation. Correcting this problem could take a significant amount of time. Therefore, this particular alarm is inhibited for five minutes after it occurs. Without this feature the alarm would reoccur instantly as soon as it is acknowledged and become a nuisance. The inhibit time for each alarm is indicated on ***AlarmOpr.vi***'s front panel. Note that ***AlarmOpr.vi*** will respond to multiple simultaneous alarms.

Many alarm conditions are taken from the Verify Panel Limits window that automatically opens at the beginning of each execution of the control software. Others are hardwired into the code. A wide variety of conditions is checked in order to protect the test panel and system from operator error or system malfunction. The alarm monitor is expected to be most valuable whenever devices are operated in manual mode.

Alarm Conditions:
The following is a summary of alarm conditions and the action taken by the computer for each alarm:

<u>Alarm Index: 1</u>
Operator Message: LOCKOUT switch must be in the AUTO position. Please move switch to this position.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

A hardware LOCKOUT switch has been provided (on the Main Control Unit panel) so that valves may be controlled either by manual switches or by software. If the LOCKOUT switch is in MANUAL, the computer will be unable to control the solenoid valves. The switch must be in AUTO when a test sequence is in progress or during shutdown. When the operator is notified of this alarm, he must move the LOCKOUT switch to the AUTO state.

<u>Alarm Index: 2</u>
Operator Message: VALVE MASTER switch must be in the AUTO position. Please move switch to this position.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

A hardware VALVE MASTER switch has been provided so that all on-off valves may be immediately returned to their unpowered state. If this switch is in CLOSE, the computer will be unable to control the solenoid valves. The switch must be in AUTO when a test sequence is in progress or during shutdown. When the operator is notified of this alarm, he must move the VALVE MASTER switch to the AUTO state. This alarm is similar to the preceding alarm.

<u>Alarm Index: 3</u>
Operator Message: Panel Pressure Limit Exceeded. V2 has been closed. V12 has been opened.
Action: V2 closed, V12 opened, and sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

If the panel pressure as measured by pressure sensor PT3 exceeds the Panel Pressure Limit entered at startup, then the pressure must be immediately reduced. The alarm routine will automatically close V2 and open V12.

<u>Alarm Index: 4</u>
Operator Message: PT3 and PT11 do not agree. V2 has been closed. V12 has been opened.
Action: V2 closed, V12 opened, and sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

PT3 and PT11 both measure the box pressure. If their pressure values differ by greater than 5 psig then at least one transducer does not represent the pressure in the box. The alarm routine will automatically close V2 and open V12 to depressurize the box.

<u>Alarm Index: 5</u>
Operator Message: Error in V2/V12 sequencing. V2 has been closed.
Action: V2 closed and sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

Valve V2 allows gas to flow into the box. Valve V12 allows gas to flow out of the box. These valves must be sequenced according to the following four rules to maintain control of box pressure: When V2 and V12 are both in automatic mode, the setpoint of V12 must be greater than or equal to the setpoint of V2 + 1 or both setpoints must equal 0. When V2 is in automatic mode and V12 is in manual mode, V12 must be 100% open. When V2 and V12 are both in manual mode, V12 must be 100% open if V2 is not completely closed. When V2 is in manual mode and V12 is in automatic mode, V2 must be open less than 5%. This alarm is not likely to occur during automatic sequencing since the above rules are programmed into the sequencing operations. It is most likely to occur when the operator attempts to set V2 or V12 directly.

<u>Alarm Index: 6</u>
Operator Message: Error in V4/V10 sequencing. V4 has been closed.
Action: V4 closed and sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

Valve V4 pressurizes the liquid helium dewar. Valve V10 shuts off the dewar outlet and isolates the dewar from the pressure box heat exchanger coils. These valves must be sequenced according to the following two rules to prevent overpressuring the dewar: When V4 is in automatic mode, V10 must be open. When V4 is in manual mode and not closed, V10 must be open. Since opening V10 could pressurize the dewar with purge gas if V9 is open, V4 is closed.

<u>Alarm Index: 7</u>
Operator Message: LHe dewar pressure exceeded 10 psig. V4 has been closed. It will be reopened if pressure drops below 8 psig.
Action: V4 closed
Inhibit Time: 30 sec

When the LHe dewar pressure exceeds 10 psig, then V4 must be closed. If the pressure drops below 8 psig, then V4 is reopened by the alarm monitor. This is the only case in which the software alarm routine takes restorative action of this kind. This function is also implemented in hardware. The operator is not required to acknowledge the restoration of V4, although this action is written to the message board.

<u>Alarm Index: 8</u>
Operator Message: Panel temperature deviation error due to heat leak or sensor failure. Correct problem.
Action: none
Inhibit Time: 5 min

The panel temperature is read by 12 sensors. The maximum and minimum values are computed each time the sensors are read. If the difference of these values is greater than the Max. Panel Deviation Temp. Alarm limit entered at startup then the operator is alerted.

<u>Alarm Index: 9</u>
Operator Message: Panel temperature is out of range.
Action: Sequencer halted (if running). If high alarm, all heaters are turned off, V13 is opened, and V5 is set to 60°F.
Inhibit Time: 2 min

The maximum and minimum panel temperatures are computed each time the panel temperature sensors are read. If the maximum panel temperature is greater than the Temp High Alarm limit or the minimum panel temperature is less than the Temp Low Alarm limit, this alarm occurs. Both limit values are entered at startup. In the first case, both internal and external heaters are immediately turned off (if on) and LN_2 cooling is enabled through V5. In both cases, the sequencer is placed in **HOLD**. No additional action is taken in the second case. The operator must manually restore V5 to its original state after the panel has cooled sufficiently.

<u>Alarm Index: 10</u>
Operator Message: Error in V8/V13 sequencing. V13 has been opened.
Action: V13 opened
Inhibit Time: 20 sec

When V8 is open, V13 must be open to vent pressure. If this alarm occurs, V13 is simply opened since there is no potential conflict with any other valve.

<u>Alarm Index: 11</u>
Operator Message: Error in V9/V10 sequencing. V9 has been closed.
Action: V9 closed
Inhibit Time: 20 sec

If V9 and V10 are both open the LHe dewar will be exposed to the purge supply pressure. The alarm routine will immediately close V9 if this condition is true.

<u>Alarm Index: 12</u>
Operator Message: Error in V5/V13 sequencing. V13 has been opened.
Action: V13 opened
Inhibit Time: 20 sec

When V5 is in automatic mode or when V5 is in manual mode and not closed, V13 must be open. If this alarm occurs, V13 is simply opened since there is no potential conflict with any other valve.

<u>Alarm Index: 13</u>
Operator Message: Error in V5/V8 sequencing. V8 has been closed.
Action: V8 closed
Inhibit Time: 20 sec

When V5 is in automatic mode or when V5 is in manual mode and not closed, V8 must be closed. The alarm routine will immediately close V8 if this alarm occurs. This function is also implemented in hardware via V5's limit switches.

<u>Alarm Index: 14</u>
Operator Message: Sequencing error: V28 and V36 have been closed.
Action: V28 and V36 closed
Inhibit Time: 20 sec

V28 and V36 must never be open simultaneously. Also, V36 and V28 must be closed if V35-1 through V35-4 are closed. Alarm routine will close both valves if either of these conditions are true.

Alarm Index: 15-26
Operator Message: Fan zone [$1 \leq x \leq 12$] hardware alarm
Action: Sequencer placed in **HOLD** (if running); if high alarm, internal and external heaters are turned off
Inhibit Time: 5 min

This is a hardware alarm triggered by the closed-loop fan motor controllers. It may be caused by too high a panel temperature, too low a panel temperature, a sensor failure on the panel, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution.

Alarm Index: 27-30
Operator Message: [Hoop 1, Hoop 2, Axial 1, Axial 2] load plate hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 5 min

This is a hardware alarm triggered by the closed-loop load plate temperature controllers. It may be caused by too high a load plate temperature, too low a load plate temperature, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution.

Alarm Index: 31
Operator Message: PT3 (V12) hardware alarm. V2 closed. V12 opened.
Action: V2 closed, V12 opened, sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

This is a hardware alarm triggered by the closed-loop controller for valve V12. It may be caused by a box pressure that is too high, a box pressure that is too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution. Since the controllers for V2 and V12 use the same input channel, both this alarm and the next are likely to occur simultaneously.

Alarm Index: 32
Operator Message: PT3 (V2) hardware alarm. V2 closed. V12 opened.
Action: V2 closed, V12 opened, sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

This is a hardware alarm triggered by the closed-loop controller for valve V2. It may be caused by a box pressure that is too high, a box pressure that is too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution. Since the controllers for V2 and V12 use the same input channel, both this alarm and the previous alarm are likely to occur simultaneously.

Alarm Index: 33
Operator Message: TT11 (V4) hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

This is a hardware alarm triggered by the closed-loop controller for valve V4. It may be caused by a temperature that is too high or too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution.

Alarm Index: 34
Operator Message: TT2 (V3) hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

This is a hardware alarm triggered by the closed-loop controller for valve V3. It may be caused by a temperature that is too high or too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution. Since the controllers for V3 and V7 use the same input channel, both this alarm and the next are likely to occur simultaneously.

Alarm Index: 35
Operator Message: TT2 (V7) hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

This is a hardware alarm triggered by the closed-loop controller for valve V7. It may be caused by a temperature that is too high or too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution. Since the controllers for V3 and V7 use the same input channel, both this alarm and the previous alarm are likely to occur simultaneously.

Alarm Index: 36
Operator Message: TT9 (V5) hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

This is a hardware alarm triggered by the closed-loop controller for valve V5. It may be caused by a temperature that is too high or too low, a sensor failure, a failure in the signal conditioning circuitry, or a controller failure. The operator must check the system state to determine the exact cause and solution.

Alarm Index: 37
Operator Message: TT6 (Internal heaters) hardware alarm.
Action: Internal heaters turned off (if high alarm) and sequencer placed in **HOLD** (if running)
Inhibit Time: 2 min

This is a hardware alarm triggered by the closed-loop controller for the internal heaters. It may be caused by a temperature that is too high or too low, a sensor failure, a failure in the input channel, or a controller failure. The operator must check the system state to determine the exact cause and solution.

Alarm Index: 38
Operator Message: Unknown hardware alarm.
Action: Sequencer placed in **HOLD** (if running)
Inhibit Time: 20 sec

This is a hardware alarm typically caused by a disconnected cable at the back of the control room rack. Only disconnected D-sub interconnection cables will produce this alarm; disconnected signal cables must be detected by other means. If a controller alarms and the condition is corrected before software has a chance to query the controllers, this alarm will also occur since the source of the alarm is unknown. This alarm may also occur if the operator accesses the front panel of a controller during a network read/write of that controller.

AlarmOpr.vi

This VI alerts the operator that an alarm condition has occurred and waits for the operator to acknowledge the alarm by pressing Continue. A message indicating specific details about the alarm is displayed. The Inhibit Time message indicates the time that will have to elapse since this alarm was first discovered before it can reoccur. The various alarms are explained above under "Alarm Conditions." Refer to Figure 72 and the description under ***AlarmMon.vi***.

Limits.vi

Limits.vi allows the operator to enter values for important setpoint limits and alarm values. Setpoints generated by subsequences or by the manual control VI's are checked against the setpoint limits entered here before being written to the controllers. Alarm values are used by the alarm monitor and the internal alarm generation logic of the Watlow controllers. This VI also reads important alarm values from the Watlow controllers and checks the validity and consistency of the alarm system.

This VI automatically opens at startup just after the permission level is determined. It is also available from the Setup menu. If the operator has a permission level greater than or equal to 2, values may be written to the system. Values stored in the controllers are read and then displayed on the front panel. If alarm values currently stored in the Watlow controllers differ from the alarm values displayed on the screen, the following message is displayed: "Warning: Inconsistent Limits!". The operator must then write correct values to the controllers.

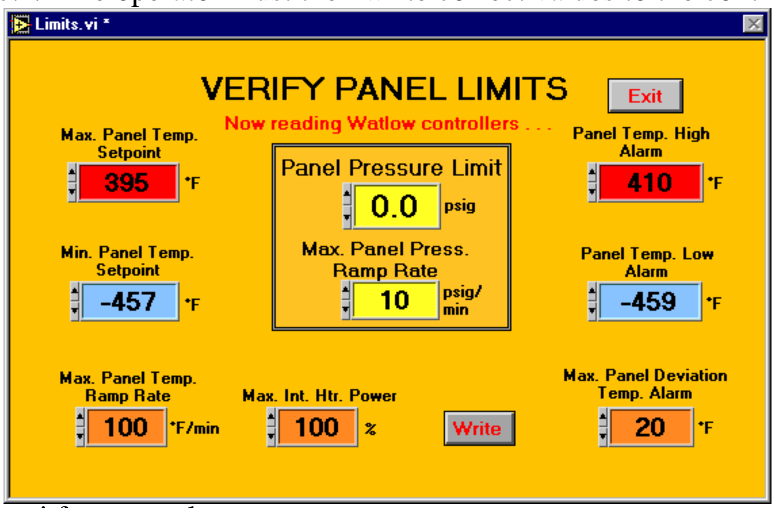

Figure 73: Limits.vi front panel

The limits, their ranges, and their default values are indicated below:

Panel Pressure Limit — Maximum allowable pressure setpoint that software will write to controllers for V2 and V12. Exceeding this limit will also generate overpressure alarms. (0 ≤ psi ≤ 53; default = 0 psig)

Max. Panel Press. Ramp Rate — Maximum allowable ramp rate for box pressure controllers V2 and V12. If 0, ramp rate stored in controller is used. If greater than 9,999, ramping is turned off. (0 ≤ psig/min ≤ 10,000; default = 10 psig/min)

Max. Panel Temp. Setpoint — Maximum allowable setpoint that software will write to the fan and internal heater controllers. (-457 ≤ °F ≤ 395; default = 395°F)

Min. Panel Temp. Setpoint — Minimum allowable setpoint that software will write to the fan and internal heater controllers. (-457 ≤ °F ≤ 395; default = 0°F)

Max. Panel Temp. Ramp Rate — Maximum allowable ramp rate for fan temperature controllers when operated in ramping mode. If 0, ramp rate stored in controller is used. If greater than 9,999, ramping is turned off. (0 ≤ °F/min ≤ 10,000; default = 0°F)

Max. Int. Htr. Power — Maximum output power level allowed for internal heaters in percent. (0 < % < 100; default = 90%)

Panel Temp. High Alarm — A temperature at any point on the panel higher than this value will cause an alarm. The radiant heater is exempt from this alarm limit. (-457 ≤ °F ≤ 410; default = 0°F)

Panel Temp. Low Alarm — A temperature at any point on the panel lower that this value will cause an alarm. (-458 ≤ °F ≤ 410; default = -459°F)

Max. Panel Deviation Temp. Alarm — A panel temperature deviation greater than this value will cause an alarm. (0 ≤ °F ≤ 1,000; default = 20)

If an out-of-range value is entered, it is coerced to the nearest value which is within range, except for the Panel Pressure Limit, Panel Temp. High Alarm, Max. Panel Temp. Setpoint, Panel Pressure Limit, and Max. Panel Press. Ramp Rate. These values are always coerced to 0 if an out-of-range value is entered to protect the panel and pressure box system.

After the values have been entered and verified, the operator selects Write to write all limits and alarm values to the system. For permission levels less than 2, Write is grayed-out; selecting Exit exits without writing. The current alarm values and messages indicating whether or not they were changed or are in error are posted to the message board.

COOLDOWN.LLB

This library contains subsequences for cooling the system using LN_2 and LHe.

BoxPCool.vi

This subsequence VI causes LN_2 to flow through the fan heat exchangers. V13 and V5 are opened and the fans are turned on.

User-entered parameters:
Box Precool Setpoint — default = -320°F

Hard-coded parameters:
none

The following steps are performed:

1. Write “Starting box precool…” to message board.
2. Open V13.
3. Write Box Precool Setpoint to controller for V5.
4. Write Box Precool Setpoint to fan controllers and set to cool mode.
5. Write “Box precool initiated” to message board.

GHePCool.vi

This subsequence VI writes setpoints for V3 and V7 to their controllers.

User-entered parameters:
GHe Precool Setpoint — default = -300°F

Hard-coded parameters:
none

The following steps are performed:

1. Write “Starting GHe precool” to message board.
2. Write GHe Precool Setpoint to controller for V3.

3. Write GHe Precool Setpoint to controller for V7.
4. Write “GHe precool initiated” to message board.

LHe_Cool.vi

This subsequence VI performs LHe cooling. The box is assumed to already be at LN_2 temperatures.

User-entered parameters:

Temperature Setpoint	default = -400°F
Tolerance	default = 10°F
LN2 Purge Dwell Time	default = 4.0 min
LIS Temperature	default = -300°F
V3, V7 Setpoint	default = -300°F

Hard-coded parameters:
none

The following steps are performed:
1. Write "Starting LHe cooling, SP = *x* °F" to message board.
2. Close V5.
3. Write Temperature Setpoint to fans and set to Cool mode.
4. Run ***LN2Purge.vi.***
5. Call ***LIS_Cool.vi*** with LIS Temperature as setpoint.
6. Call ***GHePCool.vi*** with V3, V7 Setpoint as setpoint.
7. Call ***LHe_flow.vi*** with Temperature Setpoint as setpoint.
8. Wait until load plates and box are at specified temperatures.
9. Write "LHe cooling complete." to message board.

LHe_flow.vi

This subsequence pressurizes the LHe dewar through V4 and allows LHe to flow through V10. V4 controls the flow based on V4 Temp Setpoint and the temperature at TT11.

User-entered parameters:
V4 Temp. Setpoint default = -400°F

Hard-coded parameters:
none

The following steps are performed:
1. Write "Starting LHe flow..." to message board.
2. Open V10.
3. Write V4 Temp. Setpoint to controller for V4.
4. Write "LHe flow initiated." to message board.

LIS_Cool.vi

This subsequence VI starts the flow of LN_2 through the load introduction plate cooling traces.

User-entered parameters:
LIS Setpoint default = -300°F

Hard-coded parameters:

none

The following steps are performed:
1. Write "Starting LIS cooling; SP = *x* °F" to message board.
2. Close V36.
3. Write LIS Setpoint to controllers for V35-1 through V35-4.
4. Open V28.
5. Write "LIS cooling initiated." to message board.

LN2_Cool.vi

This VI performs box cooling to LN_2 temperatures. It takes care of the load plates and the GHe precooling system. If the box temperature is already below -340°F then no action is taken.

User-entered parameters:

Temperature Setpoint	default = -300°F
Tolerance	default = 10°F
Pressure	default = 5.0 psig
LIS Setpoint	default = -300°F
V3,V7 Setpoint	default = -300°F

Hard-coded parameters:

LN_2 cooling limiting temperature	default = -340°F

The following steps are performed:
1. Open V6
2. Pressurize box to Pressure
3. Call ***LIS_Cool.vi*** with LIS Setpoint as setpoint
4. Call ***BoxPCool.vi*** with Temperature Setpoint as setpoint
5. Call ***GHePCool.vi*** with V3,V7 Setpoint as setpoint
6. Wait until load plates and box are at specified temperature.

LN2_flow.vi

This subsequence allows LN_2 to flow through V5 based on the specified setpoint and the feedback temperature from TT9.

User-entered parameters:

V5 Temp. Setpoint	default = -300°F

Hard-coded parameters:
none

The following steps are performed:
1. Write "Starting LN2 flow..." to message board.
2. Open V13.
3. Close V8.
4. Write V5 Temp. Setpoint to V5.
5. Write "LN2 flow initiated." to message board.

HOLD.LLB

This library contains VI’s which set and restore controller setpoints during a **HOLD** or **RESUME** operation.

HoldRes.vi

When the system is placed in the **HOLD** state all closed-loop controllers must maintain temperatures and pressures at their current values. ***HoldRes.vi*** is called by ***MAIN.VI*** whenever Hold or Continue is selected and changes the action of the closed-loop controllers to reflect the current system state. Note that the **HOLD** state is not at all the same as the **SHUTDOWN** state; in **HOLD**, controllers will continue to control valves and heaters, whereas in **SHUTDOWN** every device is returned to its unpowered state in an orderly manner but as quickly as possible.

When used to change from a **RUN** or **SHUTDOWN** state to a **HOLD** state, this VI stores the current setpoints and modes from the closed-loop controllers and reads and stores the states of the solenoid valves for future use. It then generates new setpoints based on current temperatures and pressures and writes the new setpoints to the controllers so that they maintain the system at the current state. No solenoid valve states are changed. If a controller is in manual mode, no setpoint change occurs.

For the fan controllers the average of the panel temperature zones is computed, ignoring the highest and lowest temperatures, and the current setpoint is set to this average. **HOLD** may therefore be used to equalize the panel temperatures if one part of the panel lags behind another part. If at least one fan is in manual mode, each manual fan is left unchanged and a new setpoint is generated independently for each automatic mode fan based on its current temperature. The load plate temperatures are not averaged; the setpoint of each load plate controller is set to the current temperature of that load plate. For all temperature controllers, if the current temperature is within 5°F of the setpoint, the setpoint is not changed. The same scenario holds for the pressure controllers with the exception that the tolerance is ±1 psi. All sequencing rules and setpoint limits are observed. For example, the new setpoint for V12 is determined by adding 1 to V2's setpoint. Hold will *not* write a setpoint to a controller which violates the alarm or setpoint limits. At the end of the **HOLD** operation the system will be in a state where all setpoints and feedback values correspond as nearly as possible.

No setpoint generation and modification is performed for V3 and V7. Their status during a **HOLD** should remain the same as their status just before the **HOLD**.

HoldRes.vi is also used to **RESUME** the test after a **HOLD** when Continue is selected. All solenoid valves are set to the state stored when the system was placed in **HOLD** and all controller setpoints and modes are restored. Again, sequencing rules and setpoint limits are observed. Note that the restored values may be accessed through the front panel MODIFY button during **HOLD** if it is desired to change the test setpoints. Even though not all controller states were changed during **HOLD**, all controllers and solenoid valves are written during **RESUME** since the current state of the controllers may have been changed manually or the modify routine may have been used to change the stored control values. At the end of the **RESUME** operation the system will progress through the remainder of the test sequence or **SHUTDOWN** operation.

modify.vi

This VI allows the operator to modify setpoints and valve states manually while in **HOLD**. Changing setpoints and valve states manually while the sequencer is running may not be practical for several reasons. However, if the operator places the system in **HOLD** and then changes setpoints, valve states, etc, using the manual routines accessible under the Setup menu, these changes will be lost when the sequence is resumed since ***HoldRes.vi*** writes setpoints stored at the initiation of a **HOLD** state back to the controllers. This VI may only be called when the system is in a **HOLD** state, and writes its values to the **HOLD** system. Therefore, the new process state will be written to the controllers and solenoid valves when the sequence is resumed.

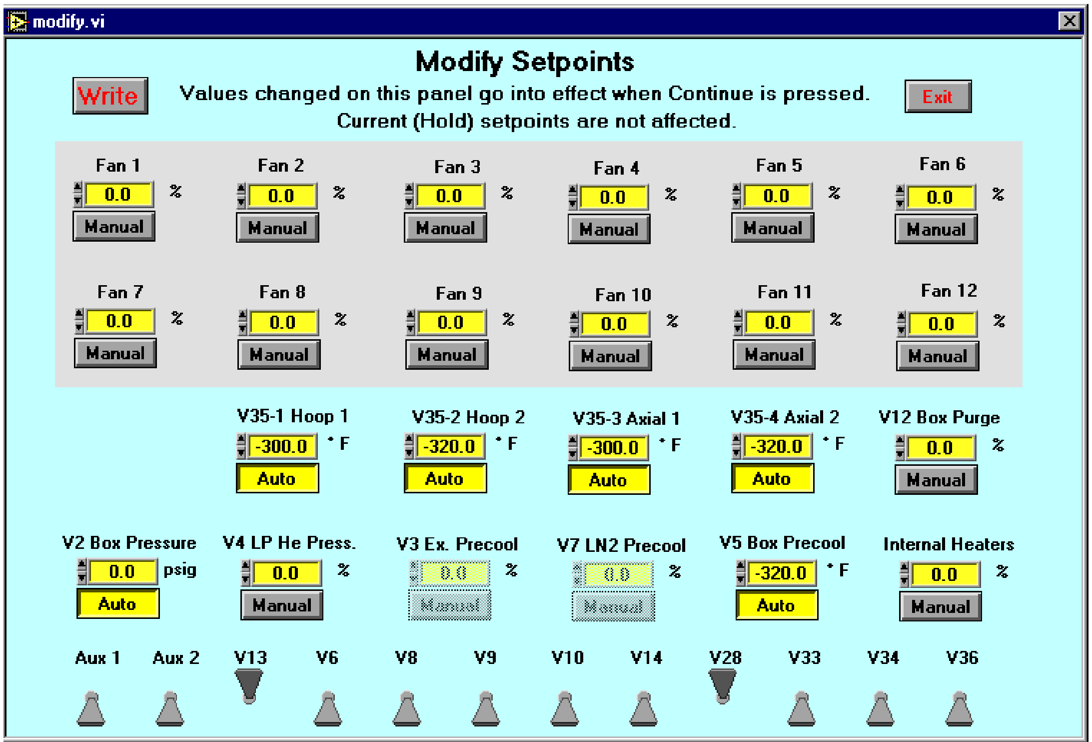

Figure 74: modify.vi front panel

After the ***modify.vi*** front panel has been opened, the mode and setpoint of all controllers and the solenoid valve states may be modified. To write these values to the **HOLD** system, select Write

MANUAL.LLB

These VI's allow the operator to manually modify the state of the valves, heaters, and fans.

BoxPress.vi

BoxPress.vi allows the operator to manually control the following valves specifically associated with pressurizing the box: V2, V12, V3, and V7. Each valve has the following controls: Set, New setpoint, Auto, Manual, Open, and Close. The following information is displayed for each valve: setpoint, feedback transducer values, controller mode, and valve status. The current controller setpoint is displayed in setpoint. Setpoint units displayed depend on the current mode. When a controller is in manual mode, the units will always be %. In automatic mode, the units will be psig or °F depending on the valve. A gauge indicator also displays the current box pressure.

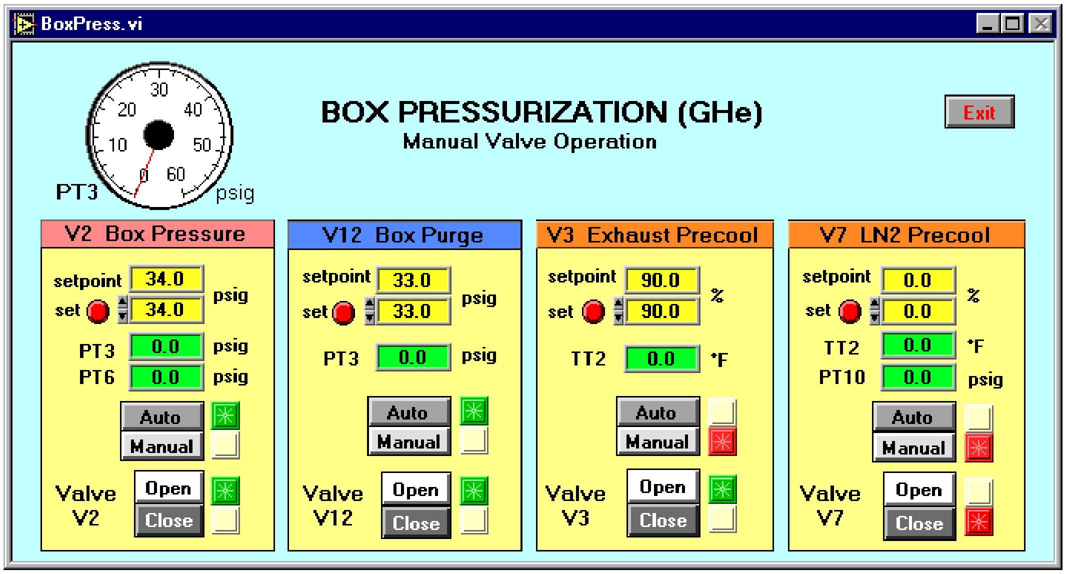

Figure 75: BoxPress.vi front panel.

Table 14: Allowable Manual Setpoints

Valve	Auto mode setpoint	Manual mode setpoint
V2	0 ≤ x ≤ 53	0 ≤ x ≤ 100
V12	0 ≤ x ≤ 54	-100 ≤ x ≤ 0
V3	-457 ≤ x ≤ 395	-457 ≤ x ≤ 395
V7	-457 ≤ x ≤ 395	-100 ≤ x ≤ 0

To open a valve 100% select Open. To close a valve (open 0%) select Close. To change to automatic mode select Auto. To change to manual mode select Manual. To change the setpoint, enter a new value to the right of the red set control and select set. Values out of the range of valid setpoints will not be written to the controllers. Pressing Exit will close the front panel and return to the setup menu. Note that if valve settings are changed manually with this VI during a **HOLD**, then they will be overwritten when Continue is selected. All manual valve operations write an indication to the message board of the action performed.

FAN_manual.vi

FAN_manual.vi allows the operator manual control over the fan motor speed. The following controls are provided: Set, setpoint, Stop, Read, Heat, Cool, Manual, and Auto. The following information is displayed for each fan: output action, mode, setpoints, and feedback temperature. In addition, the panel maximum, minimum, and deviation temperatures are summarized. The selection list allows one, several, or all twelve controllers to be written with the same command. The most common situation, and the default, is for all controllers to be written with the same command. To command the controllers to a new setpoint, first set the mode to Manual or Auto, select the setpoint, and select the Set control. In manual mode values from 0% to 100% may be entered, representing the motor speed from about 200 rpm to 2500 rpm. Note that the maximum motor speed may be limited by the global variable Max Fan Output %. In automatic mode the controller will modulate the fan speed based on the current setpoint and the panel temperature in the relevant zone. Pressing Read will read all displayed parameters from the controllers and copy them into globals except for setpoints. Because the controllers return the current setpoint rather than the final setpoint during ramping, setpoints are not updated in globals.

Because the fans are used both to heat the panel and cool the panel, this VI also allows the caller to set the controller output action. In heat mode, indirect action is used. This means that as the feedback temperature increases, the output power is reduced. In cool mode, direct action increases the output command as the feedback temperature rises. The Watlow controllers expect manual input commands from 0 to 100% in heat mode and 0% to -100% in cool mode. This VI automatically uses the correct sign depending on the current output action. Note that changing the output action using the Cool or Heat controls will turn off the controller output and require the desired output command to be rewritten.

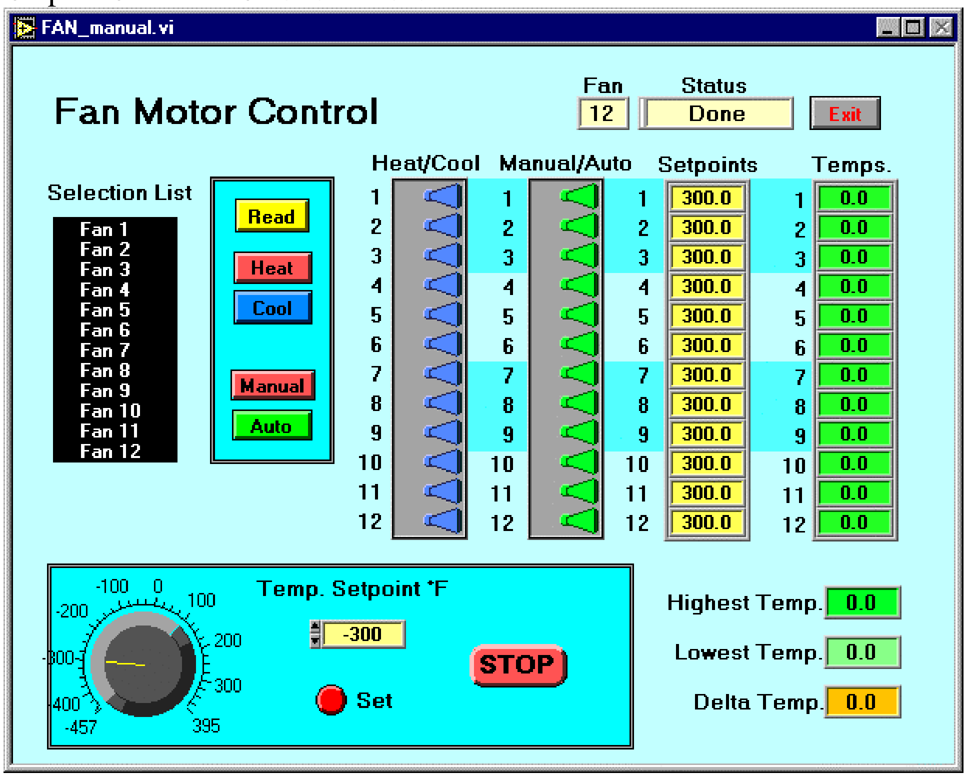

Figure 76: FAN_manual.vi front panel

IH_manual.vi

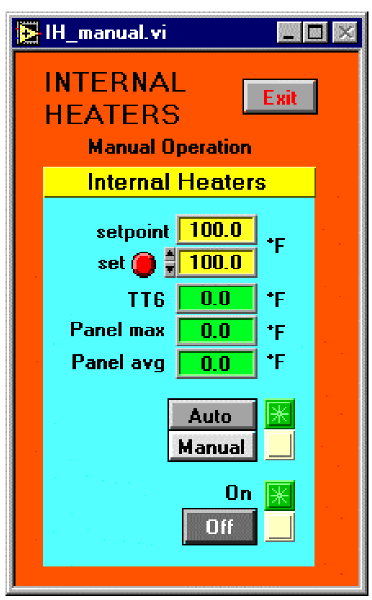

Figure 77: IH_manual.vi front panel

IH_manual.vi allows the operator to manually control the 12 internal heaters as a group. The following controls are provided: Set, New setpoint, Auto, Manual, and Off. The following information is displayed: setpoint, controller mode, heater status, average panel temperature, current maximum panel temperature, and the temperature at feedback transducer TT6. The current controller setpoint is displayed in setpoint. When a controller is in manual mode, the setpoint represents percent power; in automatic mode, the setpoint represents °F.

To turn off the heaters select Off. To change to automatic mode select Auto. To change to manual mode select Manual. To change the setpoint, enter a new value to the right of the red set control and select set. Values out of the range of valid setpoints will not be written to the controllers. Pressing Exit will close the front panel and return to the setup menu. Note that if heater settings are changed manually with this VI during a **HOLD**, then they will be overwritten when Continue is selected. Manual heater operations write an indication to the message board of the action performed.

LHe_manual.vi

LHe_manual.vi allows the operator to manually control the following valves specifically associated with liquid helium cooling: V4, V9, V10, V14, and V34. Proportional valve V4 has the following controls: Set, New setpoint, Auto, Manual, Open, and Close. The following information is displayed for V4: setpoints, feedback transducer values, controller mode, and valve status. The current controller setpoint is displayed in setpoint. Setpoint units displayed depend on the current mode. When the controller is in manual mode, the units will always be %. In automatic mode, the units will be °F. Valves V9, V10, V14, and V34 are solenoid valves and may be only open or closed. Only Open and Close controls and valve status indicators are provided for these valves.

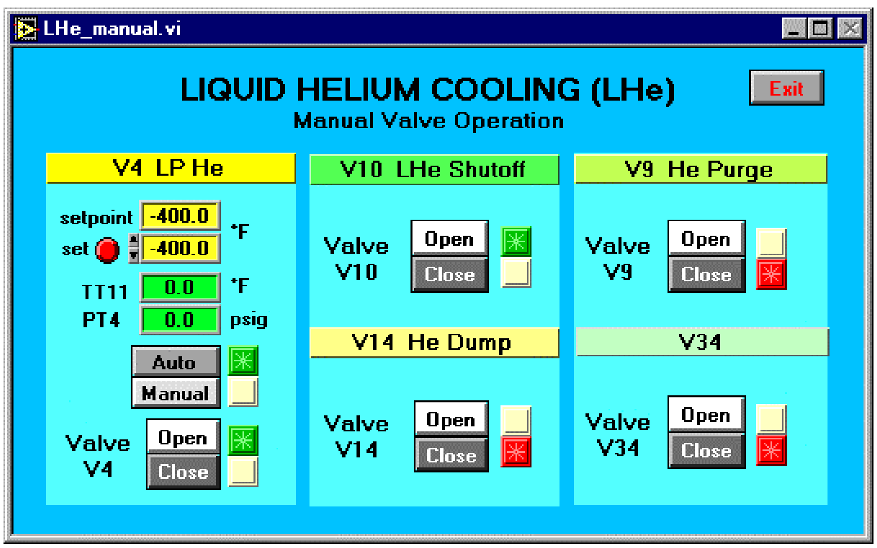

Figure 78: LHe_manual.vi front panel

To open a valve 100% select Open. To close a valve (open 0%) select Close. To set V4 to automatic mode select Auto. To change V4 to manual mode select Manual. To change the setpoint for V4, enter a new value to the right of the red set control and select set. Values out of the range of valid setpoints will not be written to the controller. Pressing Exit will close the front panel and return to the setup menu. Note that if valve settings are changed manually with this VI during a **HOLD**, then they will be overwritten when Continue is selected. All manual valve operations write an indication to the message board of the action performed.

LN2_manual.vi

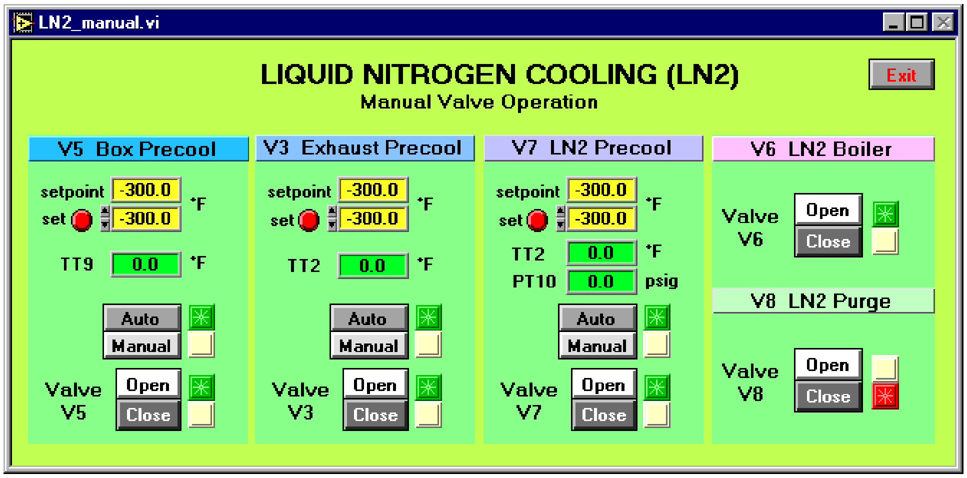

Figure 79: LN2_manual front panel

LN2_manual.vi allows the operator to manually control the following valves specifically associated with liquid nitrogen cooling: V5, V3, V7, V6, and V8. Valves V5, V3, and V7 are proportional valves controlled by a feedback controller; V6 and V8 are solenoid valves. Each proportional valve has the following controls: Set, New setpoint, Auto, Manual, Open, and Close. The following information is displayed for each valve: setpoints, feedback transducer values, controller mode, and valve status. The current controller setpoint is displayed in setpoint. Setpoint units displayed depend on the current mode. When a controller is in manual mode, the units will always be %. In automatic mode, the units will be °F. For solenoid valves, only Open and Close controls and valve status indicators are provided.

To open a valve 100% select Open. To close a valve (open 0%) select Close. For proportional valves, to change to automatic mode select Auto and to change to manual mode select Manual. To change the setpoint for a proportional valve, enter a new value to the right of the red set control and select set. Values out of the range of valid setpoints will not be written to the controllers. Pressing Exit will close the front panel and return to the setup menu. Note that if valve settings are changed manually with this VI during a **HOLD**, then they will be overwritten when Continue is selected. All manual valve operations write an indication to the message board of the action performed.

LP_manual.vi

LP_manual.vi allows the operator to manually control load introduction plate valves V35-1, V35-2, V35-3, and V35-4; all four load introduction plate heaters; and solenoid valves V28 and V36. Valves V35-1 through V35-4 and the heaters are controlled by dual-output feedback controllers. Each load introduction plate has the following controls: Set, New setpoint, Auto, Manual, Open, and Close. The following information is displayed for each load introduction plate: setpoint, feedback transducer values (TT7-1 through TT7-4), controller mode, and valve status. The current controller setpoint is displayed in setpoint. Setpoint units displayed depend on the current mode. When a controller is in manual mode, the units will always be %. In automatic mode, the units will be °F.

To open a valve 100% select Open. To close a valve (open 0%) select Close. To change to automatic mode select Auto. To change to manual mode select Manual. To change the setpoint, enter a new value to the right of the red set control and select set. Values out of the range of valid setpoints will not be written to the controllers. When in manual mode a setpoint less than 0% will cause the valves to open. At -100% the valve will be fully open; between -100% and 0% the valve will be time-proportioned. Values greater than 0% will cause the heater to turn on; the heater is fully proportional and commands correspond to output power levels.

The Master/Slave Mode boolean control allows all load plates to be operated as a group. When in Master/Slave mode, the controls for the Hoop 2, Axial 1, and Axial 2 load plates are grayed-out and inaccessible and the label "V35-1 Hoop 1" will change to "Load Plates." All operations performed at the left side of the panel under "Load Plates" will be performed for each load plate controller.

Valves V28 and V36 may be opened and closed by the V28 Open, Shutoff, and V36 Open controls. Control logic is configured so that V28 and V36 can never be open simultaneously. Pressing Exit will close the front panel and return to the setup menu. Note that if valve settings are changed manually with this VI during a **HOLD**, then they will be overwritten when Continue is selected. All manual valve operations write an indication to the message board of the action performed.

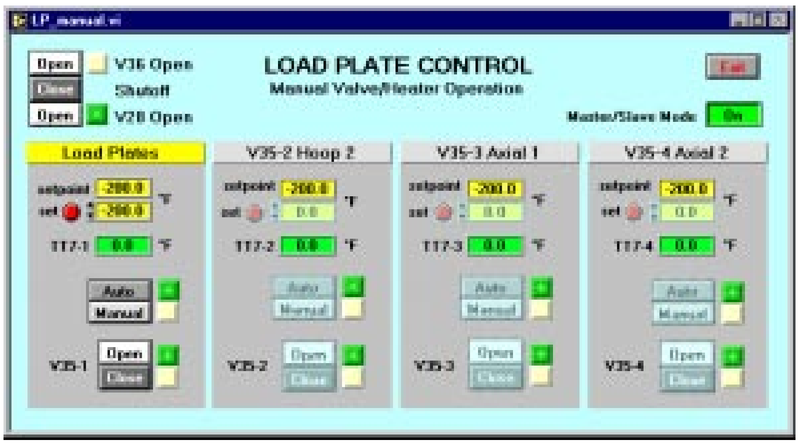

Figure 80: LP_manual.vi front panel

OPERATE.LLB

This library contains miscellaneous functions which are critical to the operation of the closed-loop controllers and the analog/digital I/O card.

FANREAD.vi

FANREAD.vi reads process values and setpoints from panel temperature zone fan motor controllers, updates the global variables in ***Globals.vi***, and graphs the panel temperature. ***MainRead.vi*** reads valve and heater controller data. This VI runs as an infinite loop and is loaded and run by ***MAIN.VI***. This function is critical to the proper operation of the program.

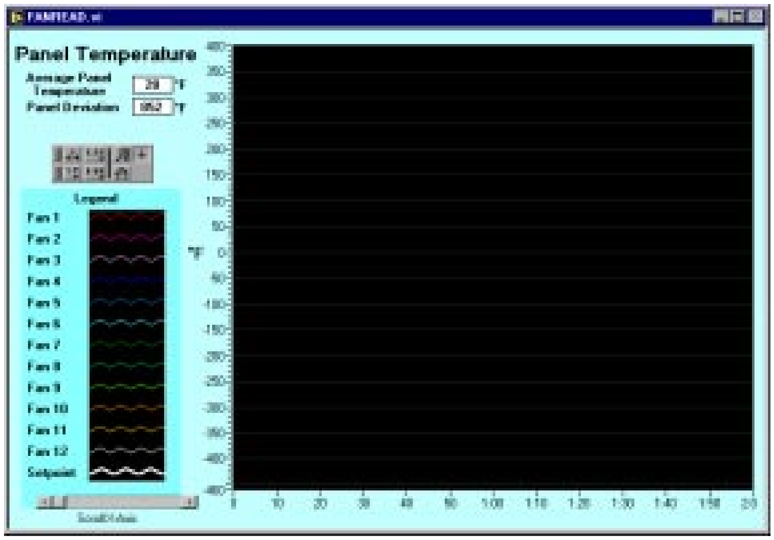

Figure 81: FANREAD.vi front panel

For setpoints, output action, and modes, the read interval is 120 seconds; for feedback temperatures, global Fan Time specifies the read interval (5 seconds). However, setpoint and output action readback is disabled by default. This is an unfortunate consequence of the use of ramping with the controllers. When a controller is in ramping mode, the setpoint returned is the current (incremental) setpoint instead of the final setpoint. For example, if the setpoint is changed from 60 to -300 with ramping set to 60 units/minute, at 1 minute the returned setpoint will be 0, at 2 minutes the returned setpoint will be -60, and so on.

The global boolean Poll Controllers prevents controller reads from taking place. It is primarily used to speed up the **HOLD/RESUME** operation. If Poll Controllers is `True`, controller values are read. Otherwise, no action is performed. At program startup, the values in ***Globals.vi*** are in an undefined state. An occurrence event is triggered as soon as ALL values (including setpoints and output actions) have been read once. The alarm monitor will not use any data in ***Globals.vi*** until the occurrence event is triggered.

A front panel chart plots panel temperature data. Each panel zone is represented by a unique color. The panel setpoint is plotted in white. If the setpoints are not all equal, then the setpoint average is plotted and a Setpoint Variation indicator is displayed. As time progresses, the chart scrolls. The operator may scroll the chart back in time, modify the x and y axis scaling, and zoom in or out.

tempavg.vi

This VI determines a value for the nominal panel temperature as measured by the Si diode fan motor control feedback sensors. It first obtains an average of all 12 temperatures. If the maximum temperature is greater than the average by the value of Max. Permitted Deviation, then the average is recomputed while ignoring this maximum value. If the minimum temperature is less than the average by the value of Max. Permitted Deviation, then the average is recomputed while ignoring this minimum. If both maximum and minimum values deviate, then the average is recomputed while ignoring both maximum and minimum values. The minimum and maximum values are passed through for use by other routines. This routine is able to produce a meaningful average even with the total failure of one or two temperature sensors. Max. Permitted Deviation is taken directly from the Max. Panel Deviation Temp. Alarm value entered at startup. Panel warm side temperatures are not considered by this function.

ValveOC.vi

This VI allows normal control of any valve. Although proportional valves V2-V5, and V7 are supported, they may only be opened or closed; intermediate valve positions are not available. Use other manual control VI's to access proportional valves if intermediate positions are requested.

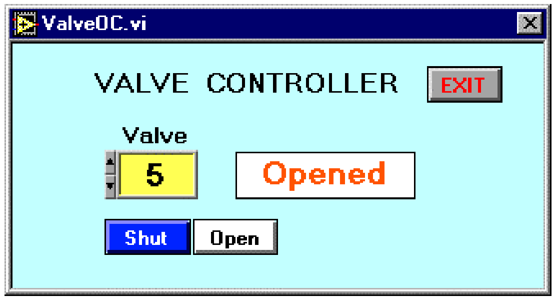

Figure 82: ValveOC.vi front panel

PURGE.LLB

This library contains subsequences for purging the system using GHe.

BoxPurg.vi

This VI performs a purge of the pressure box. The pressure is cycled several times.

User-entered parameters:

Cycles (Box)	default = 4 cycles
Dwell time per cycle (Box)	default = 4 min

Hard-coded parameters:

V2 Box Purge Pressure	default = 5 psig
Tolerance	default = 0.5 psig
Depressurization pressure	default = 0.5 psig

The following steps are performed:

1. Write "Starting box purge..." to the message board.
2. Turn on all fans to circulate the atmosphere in the box.
3. Open V3.
4. Open V33.
5. Pressurize the box to 5 psig.
6. Dwell for the amount of time specified in Dwell time per cycle.
7. Open V12 to purge the box.
8. Set V2 to 0.5 psig.
9. Repeat steps 4-7 Cycles times.
10. Turn off all fans.
11. Write "Box purge complete." to the message board.

This sequence may execute concurrently with other purge sequences to shorten the time required to purge the system.

LN2Purge.vi

This subsequence purges the LN_2 heat exchanger coils and associated piping with gaseous helium.

User-entered parameters:
  Dwell time — default = 4 min

Hard-coded parameters:
  none

The following steps are performed:

1. Write "Starting LN2 line purge..." to the message board.
2. Open V13.
3. Open V8.
4. Dwell for the amount of time specified in Dwell time.
5. Close V8.
6. Close V13.
7. Write "LN2 purge complete." to the message board.

This subsequence may execute concurrently with other purge sequences to shorten the time required to purge the system.

LPHePurge.vi

This subsequence purges the LHe heat exchanger coils in the box, the boiler pod, and the associated connections with gaseous helium. The purge consists of two stages. In the first stage, the purge gas exits through V14. After a delay, V14 is closed and the purge gas exits through the boiler pod. This prevents the fin-tube heat exchangers in the boiler pod from being contaminated with moisture from the pressure box.

User-entered parameters:
  Dwell time through V14 — default = 4 min
  Dwell time through Boiler Pod — default = 4 min

Hard-coded parameters:
  Pressure increase at PT5 — default = 5 psig

The following steps are performed:

1. Write "Starting LP He line purge..." to the message board.
2. Shut V10.
3. Open V14.
4. Open V9.
5. Wait until pressure at PT5 increases by 5 psig.
6. Dwell for the first period (Dwell time through V14).
7. Close V14.
8. Dwell for the second period (Dwell time through Boiler Pod).
9. Close V9.
10. Write "LP He line purge complete." to the message board.

This sequence may execute concurrently with other purge sequences to shorten the time required to purge the system.

MainPurg.vi

This VI runs subsequences to purge the LN_2 lines, the LHe lines, and the interior of the pressure box with gaseous helium. The subsequences (described above) are run simultaneously to shorten the time required for a system purge.

User-entered parameters:

Cycles (Box)	default = 4 cycles
Dwell time per cycle (Box)	default = 4 min
Dwell time (LN_2)	default = 4 min
Dwell time through V14 (LHe)	default = 4 min
Dwell time through Boiler Pod (LHe)	default = 4 min

Hard-coded parameters:
none

The following steps are performed:

1. Write "Starting system purge..." to the message board.
2. Run ***BoxPurg.vi***.
3. Run ***LPHePurg.vi***.
4. Run ***LN2Purge.vi***.
5. Wait until all these subsequences are done.
6. Write "System purge complete." to the message board.

SEQUENCE.LLB

The sequencer, sequence editor, and miscellaneous subsequences reside in this library.

ENDTEST.VI

This subsequence may be used to terminate any test. It performs exactly the same sequence of operations as ***SHUTDOWN.VI*** except that it is accessible as a subsequence. The operator specifies the desired ambient temperature during test setup. The operator may modify the default values for the tolerance (30°F) and the V9 Purge Dwell (5 min) with permission level 3 or greater.

User-entered parameters:

Ambient Temp.	default = 60°F
Ambient Toler.	default = 30°F
V9 Purge Dwell	default = 5.0 min

Hard-coded parameters:

Final pressure	default = 1.0 psig
Final pressure tolerance	default = 1.0 psig
Purge Delay	default = 1.0 min

The following steps are performed:

1. Turn off the radiant heater, even if it wasn't originally on (the radiant heater is never used to warm up the system from a cold state)
2. Depressurize box to 1 psig.
3. Isolate load plate cooling system - shut V28 and open V35-1, V35-2, V35-3, V35-4, and V36.
4. Shut V4, V6a, V6b, and V10.
5. If the average panel temperature is below 32°F, perform the following steps:
   - 5a. Set load plate setpoints to Ambient Temp.
   - 5b. Set fan setpoints to Ambient Temp.
   - 5c. Set internal heater setpoint to Ambient Temp.
   - 5d. Purge LHe line through V9 and V14.

   Otherwise, if the average panel temperature is greater than 125°F, do this:
   - 5a. Turn off internal heaters.

5b. Open V13
5c. Open V5 in automatic mode at Ambient Temp.
5d. Set fan setpoints to Ambient Temp.
6. Wait until panel reaches ambient temperature within Ambient Toler.
7. Wait until V9 has had time to purge.
8. Turn off internal heaters, fans, and valves V3-V8, V13, V14, V28, V33, V34, and V36. Open V35-1 through V35-4.
9. Write "End Test Complete." to the message board.

Powerdown.VI

This subsequence VI should be included at the end of every test sequence. It duplicates the functions performed as the control system exits after EXIT has been selected. Note that ***ENDTEST.VI*** and ***SHUTDOWN.VI*** actively return the box to ambient conditions, whereas this function just opens and closes valves and turns off fans and heaters. The preferred way to end a sequence is to follow ***ENDTEST.VI*** with ***Powerdown.VI*** as the last two subsequences in the sequence.

User-entered parameters:
none

Hard-coded parameters:
none

The following steps are performed:
1. Turn off the radiant heater, even if it wasn't originally on.
2. Turn off V2, V3, V4, V5, V6, V7, V8, V9, V10, V13, V14, V28, V33, V34, and V36.
3. Open V12.
4. Turn off internal heaters.
5. Turn off fans.
6. Close load plate valves V35-1 through V35-4.
7. Write "Powerdown Complete." to the message board.

Pressure.vi

This is a subsequence VI which handles all box pressurization tasks. It may be used as a sequence step or called by other subsequences. Controllers for V2 and V12 are written so that the setpoint of V12 is always greater or equal to the setpoint of V2 + 1. In order to avoid valve sequencing errors and concomitant alarms, the VI determines whether the box will be pressurized or depressurized based on the current setpoint. If the box is to be pressurized, V12 is commanded before V2. Otherwise, V2 is commanded before V12. The VI also handles ramping; the ramp rate is applied to V2 only when pressurizing and to V12 only when depressurizing. The action performed is recorded on the message board. V2 Box Pressure Setpoint always defaults to 0 psig and Pressure Ramp Rate always defaults to 10 psi/min.

User-entered parameters:

V2 Box Pressure Setpoint	default = 0.0 psig
Pressure Ramp Rate	default = 10 psig/min

Hard-coded parameters:
none

SEQUENCE.VI

This VI generates test sequences interactively from subsequences. It is called from the Setup menu. The operator may save sequences to disk and retrieve and modify previously saved sequences. Sequences are stored as text files, allowing the operator to print the test out using a text editor. To load a sequence for modification select Open. Select the desired filename and select OK. The sequence will appear in the Test Sequence window and the filename will appear in the Test Name display. To begin a sequence from scratch if the Test Sequence window is not empty select Erase All. Select a subsequence from the selection list. The subsequence name will appear in the selection list box but not in the Test Sequence window. To add the sequence after the currently marked sequence (or as the first sequence) select Add. The subsequence name will appear at the cursor in the Test Sequence window. One or more dialog boxes will pop up requesting setpoints or other sequence parameters. Enter the desired data (or do nothing to use the default value) and select OK. If the data is out of range a message will appear and the default will be restored. If the value is in range, when OK is selected the parameter will be entered into the Test Sequence window at the cursor location.

Insert and Replace may also be used to enter a subsequence. Insert will enter the new subsequence before the cursor, Replace will replace the current subsequence with the new subsequence, and Delete will delete the current subsequence. To modify a parameter in a previously entered subsequence the Replace function must be used. A new Test Name may be entered to identify the test. To save the test, select Save. The Test Name will be used as the file name. A .SEQ extension will be appended. After a test has been created, it must be applied. Select Apply Test to load the test into the sequencer. The Valid indicator will be lit. The operator may also modify an applied and running test after initiating a **HOLD**. If the system is in the Hold state, only users with permission level 2 and above may modify a test sequence. Only the subsequences which have not yet been started may be modified.

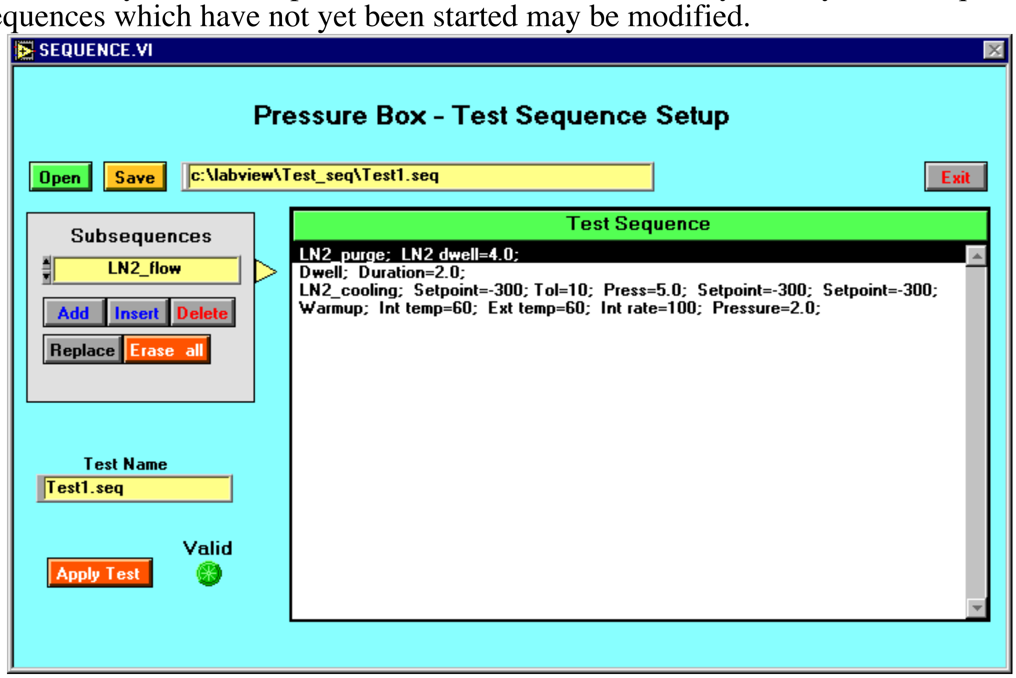

Figure 83: SEQUENCE.VI front panel

LabVIEW contains only primitive resources for printing. To print out a copy of the test sequence, another Windows application must be used. However, because LabVIEW uses so much of the available system processing bandwidth, it is currently not possible to run other Windows applications while the control system is running. In order to print out a test sequence for review, the best procedure is to use the Save control to open a file dialog box and save the subsequence to a removable storage device (e.g. a floppy disk) and print it out elsewhere.

If the desired test cannot be made up from existing subsequences, then a proficient LabVIEW programmer may program a new subsequence and add it to the system. This requires a detailed knowledge of system operation.

TurnBuck.vi

TurnBuck.vi is a subsequence VI to allow the operators to pause and adjust the hoop load turnbuckles. The sequence pressurizes the box to 5 psig, delays for a user-specified time period, and then depressurizes the box to 2 psig. These pressures may be modified at sequence startup by operators with a permission level 3 or greater. The operator is instructed to manually deenergize and reenergize the radiant heaters for safety.

User-entered parameters:

X Pressure	default = 5 psig
Dwell Time	default = 1.0 min
U Pressure	default = 2.0 psig

Hard-coded parameters:

Tolerance	default = 1.0 psig

The following steps are performed:

1. Write "Starting turnbuckle adjustment..." to the message board.
2. Open V3
3. Pressurize box to X Pressure
4. Dwell for Dwell Time
5. Depressurize box to U Pressure
6. Shut V28
7. Instruct operator to verify that radiant heater system is deenergized
8. Instruct operator to remove key from Turnbuckle Overpressure Protection switch.
9. Inform operator that access to the box is now possible.
10. Wait until operator returns from the box and selects "OK."
11. Instruct operator to insert key into Turnbuckle Overpressure Protection switch and turn.
12. If operator specifies, repeat steps 1 through 10
13. Instruct operator to energize radiant heater system.
14. Open V28 if it was open originally.

SETPOINT.LLB

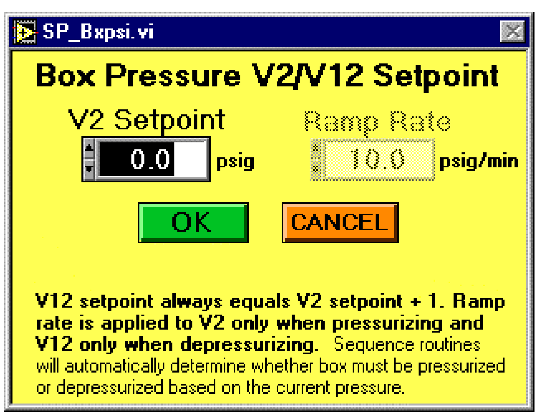

Figure 84: SP_Bxpsi.vi front panel

This library contains VI's which are used by ***SEQUENCE.VI*** when setting up a test sequence. Each VI is a dialog box which prompts the user for test sequence variables such as setpoints, dwell times, ramp rates, etc. Many parameters are only accessible for a permission level of 3 or higher. After entering values select OK. All values (including defaults) are checked against the alarm limits. The VI will only exit if values are within range. If system limits are set so that a default value is out of range, then the operator must select CANCEL and either change the system limits or change to permission level 3 in order to modify the offending value.

Since these VI's are all similar, they are not individually discussed. The following table records the parameters obtained by each VI, the default values, and the permitted range of values. The first parameter label is that which appears on the front panel. The label used in the range statement is returned to ***SEQUENCE.VI*** and appears in the test sequence. After each VI name is a list of associated subsequences.

Table 15: Subsequence Setpoint Summary

SP_BxPCL.vi	Box_precool	
	Setpoint = -320°F	(-320°F ≤ SP ≤ Temp Max. Setpoint)
SP_Bxpsi.vi	Box_Pressure	
	V2 Setpoint = 0.0 psig	(0 ≤ SP < Panel Pressure Limit)
	*Rate = 10.0 psig/min	(0 ≤ Rate ≤ Max press.rate)
SP_Dwell.vi	Dwell	
	Dwell time = 1.0 min	(0.1 ≤ Dwell ≤ 2400)
SP_EHeat.vi	External_Heaters	
	Setpoint = 60°F	(Temp Min. Setpoint ≤ SP ≤ 1000)
SP_End.vi	EndTest	
	Setpoint = 60°F	(Temp Min. Setpoint ≤ SP ≤ Temp Max. Setpoint)
	*Tolerance = 10°F	(1 ≤ Tol ≤ 100)
	*V9 Purge Dwell = 5.0 min	(0.1 ≤ V9 Dwell ≤ 120)
SP_GHePC.vi	LN2_cooling, GHe_precool, LHe_cooling	
	Setpoint = -300°F	(-457 ≤ SP ≤ 395)
SP_HPurg.vi	Main_purge, LP_He_purge	
	*Dwell Time thru V14 = 4.0 min	(0.1 ≤ Dwell 1 ≤ 1200)
	*Dwell Time thru Boiler Pod = 4.0 min	(0.1 ≤ Dwell 2 ≤ 1200)
SP_IHeat.vi	Internal_Heaters	
	Setpoint = 60°F	(Temp Min. Setpoint ≤ SP ≤ Temp Max. Setpoint)
	*Temp. Ramp Rate = Max. temp. rate	(0 ≤ Rate ≤ Max. temp. rate.)
SP_LHeCl.vi	LHe_cooling	
	Setpoint = -400°F	(Temp Min. Setpoint ≤ SP ≤ -250)
	*Tolerance = 10°F	(1 ≤ Tol ≤ 200)
SP_LHeFl.vi	LHe_flow	
	Setpoint = -400°F	(Temp Min. Setpoint ≤ SP ≤ -250)
SP_LIS.vi	LN2_cooling, LIS_cooling, LHe_cooling, Wait_LIS	
	Setpoint = -300°F	(-320 ≤ SP ≤ Temp Max. Setpoint)
SP_LN2Cl.vi	LN2_cooling	
	Setpoint = -300°F	(Temp Min. Setpoint ≤ SP ≤ Temp Max. Setpoint)
	*Tolerance = 10°F	(1 ≤ Tol ≤ 40)
	*Pressure = 5.0 psig	(0 ≤ Press < Panel Pressure Limit)
SP_NPurge.vi	Main_purge, LN2_purge, LHe_cooling,	
	*Dwell Time = 4.0 min	(1 ≤ LN2 Dwell ≤ 120)
SP_PPurge.vi	Main_purge, Box_purge	
	*Cycles = 4	(1 ≤ Cycles ≤ 100)

*Dwell time per cycle = 4 min (1 ≤ Cycle Dwell ≤ 120)

SP_TBuck.vi Adj_turnbuckles

*X Pressure = 5 psig (0 ≤ X press < Panel Pressure Limit)

*Dwell time = 1 min (1 ≤ Dwell ≤ 120)

*Y pressure = 2 psig (0 ≤ Y press < Panel Pressure Limit)

SP_Wait.vi Wait_Pressure, Wait_Temperature, Wait_LIS

*Tolerance = 0.5 (0.1 ≤ Tol ≤ 200)

*Timeout = 7200 min (0 < Timeout)

SP_Warm.vi Warmup

Int. Heater Temp = 60°F (Temp Min. Setpoint ≤ Int Temp ≤ Temp Max. Setpoint)

*Int. Heater Rate = 100°F/min (0 ≤ Int Rate ≤ Max. temp. rate)

Ext. Heater Temp. = 60°F (Temp Min. Setpoint ≤ Ext Temp ≤ 1000)

*Pressure = 2.0 psig (0 ≤ Press < Panel Pressure Limit)

* These parameters are unavailable for permission levels less than 3.

SETUP.VI

This function provides software access to all Watlow 988 setup prompts which are relevant to system operation. Most of these values should never be changed since they are determined by the control system design. However, some parameters which relate to system tuning may require relatively frequent access. To modify a parameter, first select Read All Menus to load the current controller values into the computer. After the modifications have been made, the control parameters may be rewritten back to the controller. This process helps prevent unintended changes. Refer to the *Watlow Series 988 User's Manual* for detailed instructions on controller setup and operation.

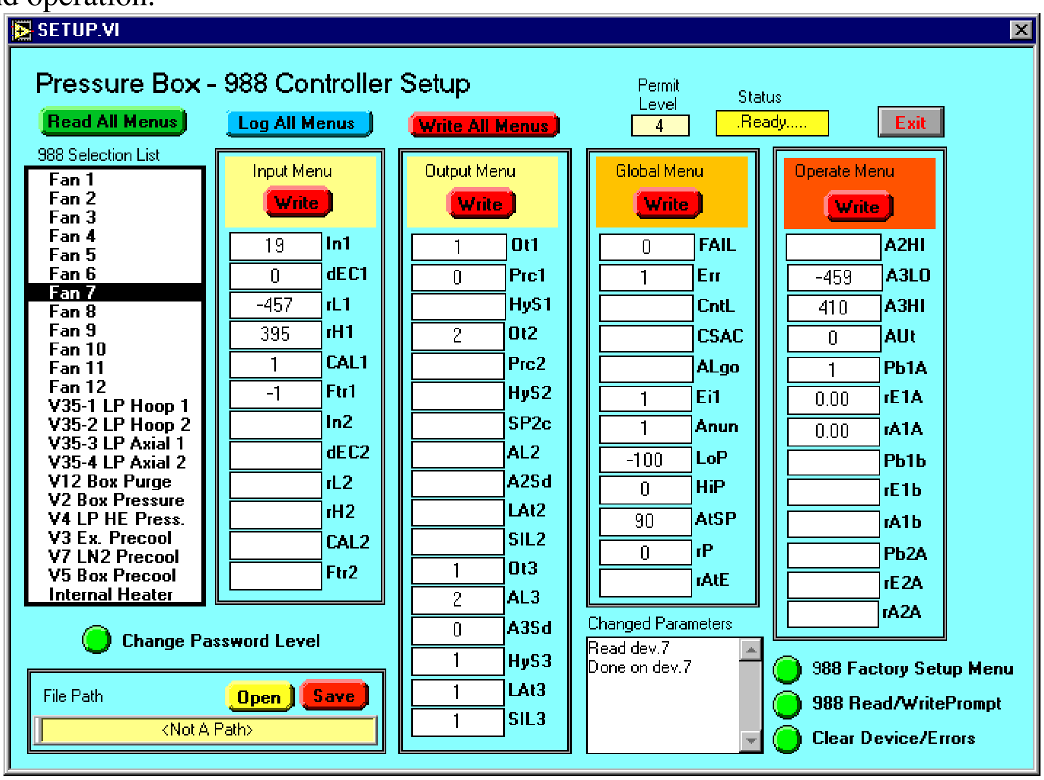

Figure 85: SETUP.VI front panel

A selection box appears on the left side of the front panel with one entry for each Watlow 988 controller. Group selection is allowed for any range of controllers. This is especially useful when writing to the fans and the load plates, since each group will have identical setup values. Group selection may also be used when logging. Selecting all controllers, regardless of their configuration, and pressing **Log All Menus** will generate a complete parameter listing for all controllers. Except when logging setup values, group selection should never be used for controllers with dissimilar setups.

Setup parameters may be stored in two different file formats. The **Log All Menus** control writes parameters together with their labels to an ASCII text file for operator review (file extension: *.LOG). The **Save** control writes the current menu contents to a machine-readable file (file extension: *.988). The **Open** control will open a file previously saved with **Save** and read it into the front-panel menus. These values may then be written to a controller. With the exception of the fan controller group and the load plate controller group, there must be a separate file for each controller. Controller setup parameters are stored in the SETUP directory under the following names:

Table 16: Setup Parameter File Names

FANS.988	Fan 1 - Fan 12 (controllers 1-12)
LPLATES.988	V35-1 Hoop 1, V35-2 Hoop 2, V35-3 Axial 1, V35-4 Axial 2 (controllers 13-16)
V12.988	V12 Box Purge (controller 17)
V2.988	V2 Box Pressure (controller 18)
V4.988	V4 LP He Pressure (controller 19)
V3.988	V3 Exhaust Precool (controller 20)
V7.988	V7 LN2 Precool (controller 21)
V5.988	V5 Box Precool (controller 22)
IH.988	Internal Heaters (controller 23)

Depending on the hardware and software options installed in the controller, and also on the controller configuration, some prompts may be inactive for a given controller. ***SETUP.VI*** neither reads nor writes inactive prompts to prevent communication errors. Also, there are some prompts that, when written to a controller, will reset a number of other prompts for that controller. ***SETUP.VI*** is configured to write prompts in the correct order. It is recommended that whenever the Input menu or Output menu prompts must be written all prompts should be written using the **Write All Menus** control. This will ensure that the correct write order is preserved and that any prompts reset by the controller will be written by software.

All operations are password protected as follows:

Table 17: Setup Accessibility

Level 0	SETUP.VI is not accessible from level 0
Level 1	Operators may read all menus and may look at files, but may not write to controllers or *.988 files. Operators may clear controller communication errors
Level 2	In addition to the operations allowed in level 1, operators may write prompts under the Operate menu
Level 3	In addition to the operations allowed in level 2, operators may write prompts under the Global menu
Level 4	All operations are accessible

When reading prompts from the controllers, ***SETUP.VI*** will automatically compare the prompt values read with the prompt values currently in memory for a given controller. There is no reason to compare prompt values from controllers with different configurations, so ***SETUP.VI*** will not compare dissimilar controllers. However, the fan controllers and load plate controllers each form groups with essentially identical configurations (within each group). If the prompt values stored in memory were read from a fan controller and the prompts from any fan controller are read, prompts will be compared. The same situation holds with the load plate controllers. This automatic comparison feature may be used to verify that the controller is operating with the correct parameters by, for each controller, first opening the appropriate *.988 file and then reading the actual controller prompt values. Any differences will be listed in the Changed Parameters text box.

UTILITY.LLB

This library contains miscellaneous VI's which support system operations.

backup.vi

The backup controller VI allows the operator to switch between default and backup input channels for most controllers. This function is accessed through the setup menu (***Setupmen.vi***). Input channels may also be selected with front panel switches. Before setting input channels through the computer, the SENSOR BACKUP switch for the relevant controller must be in the AUTO position.

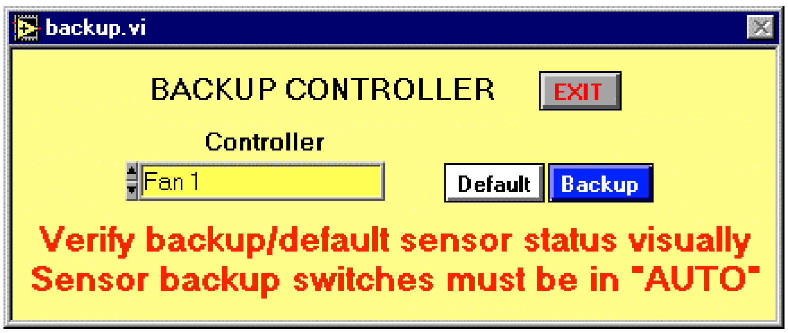

Figure 86: backup.vi front panel

To select a new input channel, choose the controller using the selection box and then select Default or Backup. The chosen input channel is changed and a message is written to the message board indicating this fact: "Controller *x* set to [backup, default] sensor". Some controllers do not have backup input channels. For these devices the message "Controller *x* does not have a backup sensor" is displayed. Note there are also a few controllers which have backup input channels but do not have a connected backup input sensor. Switching to a backup sensor for one of these controllers will open the control loop. There is no feedback to the computer from the backup multiplexers; the effect of using the backup controller must be verified by the panel indicators beneath each controller. The yellow LED under the appropriate controller will light if it has been placed in backup mode. The backup multiplexers do not have a memory; any input configuration set through software will be lost when SENSOR BACKUP is switched to MANUAL.

Logger.vi

All process value data logging is performed by ***Logger.vi***. Only process values (temperatures, pressures, levels) are recorded. Setpoints, system state, controller modes, etc. are not recorded in the process log output file; this information may be recorded by logging the contents of the message board. The operator selects the data logging function by pressing the Logger button on the setup menu. A window will be displayed with data logger setup information. The user selects the various logging periods, chooses a file name, and moves the

ON/OFF switch to ON to start logging. Moving the switch to OFF will cause logging to cease. Indicators display the time at each data write and the current file size.

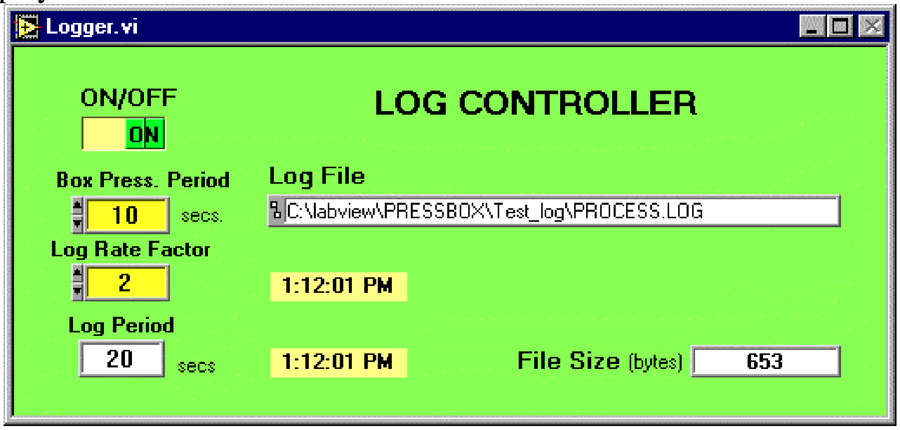

Figure 87: Logger.vi front panel

Provision has been made to record the box pressure from sensor PT3 at more frequent intervals than the values obtained by other sensors, since it is available more frequently through the A/D input board. Box Press. Period is the number of seconds in the interval between box pressure writes. Log Rate Factor is a multiplier which determines the length of the interval between writes of all other data. The actual log rate of this other data, displayed in Log Period, is the product of Box Press. Period and Log Rate Factor. The default values of 10 and 2, respectively, will record the box pressure every 10 seconds and all other data every 20 seconds. Other recommended values are given in Table 18.

Table 18: Recommended Log Factors

Box Pressure Period	Log Factor
2 sec.	1, 5, 10
5 sec.	1, 2, 5, 10
10 sec.	1, 2,3, 6
20 sec.	1, 3, 6
30 sec.	1, 2, 4
60 sec.	1, 2

Any values permitted by the data range restrictions may be used, but those which divide the minute into a whole number of parts are preferred. A 2 second minimum box pressure period has been incorporated to prevent excessive overhead. Note that values written to the log file are taken directly from ***Globals.vi***, and ***MainRead.vi*** and ***FANREAD.VI*** govern data read rates (except for PT3, which is read by ***BOXAIn.VI***). There is no advantage in logging data values more often than they are read by these VI's.

Logged data is stored in a text file as a series of tab-delimited lines which may be loaded into a spreadsheet, text editor, or read by a custom program. The first line contains the complete file name (including drive and path). The second line contains the phrase "Process Value Log File". The third line contains column headings for the logged data. The fourth line is blank. Data starts at the fifth line. The first entry in each data line is a time stamp in the form hours:minutes:seconds followed by a space, the designation "AM" or "PM", and the tab character. Real time is used rather than test start time, since data logging may be enabled whether or not a test sequence has been started. Each data entry may contain up to five digits with one digit to the right of the decimal point. A negative sign may be prefixed. The following example lines demonstrate the data file format:

```
01:42:30 PM   2.0    -340.0  60.0   .      .      .
01:42:35 PM   2.0
01:42:40 PM   2.1    -340.0  61.0   .      .      .
01:42:45 PM   2.1
```

Data is recorded in the following sequence: Time, PT3, TT1, TT2, TT3, TT4, TT5, TT6, TT7-1 through TT7-4, TT9, TT10, TT11, TT12-1 through TT12-12, TC1 through TC8, PT1, PT2, PT4, PT5, PT6, PT7, PT8, PT9, PT10, PT11, LN_2 level, and LHe level.

OperPass.vi

OperPass.vi displays a message, writes it to the message board, and requests the operator to enter a password. This VI will not exit until the password has been entered.

Permit.vi

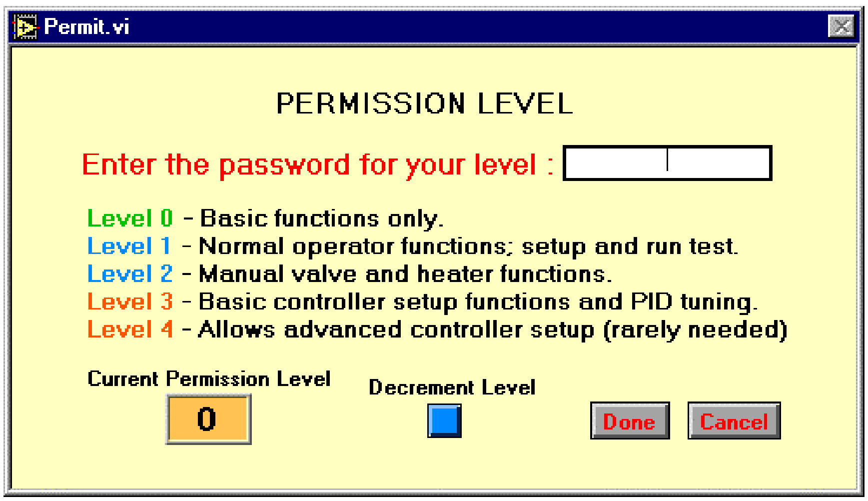

Figure 88: Permit.vi front panel

In order to protect critical functions, a password mechanism prevents unauthorized users from accessing certain program areas. ***Permit.vi*** sets the current permission level based on the password entered by the operator. There are five levels of access. Level 0 allows access only to the basic operator functions. It is intended for use by an "operator-observer." Level 0 operators may not access any setup functions, including test sequence setup. Level 1 adds access to test sequence setup, the fan controllers, and the data logger. Level 2, in addition to the previous functions, allows access to manual operations. Level 3 permits access to sequence step mode and basic controller setup and tuning. Level 4 allows advanced controller setup functions. To set the permission level, type the appropriate password at the prompt. The actual typed characters are displayed by the Permission Level indicator after the <Enter> key is pressed. Select Done to set the permission level and close the panel. The Decrement Level control may be used after performing advanced setup operations to restore the permission level to a lower level.

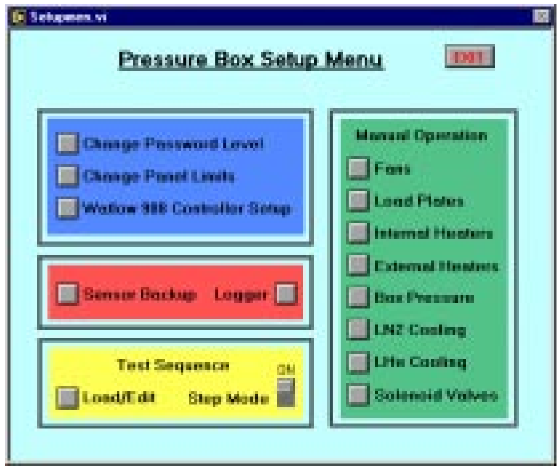

Figure 89: Setupmen.vi front panel

Setupmen.vi

Setupmen.vi serves as a menu to allow the operator to select various setup functions and manual operations. Selecting a front panel button invokes a VI which performs the desired operation.

Available menu options are restricted according to the current permission level. Table 19 is a summary of the operations accessible through this VI:

All controls are pushbuttons except for Step Mode, which is an ON/OFF slide switch. Menu names are self-explanatory; refer to the called VI for detailed information. If the front panel has been open for at least 30 seconds but is no longer the active window, then it will be automatically closed.

Table 19: Available Setup Menu Selections

Option	Permission Level	Calls
Change Password Level	0-4	Permit.vi
Change Panel Limits	1-4	Limits.vi
Watlow 988 Controller Setup	3-4	SETUP.VI
Sensor Backup	2-4	backup.vi
Data Logger	1-4	Logger.vi
Test Sequence Load/Edit	1-4	SEQUENCE.VI
Step Mode	3-4	
Fans	1-4	FAN_manual.vi
Load Plates	2-4	LoPlate.vi
Internal Heaters	2-4	IH_manual.vi
External Heaters	2-4	Dim2Main.vi
Box Pressure	2-4	BoxPress.vi
LN_2 Cooling	2-4	LN2_manual.vi
LHe Cooling	2-4	LHe_manual.vi
Solenoid Valves	3-4	ValveOCM.vi

WAIT.LLB

The ***WAIT.LLB*** library contains routines used when waiting for a system to reach a temperature or pressure. For example, after enabling LN_2 flow through the fan heat exchangers using ***LN2_flow.vi***, ***WaitCool.vi*** should be called to cause the sequencer to wait until the panel has actually cooled down.

WaitLIS.vi

WaitLIS.vi waits until the average of all four load plate temperatures reaches the specified value. This VI may be used either during cooling or heating. If the setpoint is changed during the wait then this VI will continue to wait until the old, unchanged setpoint has been reached. The wait will expire after a timeout period whether or not the setpoint has been reached. Periodic messages are written to the message board. This VI may be used as a subsequence.

User-entered parameters:	
Setpoint	default = -300°F
Tolerance	default = 0.5
Timeout	default = 7200 min
Hard-coded parameters:	
Message Update Time	default = 1.0 min

WaitPress.vi

WaitPress.vi waits until the box pressure reaches the box pressure setpoint stored in V2 Setpoint. If this is changed during the wait period, then the VI will wait until the new setpoint is reached. The wait will expire after a timeout period whether or not the setpoint has been reached. Periodic messages are written to the message board. This VI may be used as a subsequence.

User-entered parameters:	
Tolerance	default = 0.5
Timeout	default = 7200 min
Hard-coded parameters:	
Message Update Time	default = 1.0 min
Setpoint	obtained from system

WaitTemp.vi

WaitTemp.vi waits until the panel average temperature reaches the value stored in global Temp. Setpoint. This VI may be used either when cooling the panel or heating the panel; the temperature may approach the setpoint from either direction. If Temp. Setpoint is changed during the wait period, then the VI will wait until the new setpoint is reached. This VI may be used as a subsequence.

User-entered parameters:	
Tolerance	default = 0.5
Timeout	default = 7200 min
Hard-coded parameters:	
Message Update Time	default = 1.0 min
Setpoint	obtained from system

WaitTime.vi

This subsequence VI inserts a delay into a sequence equal to the time specified. Time spent in a **HOLD** state is not counted.

User-entered parameters:
Dwell time — default = 1.0 min

Hard-coded parameters:
none

WARMUP.LLB

This library contains subsequence VI's used to warm up the system from a cold state or to heat the system to elevated temperatures.

CryoShut.vi

This subsequence turns off valves primarily involved in cryogenic operations. The following valves are closed: V4, V7, V7, V10, and V28. Valves V3 and V35-1 through V35-4 are opened.

User-entered parameters:
none

Hard-coded parameters:
none

The following steps are performed:
1. Write "Starting Cryo shutoff…" to message board.
2. Close V4.
3. Close V10.
4. Open V3.
5. Close V7.
6. Close V6.
7. Close V28.
8. Open V35-1 through V35-4.
9. Write "Cryo shutoff complete." to the message board.

ExtnHeat.vi

This subsequence writes a setpoint to the radiant heater. The setpoint is entered during test setup. Any contiguous range of zones may be selected based on the heater configuration. The zone range is not accessible during test setup; it must be entered into the ***ExtnHeat.vi*** front panel.

User-entered parameters:
External Heater Setpoint — default = 60°F

Hard-coded parameters:
First Zone — default = 1
Last Zone — default = 8

IntnHeat.vi

IntnHeat.vi is a subsequence which may be called to initiate the internal heaters. The operator enters the setpoint at test setup. If the permission level is 3 or greater, the ramp rate used by the controller may be changed as well.

User-entered parameters:
Internal Heater Setpoint — default = 60°F

Temp. Ramp Rate default = 60°F/min

Hard-coded parameters:
none

The following steps are performed:
1. Write "Starting internal heaters.." to the message board.
2. Set fans to Internal Heater Setpoint in Heat mode.
3. Write Internal Heater Setpoint to internal heaters controller.
4. Writes "Internal heaters initiated." to the message board.

Warmup.vi

This subsequence uses the internal and external heaters to warm up the panel. The load plate heaters are not enabled. At test setup, the operator enters the internal heater setpoint and the external heater setpoint. If the operator has level 3 access or above, the internal heater rate and box pressure may also be changed. The subsequence asks the operator whether or not the box pressure should be changed.

User-entered parameters:

Internal Heater Setpoint	default = 60°F
Internal Temp. Ramp Rate	default = 100°F/min
External Heater Setpoint	default = 60°F
Box Pressure	default = 2 psig

Hard-coded parameters:

V5 setpoint increment	default = 5°F
Panel temperature tolerance	default = 10°F

The following steps are performed:
1. Write "Starting box warmup; SP = *x* °F" to message board.
2. Call ***CryoShut.vi*** to shut off all cryogens.
3. Open V36.
4. Query operator to determine if pressure should be reduced.
5. Call ***IntnHeat.vi*** with Internal Heater Setpoint and Internal Temp. Ramp Rate.
6. Call ***ExtnHeat.vi*** with External Heater Setpoint.
7. Open V13.
8. Wait until box reaches setpoint.
9. Write "Warmup sequence done." to the message board.

WATLOW.LLB

This library contains VI's used when communicating with the Watlow 988 PID controllers.

Any988.vi

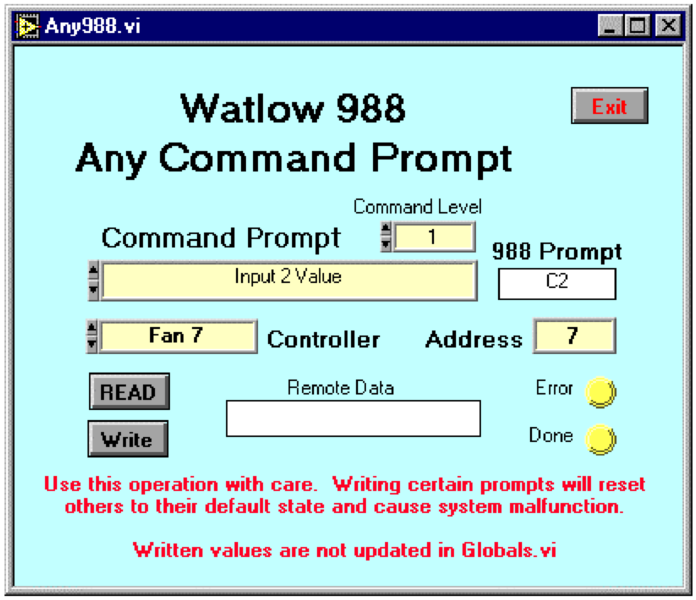

Figure 90: Any988.vi front panel

This VI, called only by ***SETUP.VI***, allows the operator to read or write any prompt to the Watlow Series 988 controllers. This VI is intended only for use in modifying system parameters or when troubleshooting. Prompts are grouped into four levels as follows:

Level 1: Frequent access by program or operator.
Level 2: Occasional access by operator; no automated access.
Level 3: System setup, tuning, or diagnostics.
Level 4: Hardware setup only - never changed.

These command levels are somewhat arbitrary and bear no relation to the permission level system used to protect parts of the system from unauthorized access. To read or write a prompt, set the desired command level, select the command prompt from the selection list, select the controller address, and select Read or Write. A subset of all possible Watlow controller prompts has been implemented; however, the implemented prompts represent a superset of those actually used by the control system and therefore many prompts are inactive.

Caution must be taken when writing to a controller using this VI. Writing a prompt from this VI will NOT update ***Globals.vi***; this method of writing Watlow controller prompts should therefore be used with care (if at all) while software is controlling the pressure box. Not all prompts are active on all controllers. Reading or writing an inactive prompt will result in an error. A message will be displayed indicating that a 988 communications error has occurred because the prompt is not active. The operator must acknowledge the error to continue. Finally, writing certain prompts will reset other prompts to their default state. ***SETUP.VI*** allows a more robust and preferred interface to controller setup parameters.

FactMenu.vi

This VI, called only by ***SETUP.VI***, allows the operator to read and write many prompts from the Watlow 988 controller Factory menus for a selected controller. Controller front panel and menu lockout functions are completely implemented. Controller input types, output types, serial number, and internal temperature may be read. To read prompt values, select the controller and select Read. To write a specific lockout value, select the corresponding boolean control to write the new lockout status directly to the controller. The control's color depends on the current lockout state. For menu lockout controls, green = no lockout, yellow = read only, and red = full lockout; for the front panel lockout control (read in frame 0.1) green = no lockout, yellow = mode key lockout, red = auto/manual key lockout, and blue = all front panel keys locked out. The status of each lockout parameter is also displayed in text. Pressing Exit closes the front panel and returns control to ***SETUP.VI***.

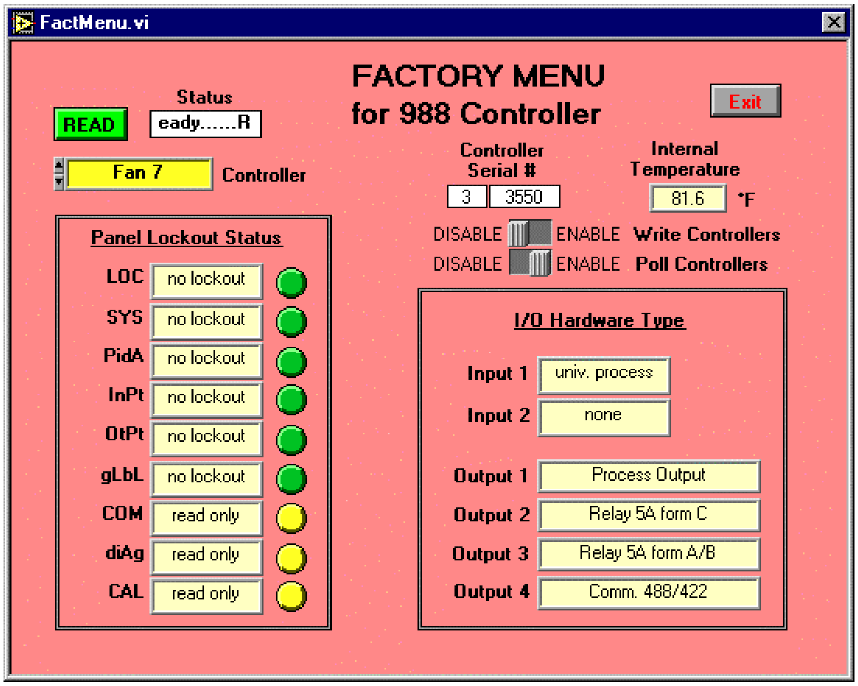

Figure 91: FactMenu.vi front panel

Concluding Remarks

The design of a load introduction structure, control system, and cryogenic systems were performed for the NASA Langley Research Center cryogenic pressure box facility. A finite element analysis of the load introduction structure and test panel were performed and compared to a cell model of the tank. The stresses in the test panel were similar to those of the cell model and the stresses in the load introduction structure were within the allowables, indicating that the load introduction structure is designed properly. A nonlinear analysis was also performed. The load introduction structure did not require a nonlinear analysis, but future panel analyses should include a nonlinear analysis. The control system has been designed and fabricated with a high degree of safety and redundancy. The control system software provides an easy to use and reliable user interface to the control system hardware. The use of LabVIEW as a programming language allows the software to be easily monitored and upgraded. Seals have been developed to seal the cryogenic pressure box using a Gore-tex fabric.

The system design meets the requirements of the ASME Boiler and Pressure Vessel Code Section VIII, Div. I. The corner connections of the inner pressure vessel will require some additional study prior to fabrication to minimize the stress concentrations. The boiler pod hardware easily exceeds the requirements and can be fabricated with no additional study. The thermal and structural design are sufficient to meet the requirements set forth in the statement of work. The risk mitigation studies have provided insight that led to efficient design of the system thermal components. Structurally, the design has a positive margin of safety of about 20% over what is required by the ASME Code. The code itself assumes a safety factor of 4.

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Appendix A: As Fabricated Cryogenic Pressure Box

This appendix presents photographs of the as built pressure box with brief descriptions of each photograph. No attempt is made to cover all aspects of the pressure box, but rather a few of the important features. Figure 92 is a photograph of the cryobox facility under construction. The large support structure can be seen in the photograph. At the center of the support structure is the cryobox with an aluminum cover over it (see arrow). Small utility sheds housing parts of the control system are seen behind and to the left of the support structure. A weather shelter has since been built over the support structure to protect the facility.

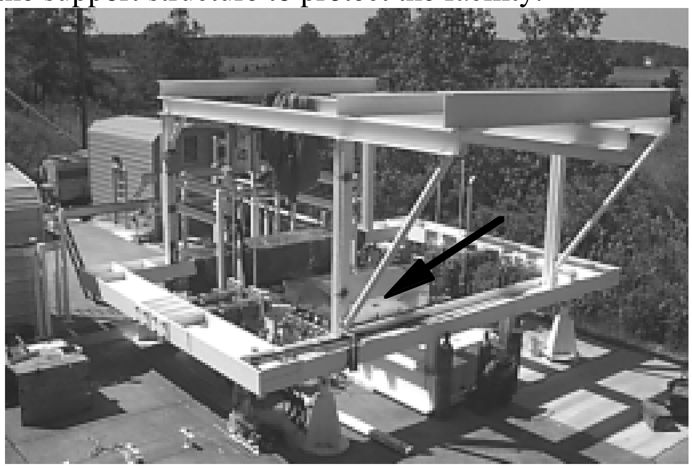

Figure 92: Photograph of the cryobox facility under construction.

Pressure Box

Figure 93: Photograph showing the inside of the pressure box.

A photograph of the inside of the pressure box is shown in Figure 93. The view is in the axial direction. Inside the box can be seen the twelve fan heat exchangers. Along the outer most perimeter of the box can be seen structural reinforcement for the box. Inside of the box reinforcement is the surface where the transition channel mounts to the pressure box. The line of bolt holes, spaced 2 in. apart, can been on that surface. Along the right inside of the box are the electrical connectors for the fan heat exchanger heaters and diode wires. The coolant supply and return lines can be seen surrounding the fan heat exchangers. There are four different coolant lines, LN2 supply and return, and LHe supply and return, with each having a separate manifold assembly. The manifold assembly for each coolant line was preassembled and then placed in the box.

Figure 94 shows a close view of a fan heat exchanger. A cover is placed over the fan to prevent items from falling into the heat exchangers. The coolant lines can be seen in the figure. The copper coils wrapped around the cylindrical shell with the fan in the middle carry LHe. The LN2 lines cool only the flat copper plates on the bottom. A diode can be seen mounted on the flat part of the heat exchanger.

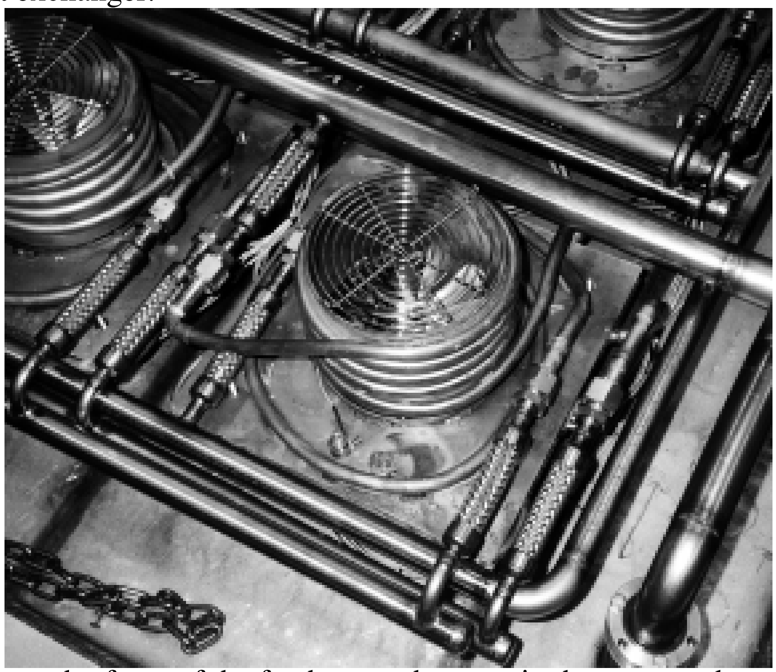

Figure 94: Photograph of one of the fan heat exchangers in the pressure box.

The fan motors are located in shrouds underneath the pressure box. Figure 95 is a photograph of the shrouds under the pressure box. Each shroud has a feed through for the fan connections. In addition to the fan motors, a second fan is placed on the motor shaft on the opposite side of the fan heat exchanger, i.e., near the bottom of the shroud. The second fan is used to keep the motor from getting too hot.

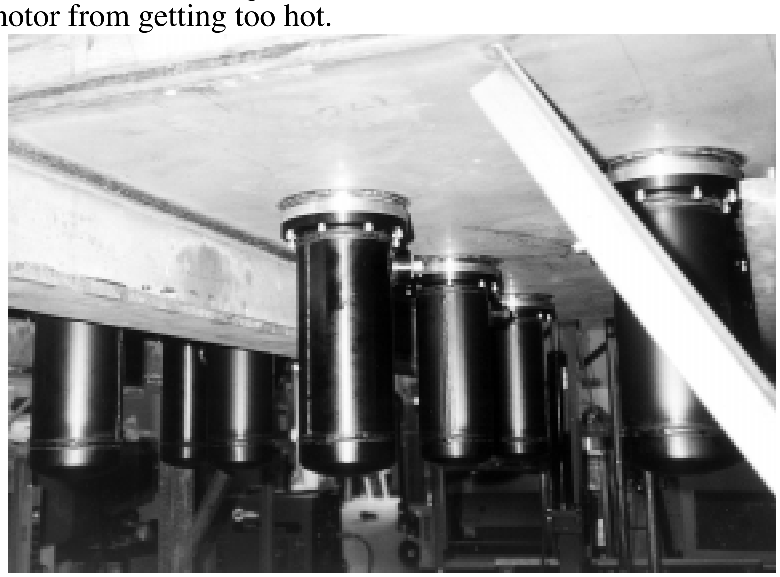

Figure 95: Photograph of the fan shrouds underneath the pressure box.

Boiler Pod

Figure 96: Photograph of the boiler pod.

A photograph of the boiler pod is shown in Figure 96. The boiler pod consists of the main boiler pod, shown on the left, and a heat exchanger pod, shown on the right. The initial design called for several of the heat exchangers to be placed inside the pressure box. However, due to space limitations in the box, it was decided to move the heat exchangers out of the pressure box. Since fabrication had already begun on the boiler pod, an extension was fabricated to attached the heat exchangers to the boiler pod. The entire boiler pod unit is located on a skid to facilitate handling. A box is shown on the boiler pod where all the valve connections will be made. A second box, not seen in the photograph, will be used for all the pressure transducer connections. A support ring is placed circumferentially around the boiler pod in the center of the boiler pod. A proportional valve can be seen on the skid between the boiler pod and heat exchanger pod. Finally, many of the cryogen lines can be seen penetrating the top of the boiler pod.

Figure 97 is a photograph of a proportional valve mounted on the boiler pod skid. The valve shown here is the same kind as shown in Figure 96. Both valves have an I/P (current to pressure) converter.

Figure 97: Photograph of a proportional valve on the boiler pod.

Seals

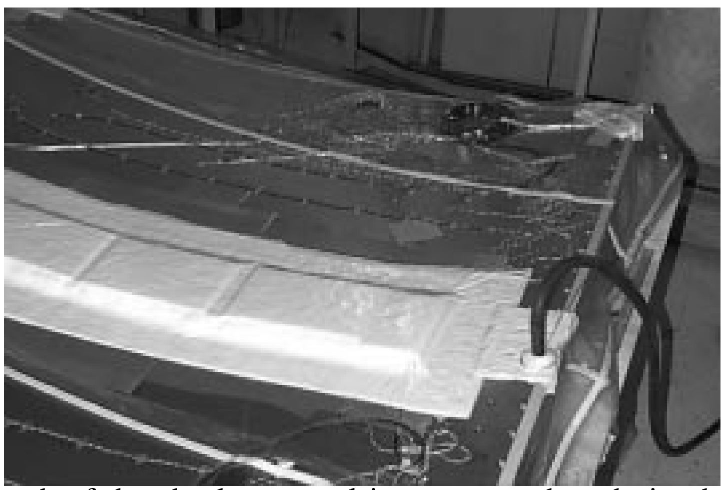

Figure 98: Photograph of the checkout panel in a vacuum bag during bonding of the splice plate seal.

The checkout panel is the first panel to be tested in the pressure box. A photograph of the checkout panel during installation of the splice plate seal is shown in Figure 98. The entire panel is enclosed in a vacuum bag. The splice plate seal is under the white felt and cannot be seen in the photograph.

Rohacell foam bolt covers were placed over each row of splice plate bolts to prevent the seal from tearing on the bolts. Figure 103 shows a photograph of a bolt cover. A 1-in-wide strip of aluminized mylar was draped over the bolt covers and bonded to the splice plate between bolt covers. The purpose of the mylar is to hold the bolt covers in place should the bondline between the Rohacell and the splice plate fail. The splice plate seal is folded back over the end bolt cover in the photograph. That portion of the seal will be bonded to the finger seal.

Figure 99: Photograph of the end Rohacell foam bolt cover over the splice plate bolts. The splice plate seal is folded back and will be bonded to the finger seal over the end bolt cover.

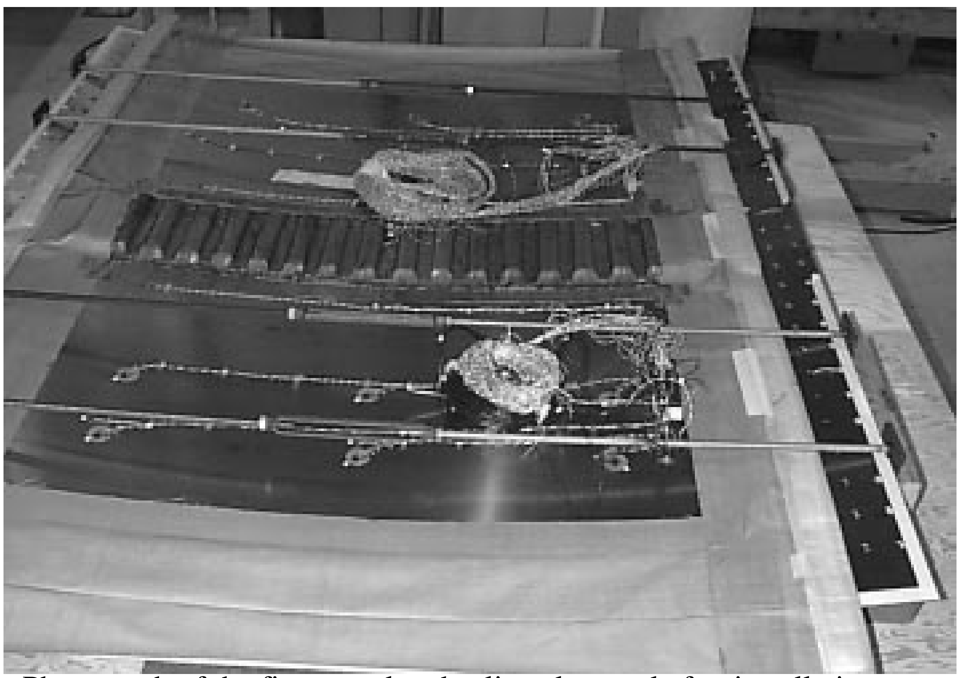

Figure 100: Photograph of the finger seal and splice plate seal after installation.

Figure 100 is a photograph of the finger seal and splice seal after final installation. The bolt covers under the splice plate seal can be seen in the center of the panel. Thermocouple and strain gage wire can been seen wound up on the panel. The splice plate seal and the finger seal are bonded together at the intersection of the two seals to prevent leakage of the pressurization gases. EA 9394 was used for all the bonding. Four turnbuckles (seen in the photograph) were used to maintain a chord length of 66 31/32 in.

Rohacell foam was bonded to the outside of the panel for use as cryogenic insulation. EA 9394 adhesive was again used for all the bonding. Figure 101 shows an axial end view of the panel after the foam had been bonded to the panel. Two layers of 1-in-thick foam were used for the insulation. The foam was thermally formed prior to bonding onto the panel. A vacuum bag was used to apply the required pressure, but all bonding was performed at room temperature. The top and bottom layers of foam are composed of several sheets. The sheets were staggered so that no butt joint between sheets on the top coincided with one on the bottom layer.

Figure 101: Photograph of the checkout panel with the Rohacell foam insulation bonded on the outside surface.

The stringers on the test panel increased the complexity of bonding the finger seal. Initially, a paper template was cut out that would follow the contours of the stringers and remain flat when bolted to the fingers. The template shape resembled an arc. After the paper template was finalized, a fabric one was cut, placed over the stringers and a vacuum bag was placed over the material. During this operation, all the steps of the actual bonding were taken except that no adhesive was used. This trial run enabled all the requirements to be determined prior to bonding the actual seal.

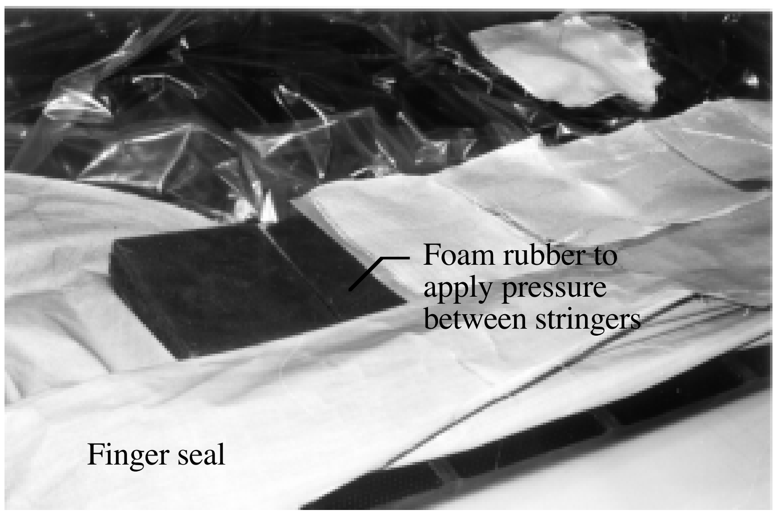

Figure 102: Photograph of finger seal in preparation for bonding with foam rubber used to apply pressure between stringers.

After the procedure was finalized, a section of the seal material was cut to shape. The seal surfaces to be bonded were etched with tetraetch, and the panel surfaces to be bonded were lightly sandblasted. The finger seal was then bonded to the panel with EA 9394 adhesive. A piece of rubber foam was placed over the seal between each stringer in an attempt to force the seal material to follow the contour of the panel and not bridge the corners of the stringers and the panel. Figure 102 shows a piece of the foam rubber over the seal material. Release cloth was placed above the foam rubber.

After all the pieces of foam rubber were placed between the stringers, a vacuum bag was placed over the entire seal. Figure 103 shows the vacuum bag with a vacuum pulled on the seal, resulting in 1 atm on the bondline. In the far left of the photograph can be seen the port to pull the vacuum.

Figure 103: Photograph of the finger seal with a vacuum bag used to apply 1 atm for bonding.

Figure 104 shows the finger seal after bonding. The finger seal followed the contour of the panel quite well. A few locations were noticed where bridging was present, but these did not seem to penetrate through the entire bondline, which was approximately 4-in. thick.

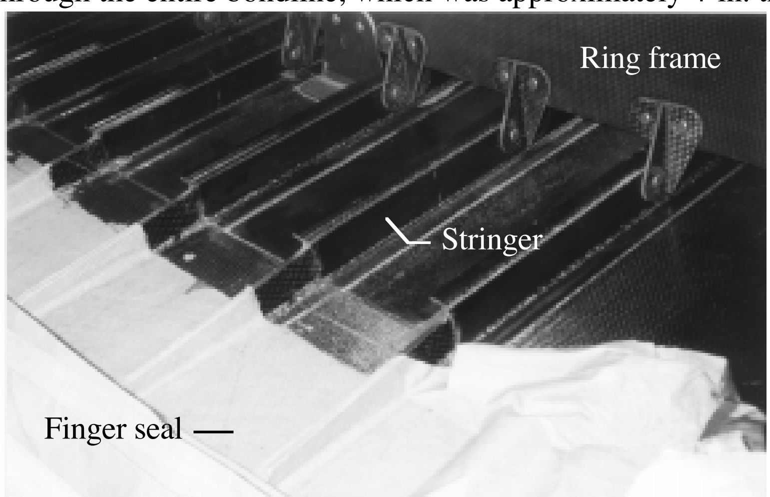

Figure 104: Photograph of the finger seal after bonding to the panel.

Appendix B: Test Panel Planform

The inside dimensions and bolt lines of the transition channel are shown in Figure 105. The transition channel, with inside dimensions 74 11/16 in. x 62 7/8 in. is bolted to the top of the pressure box. The inside dimensions of the pressure box are 74 in. x 62 in. The difference in the inside dimensions between the pressure box and the transition channel results in part from a 0.5-in-thick plate on the inside of the pressure box that is not on the transition channel.

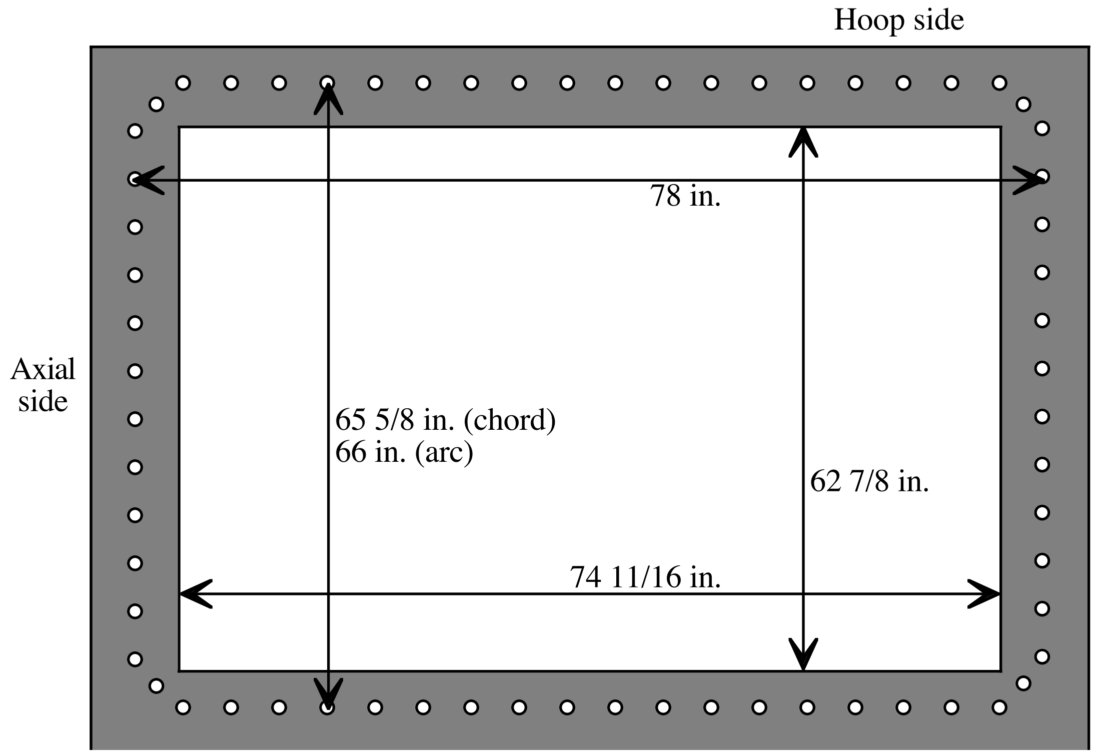

Figure 105: Schematic diagram showing inside dimensions of the transition channel and bolt line on the transition channel.

A reaction load due to internal pressure and applied load from the hydraulic actuators is transferred to the test panel from the load plate by way of metallic fingers. The test panel and load plate are sandwiched between the fingers as shown in Figure 106. There is a 1-in-wide gap between the test panel and the load plate. A single screw is located in the center of the 1-in gap on the lower finger to attach the C-seal to the lower finger. The bottom of the C-seal is attached to the top of the transition channel by bolts that are located approximately 1 5/8 in. (measurements ranged from 1 7/16 to 1 3/4) from the inside surface of the transition channel, as shown in the figure. It is beneficial to locate the C-seal attachments in a vertical plane so the C-seal, when pressurized, will form a semi-circular shape. A semi-circular shape will prevent a large flat portion of pressurized seal bearing on the load plate or transition channel.

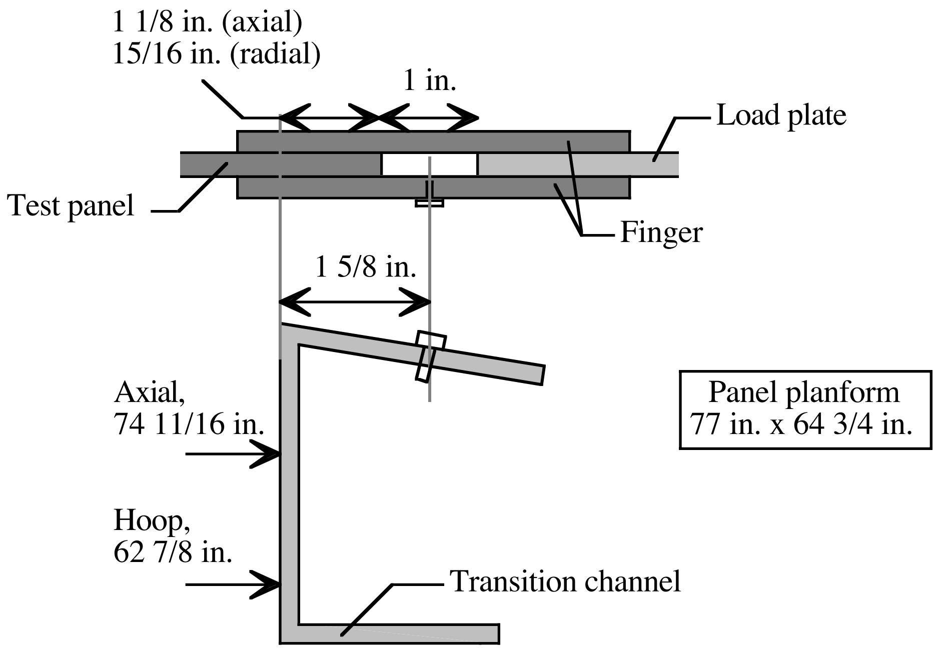

Figure 106: Schematic diagram showing the location of the test panel relative to the transition channel.

Two different measurements can be used to determine the required panel planform. The first used the bolt hole centerline to bolt hole centerline distance across the transition channel in both the axial and hoop directions. In the axial direction, this distance is 78 in., and in the hoop direction the chord length is 65 5/8 in. (arc length is 66 in.) A 1-in. gap between the panel and the load plates requires that 0.5 in. be taken off of each side, giving a panel planform of 77 in x 64 5/8 in.

The panel planform can also be determined by adding the distance from the inside surface of the transition channel to the bolt hole centerline to the distance across the transition channel. The difficulty here is the wide variation in the distance from the inside surface of the transition channel to the bolt hole centerline. In the axial direction, with bolt holes approximately 1 5/8 in from the inside surface, a 1 1/8 in overlap on the panel is required. The axial dimension is thus 74 11/16 in. + 1 1/8 in. + 1 1/8 in. = 76 15/16 in. In the hoop direction, the bolt hole centerline is approximately 1 7/16 in. from the inside surface. Thus the hoop dimension is 62 7/8 in. + 15/16 in. + 15/16 in. = 64 3/4 in.

The two measurements are similar, but are different due to the variation in the distance from the inside surface of the transition channel to the line of bolts. The test planform can be taken to be 77 in x 64 3/4 in.

Diodes are used on the test panel to control the fan heat exchanger cooling. Twelve diodes are located on the test panel centered directly above each fan heat exchanger, and one diode is located in the center of the panel. Figure 107 shows the positioning of the fan heat exchangers relative to each other. The fan heat exchangers are centered in the pressure box, and under the test panel. The diodes should thus be positioned symmetrically on the test panel. In the axial direction, the diode spacing and heat exchanger spacing are equal, but in the hoop direction, the arc length on the panel between diodes is slightly larger than the distance between heat exchangers on the flat surface of the pressure box.

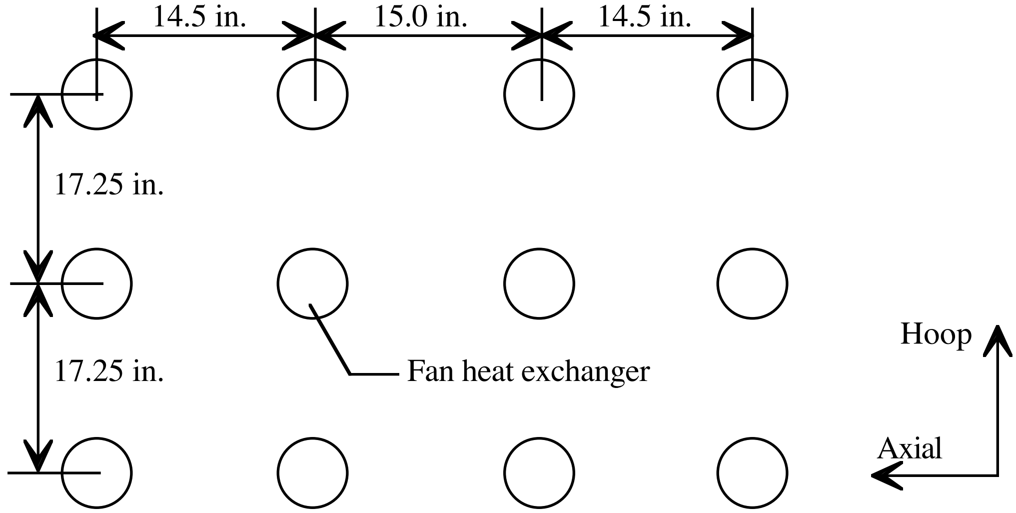

Figure 107: Schematic drawing showing relative location of the fan heat exchangers.

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13. ABSTRACT (Maximum 200 words)
A cryogenic pressure box was designed and fabricated for use at NASA Langley Research Center (LaRC) to subject 72 in. x 60 in. curved panels to cryogenic temperatures and biaxial tensile loads. The cryogenic pressure box is capable of testing curved panels down to -423°F (20K) with 54 psig maximum pressure on the concave side, and elevated temperatures and atmospheric pressure on the convex surface. The internal surface of the panel is cooled by high pressure helium gas that is cooled to -423°F by liquid helium heat exchangers. An array of twelve independently controlled fans circulate the high pressure gaseous helium to provide uniform cooling on the panel surface. The load introduction structure, consisting of four stainless steel load plates and numerous fingers attaching the load plates to the test panel, is designed to introduce loads into the test panel that represent stresses that will be observed in the actual tank structure. The load plates are trace cooled with liquid nitrogen to reduce thermal gradients that may result in bending the load plates, and thus additional stresses in the test panel. The design of the cryogenic systems, load introduction structure, and control system are discussed in this report.

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