Safety Evaluation of the CERN Vertex Magnet's *LHe* Pump Dewar

J. Patrick Kelley

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MUON DESIGN NOTE NO. 35

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NOMENCLATURE

Capital Letters

A -	Area
A' -	Reduced area for a rupture disc
A_4 -	Roark and Young [1] defined value for elastic foundation beam solution
A_b -	Minor area of a single bolt
B_4 -	Roark and Young [1] defined value for elastic foundation beam solution
C -	Flow coefficient for a square edged orifice
C_4, C_7, C_8, C_9 -	Roark and Young [1] defined value for annular plate solutions
D -	Roark and Young [1] defined value for annular plate solutions
E -	Weld efficiency
E^C -	Weld efficiency for a circumferential weld
E^L -	Weld efficiency for a longitudinal weld
F_G -	Force applied by annular flange inner O-ring
F_{ID}-	Total force on inner edge of annular flange
F_{OD}-	Total force on outer edge of annular flange
$F_{Pe}(r)$ -	Force due to external pressure - $\pi r^2 P_e$
$F_{Pi}(r)$ -	Force due to internal pressure - $\pi r^2 P_i$
G_i -	Factor used for relief sizing for insulated vessels
K -	Resistance coefficient
$\overline{K}$ -	Average thermal conductivity
K_{cv} -	Resistance coefficient for the CERN check valve
K_{RD} -	Resistance coefficient for the Fike rupture disc
K_{mb} -	Value used for annular plate moment calculation
L -	Inside crown radius for torispherical head
L_b -	Load on a single bolt
L_e -	Equivalent length
L_b^T -	Total load on the bolts coupling the flat head to the annular flange
L_6, L_9, L_{14}, L_{17} -	Roark and Young [1] defined values for annular plate solutions.
M -	Code defined value for evaluating torispherical heads
M_a -	Moment at a
M_b -	Moment at b
M^T -	Total moment at a point
P -	Maximum allowable working pressure
P_e -	External pressure
P_i -	Internal pressure
P^c -	Maximum allowable working pressure for circumferential stress
P^l -	Maximum allowable working pressure for longitudinal stress

P^H_{mawp} - Maximum allowable working pressure based on the hydrostatic pressure test

P_1' - Absolute pressure upstream of an orifice

ΔP - Pressure drop

Q - Heat load, BTU/Hr.

R - Inside radius

S - Maximum allowable stress based on code values and the Fermilab required factor of .8.

S_b - Maximum allowable stress in the bolts coupling the flat head to the annular flange

T - Throat dimension

ΔT - Temperature difference

U - Thermal conductivity of lading saturated insulation per unit thickness of insulation

V - Volumetric flowrate

V' - Reduced volumetric flowrate for a rupture disc

V_{cs} - Volumetric flowrate through one Circle Seal relief valve

V^T_{cs} - Total volumetric flowrate through all the Circle Seal relief valves

W_C - Weight of cryogen

W_D - Weight of dewar without the flat head

W_F - Weight of annular flange

W_{F1} - Annular plate weight in Problem 1

W_{F2} - Annular plate weight in Problem 2

W_{He} - Weight of cryostat lading (LHe)

W_V - Weight of the vacuum vessel

ΔX - Insulation thickness

Y - Net expansion factor

Small Letters

a -	Outer radius of an annular plate or flange
b -	Inner radius of an annular plate or flange
d -	Diameter
d_0 -	Orifice inlet diameter
d_1 -	Orifice diameter
f_T -	Turbulent friction factor
g -	Gravity
k -	Ratio of the specific heats
l -	Maximum length affected by a load
m -	Loading application limits for an Elastic Foundation problem
n -	Loading application limits for an Elastic Foundation problem
r -	Radius
r_K -	Inside knuckle radius for torispherical head
r_o -	Point of application of a load
t -	Wall thickness
v -	Velocity
w -	Line load
w_{ID} -	Line load on the inside diameter of the annular flange

Greek Letters

σ -	Stress
σ_H -	Stress during hydrostatic test
σ_{mawp} -	Stress at maximum allowable working pressure of vessel
σ_b -	Stress in a bolt
ρ -	Density
λ -	Wave length used to determine affected length resulting from a load
Θ -	Angle used to calculate weld throat diminension

1 Introduction and History

The LHe pump dewar for the CERN Vertex Magnet (CVM) was one of four identical dewars built for CERN by Cryodiffusion of Lery, France in 1977. The dewar was designed by Michel Marquet, a cryogenic engineer, who was then, and is presently, working at CERN. The dewars were constructed of 304L stainless steel, and were designed for a pressure of 65 *psia* (4.5 *bar abs.*). These four dewars have all operated, for various periods of time, at CERN without incident. The vessels were designed, as much as possible, to the SNCT code, the French equivalent to the ASME Boiler and Pressure Vessel Code (BPVC). Material controls and welding procedures and certifications were applied to the construction of the dewars, however, the applicable records are not obtainable. All of the vessels were examined radiographically, in accordance with the International Federation of Welding rules, with 100% of the longitudinal welds being examined and 10% examination of all other welds. Records of the radiography performed on our vessel are not available, however, a copy of the CERN Safety Document for the vessel, RP156, has been obtained (see Appendix A for a translated copy of this document). RP156 indicates that the radiography was carried out, and that it was checked by the CERN Safety Department. RP156 also indicates that the vessel was hydrostatically tested to 5.75 $bar(83.34psi)$. During this test the cryostat's head was instrumented with strain gauges and a maximum stress of 9246 $psi(6.5Kg/mm^2)$ was recorded.

It is the purpose of this document to evaluate the CVM's pump dewar for a maximum allowable working pressure of 32 *psig*. This evaluation will be accomplished following the tenets of Fermilab's Engineering Standard SD-37B. The pump dewar is a used vessel and, under the tenets of SD-37B, is to be treated as an existing vessel, as described by paragraph 4.5. Since the dewar is a non-coded vessel (does not carry an ASME BPVC U stamp, indicating that it was not built in accordance with the BPVC), it is required that

- an analysis cumulating in an engineering note be performed using a penalty factor of .8 on the maximum allowable stress value given by the BPVC Section VIII (referred to as "the Code") to offset the assumed lack of material controls and third party inspection. Included in the engineering note shall be an analysis of the vessel's venting system to verify that overpressurization beyond the limits of Paragraph UG 125 of the BPVC Section VIII Division 1 will not occur.

- the vessel has been tested per code rules at sometime in its history.

- if no qualified welding (per code rules) is documented, the vessel shall be examined and judged per the nondestructive examination procedures of the Code by personal qualified per Code rules.

The order in which this document will consider these requirements shall be in the reverse order of the above listing.

The primary reference print to be used for this evaluation of the CVM's pump dewar is CERN Drawing Number 303605. This and all other referenced prints are included in Appendix B.

The dewar is actually two vessels; an inner pressure vessel or cryostat and an outer vacuum vessel. The outer or vacuum vessel falls under the provisions of the tentative Fermilab Vacuum standard, SD-41, and has been previously evaluated in the Muon Cryosystem Design Note #29. A copy of this design note is included in Appendix C. Therefore the components of interest as shown in Drawing #303605 are

Component	Item #	Additional Reference
Vessel Neck	13	—
Conical Reducer	12	—
Vessel Body	11	—
Lower Torispherical Head	4	—
Upper Head	32	314001
Annular Flange	19	313999

These components make up the pressure boundary of the vessel and, hence, are the major topic of this document.

2 Non-Destructive Examination of the CVM's Pump Dewar's Cryostat

2.1 Radiography

Since the certifications stating that qualified welding was performed on the pump dewar cryostat are unavailable, the welds of the vessel were radiographed. The radiography and subsequent evaluation of the exposed film was performed by personnel from Argonne National Laboratory's Support Services Division/Inspection Group. These individuals have been qualified per code rules to examine and judge the quality of welds per code rules. Copies of their individual certifications are included in Appendix D.

Results of the radiography are given in Table 1, and copies of the individual radiography records are included in Appendix E. The columns in Table 1 are as follows. Column 1 identifies the components joined by a weld. Column 2 gives the number assigned to the weld by Argonne's NDT personnel and is necessary for easy cross-referencing to the records in Appendix E. The third column identifies by item number (Drawing #303605) the components being joined. Column 4 lists the code category of each weld, as defined by paragraph UW-3 of the BPVC. The weld type, as defined by the BPVC in Table UW-12, is given in Column 5. Column 6 lists the percentage of the weld radiographed and Column 7 defines the amount of radiography required for each weld by the code in paragraph UW-11. Column 8 lists whether the weld met the code standards, and the last column lists the weld efficiency, E, allowed for the weld by the code for code based calculations of allowable thicknesses and pressures. Please note that all of the welds were found to be satisfactory. It should also be noted that the conical reducer and the torispherical head, items #12 and 4, respectively, are formed pieces and, hence, have no longitudinal welds.

Some comments should briefly be made about the weld connecting the Cryostat Neck to the Annular Flange (ANL #J3). This weld is not a code-type weld, however, it is not forbidden by the code. This circumstance is covered by paragraph U-2(g) of the code which permits its use if it can be satisfactorily demonstrated that the weld is as safe as those provided by the rules of the code. In Section 4.5, we shall demonstrate, by analysis, that the stress levels in the weld will never exceed the maximum allowable stress of the weld material.

2.2 Ultrasonic Testing

Ultrasonic thickness measurements were also performed on the vessel. This was done primarily because two of the components were formed pieces and, hence, would have considerable variation in wall thickness. Four of the six vessel components were inspected, the annular flange and the flat head, items 32 and 19, being the exceptions. The ultrasonic testing was performed by the same group that performed the radiography described above. These people are code-certified to ultrasonically examine materials and interpret the results. Copies of their personal certifications are included in Appendix F.

Results of the ultrasonic thickness measurements are summarized in Table 2. Included there are the number of readings made on a component (sample size), the resulting grid size based on a uniform distribution of the readings over the component's surface, the minimum and maximum reading of the sample, and the statistical average, median and standard deviation of the sample. It should be noted that, though 60 readings were made on the conical reducer, the grid for the reducer is based on 48 readings. After establishing the grid, an additional 12 readings were made, six on the upper (outward) bend and six on the lower (inward) bend of the reducer. The 12 individual readings each represent the thinnest point of the bend between the pair of grid points that straddle the bend. The readings were obtained by moving vertically over the bend and recording the smallest reading observed. Note that these points will skew the statistics, which are based on all 60 readings.

Copies of the ultrasonic technique records are given in Appendix G, as are

Table 1: Summary of Vessel Radiography

Weld	ID #	Component Numbers	Code Category Para UW-3	Code Weld Type Table UW-12	% Radiography	Code Classification	Pass ?	Code Weld Efficiency-E
Cryostat Neck to Annular Flange	J3	13 to 19	C	–	100	Full	Yes	–
Cryostat Neck's Longitudinal Weld	J1	13	A	1	100	Full	Yes	1
Cryostat Neck to Reducer	J4	13 to 12	B	3	18.5	Partial	Yes	.8
Reducer to Cryostat Body	J5	12 to 11	B	3	14.8	Partial	Yes	.8
Cryostat Body's Longitudinal Weld	J2	11	A	1	100	Full	Yes	1
Cryostat Body to Torispherical Head	J6	11 to 4	B	3	14.8	Partial	Yes	.8
Torispherical Head's Cap (outer)	J7	4	A	3	18.6	Partial	Yes	.8
Torispherical Head's Cap (inner)	J7	4	A	3	11.9	Spot	Yes	.8

Table 2: Summary of Vessel's Ultrasonic Thickness Measurements

Component	Item	# Readings	Grid	Grid Exception	Minimum Reading	Maximum Reading	Average	Median	Standard Deviation
Cryostat Neck	13	48	4″	–	.0587″	.0600″	.0596″	.0595″	.0003″
Conical Reducer	12	60	$1\frac{3}{32}''$	Based on 48 Pts.	.0883″	.1471″	.1095″	.1177″	.0153″
Cryostat Body	11	48	$3\frac{13}{16}''$	–	.0792″	.0805″	.0799″	.0799″	.0003″
Torispherical Head	4	48	2″	–	.1295″	.1611″	.1503″	.1453″	.0094″

Table 1: Summary of Vessel Radiography

Table 2: Summary of Vessel's Ultrasonic Thickness Measurements

sketches of the locations of all grid points. Note that the resolution of the instrument used to make the measurements is $\pm.0001''$. The accuracy of inspection was $\pm.0005''$.

3 Pressure Test of the CVM's Pump dewar

CERN hydrostatically tested the CVM pump dewar's cryostat for two reasons. The first was to proof-test the fabrication of the vessel, and the second was to verify that their design for the cryostat's flat head was adequate. As was noted previously, the head was instrumented with strain gauges which recorded a stress of 6.5 Kg/mm^2 (9246 psi) when the vessel was hydrostatically pressurized to 5.75 bar(83.34 $psid$). The ASME BPVC requires that the vessel be hydrostatically proof-tested at a pressure of 1.5 times the maximum allowable working pressure (MAWP) of the vessel. This implies that the MAWP of the vessel could be as high as

$$\begin{aligned} P^H_{MAWP} &= \frac{1}{1.5} * 5.75\ bar\ diff * \frac{14.5\ psi}{1\ bar} \\ &= 55.58\ psid\ , \end{aligned}$$

or

$$P^H_{MAWP} = 40.88\ psig\ .$$

Since it is our intention to relieve the vessel at 32 $psig$(46.7 $psia$), the CERN hydrostatic test satisfies our requirements for a proof-test of the vessel.

4 Analysis of Vessel Components

In this section, we shall

- evaluate, by analysis, five of the six vessel components,
- discuss the hydrostatic test of the cryostat's flat head, and
- evaluate the weld coupling the cryostat's neck to the annular flange.

In all cases, the maximum allowable stress, S, shall be the value given by the code in Table UHA-23 for 304L stainless steel of 15700 *psi* times a factor of .8, as required by Fermilab's Standard SD-37B. Therefore

$$S = .8 * 15700\ psi\ ,$$
$$S = 12560\ psi\ .$$

It should be noted that three of the components are covered explicitly by the code, and hence shall be evaluated using the code's equations. These three components are the cryostat's neck and body and the torispherical head. Since the other components are not covered by the code, other methods must be used to demonstrate that they are as safe as a code-evaluated component. For the conical reducer, the Finite Element Code ANSYS is used to apply an ASME BPVC Division 2 type analysis to the component. The annular flange is evaluated by applying the formulas found in Roark and Young [1] to the flange. As mentioned previously, an instrumented hydrostatic test was applied to the flat head to evaluate its' stress levels.

4.1 Evaluation of the Cryostat's Neck and Body

The cryostat's neck and body, both being cylindrical shells under internal pressure, are evaluated using the same equations. From paragraphs UG-27(c) (1) and (2) of the code, the maximum allowable working pressure for these components is the lesser of

$$P^c = \frac{SE^Lt}{R+.6t} \qquad \text{Circumferential Stress (Longitudinal Joints)}$$

or

$$P^L = \frac{2SE^ct}{R-.4t} \qquad \text{Longitudinal Stress (Circumferential Joints)}$$

The values for the variables for each component are given in Table 3 as are the calculated values of pressure. Note that the thickness used in the calculations is the minimum thickness found using the ultrasonic thickness measurements from

Table 3: Cryostat Neck and Body Values

	S psi	E^c	E^L	t $in.$	R $in.$	P^c $psid$	P^L $psid$
$Neck$	12560	.8	1	.0582	11.81	61.71	98.73
$Body$	12560	.8	1	.0787	15.67	62.89	101.13

Table 2 minus the accuracy of inspection, .0005″. Additionally note that since circumferential stresses are applied to longitudinal joints, the weld efficiency used in calculating the maximum pressure resulting in a circumferential stress value equivalent to the maximum allowable stress is the efficiency of the longitudinal weld joint. A similar situation exists for longitudinal stresses and circumferential welds.

Our results in Table 3 indicate that the circumferential stresses lead to the more conservative values of the maximum allowable working pressure. Since we shall be relieving the vessel at 32 *psig*, the neck and body of the cryostat, with an applied exterior vacuum, could see 46.7 *psid*. Since this value is less than the MAWP for either component, the cryostat's neck and body are adequately sized.

4.2 Evaluation of the Torispherical Head

The MAWP for the torispherical head of the cryostat may be evaluated using the equations of Mandatory Appendix 1 of the code. For a torispherical head under internal pressure, the MAWP for a given wall thickness is defined to be

$$P = \frac{2SEt}{LM + .2t}$$

where

$$M = \frac{1}{4}\left[3 + \left(\frac{L}{r_K}\right)^{1/2}\right].$$

Table 4 lists the variable values for the cryostat's head, and the results obtained upon their substitution into the above equations. Note that the value for the weld efficiency, E, is obtained from Table 1 for the joints in the torispherical head. Thickness used is again the minimum value given in Table 2 for the head minus the accuracy of inspection. The MAWP obtained for the head, 53.76 *psid*, is greater than the maximum differential pressure the head will see during operation: the relief pressure of 46.7 *psid*. Hence, the torispherical head is adequate for the service demands of the vessel.

Table 4: Values for the Cryostat's Torispherical Head

	S psi	E	t in.	L in.	r_k in.	M	P psid
Torispherical Head	12560	.8	.1290	31.50	3.20	1.53	53.76

4.3 Evaluation of the Conical Reducer

An evaluation of the cryostat's conical reducer has been carried out by Mr. Robert H. Wands of Fermilab's RD/Cryogenic Department. Mr. Wands conducted his evaluation using the Finite Element Code ANSYS. His results were found to satisfy the requirements set by the ASME BPVC Section VIII, Div. 2, Appendix 4, for a maximum allowable stress of 12560 *psi*. Mr. Wands discusses the analysis and results in a memo to the author. A copy of this memo is included in Appendix H.

4.4 Evaluation of the Annular Flange

The code has no rules that adequately govern the design of an annular flange which also serves as the head of another (vacuum) vessel. We therefore utilize existing solutions for annular plates found in Roark and Young [1] with the principle of superposition to evaluate the stresses in the flange. Note that the CERN drawing for this flange, #313999, is included in Appendix B.

Figure 1 is a free body diagram of the cross-section of the flange. The inner edge of the flange sees a line load that is the distributed sum of the cryostat's weight, W_C, the weight of the cryogen, W_{He}, and the force resulting from the internal pressure of 46.7 *psid* on the area equivalent to the mouth of the dewar neck, $F_{p_i}(r = 11.87'')$. Defining F_{ID} as the sum of these three forces, we have

$$F_{ID} = W_C + W_{He} + F_{P_i}(r = 11.87'')$$

where, in general, $F_{p_i}(r)$ may be written

$$F_{p_i}(r) = \pi r^2 P_i \ .$$

Next there is the internal pressure of the cryostat applied to the area of the flange between the flange's inner edge and the outer edge of the O-ring sealing the flat head to the annular flange. At the O-ring there is a force, F_G, arbitrarily chosen to have a value of 500 lb., resulting from the initial preloading of the bolts. Since the flat head of the vessel is securely mounted to the vessel's support structure there is, at the bolt circle, a reaction load. This load is the sum of the weight of the vessel, W_D, plus the force resulting from the internal pressure distributed over the area bound by the O-ring, $F_{p_i}(r = 14.13'')$. It is these two forces that are trying to separate the flange from the head. The next load considered is the atmospheric pressure, P_e, applied between the inner and outer O-rings of the flange. The weight of the flange, W_F, though not significant, is included in the analysis. Finally, at the outer O-ring there is a load applied that is the difference between the pressure load on the outside of the vacuum vessel, $F_{p_e}(r = 20.57'')$, and the weight of the vacuum vessel, W_V. Defining F_{OD} as the differences of these two forces, we have

$$F_{OD} = W_V - F_{p_e}(r = 20.57'') \ ,$$

where

$$F_{p_e} = \pi r^2 P_e \ .$$

Note that all of the forces described above are applied as line loads at the radius of the application. A summary of the loads on the annular flange is given in Table 5.

To find the maximum stress in the annular flange, we shall divide the problem into two small problems and sum the results. Since the annular flange is bolted directly to the flat head, which is fixed to the dewar support structure, we shall regard the flange as fixed at the bolt circle. This allows us to divide the problem into the two smaller problems of an annular flange with a fixed outer radius (Problem 1), and an annular flange with a fixed inner radius (Problem 2). Note that since the wall thickness of the cryostat's neck, is much less than the thickness of the flange, the moment applied to the inner edge of the flange is negligible. Hence, the second boundary condition of Problem 1 is taken to be a free inner edge with an applied load. The outer edge of the flange may also be regarded as having a free boundary condition with a known applied load. Free-body diagrams for these two problems are shown in Figure 2. It should be mentioned that the point of application for the flange weight was found by calculating the center of mass for a section of the flange, with an arc length of one inch along the inner edge of the flange. This same section was used to calculate the centers of mass for the two smaller problems.

Many of the existing solutions for annular plates, with various load and boundary conditions, have been collected by Roark and Young [1] and are presented in their Table 24. For Problem 1, we have five line loads or pressures applied to an annular plate with a free inner edge and a fixed outer edge. General solutions for this set of boundary conditions with individual line loads or applied pressures are respectively given by Case 1e and Case 2e of Roark and Young's Table 24. Reproducing the general solutions for the moment at the fixed edge for the two load conditions, we have

<u>For line loads</u>

$$M_a^w = -wa \left[L_9 - \frac{C_7 L_6}{C_4} \right] \tag{1}$$

where

$$C_4 = \frac{1}{2} \left[(1+\nu)\frac{b}{a} + (1-\nu)\frac{a}{b} \right]$$

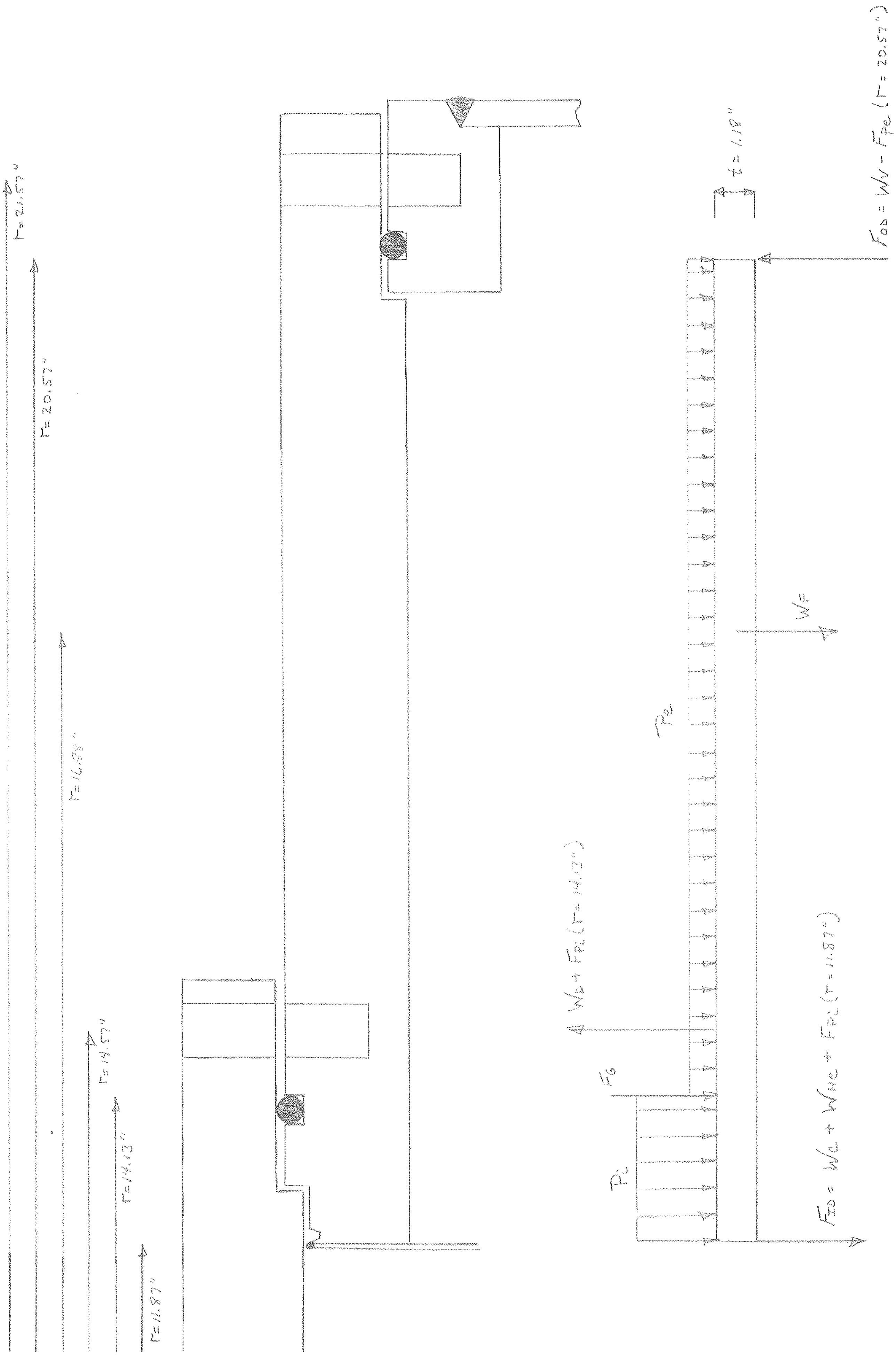
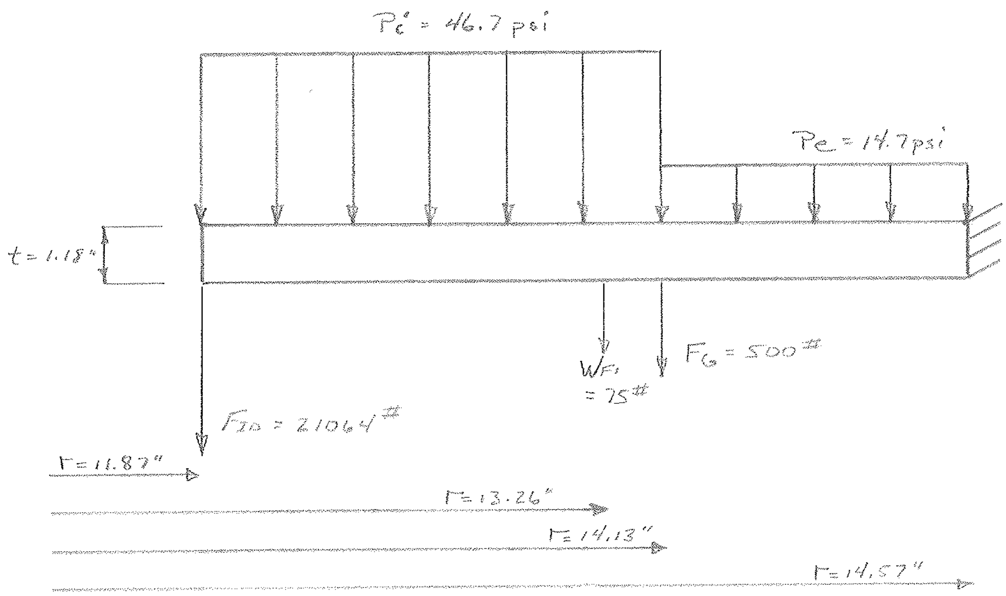
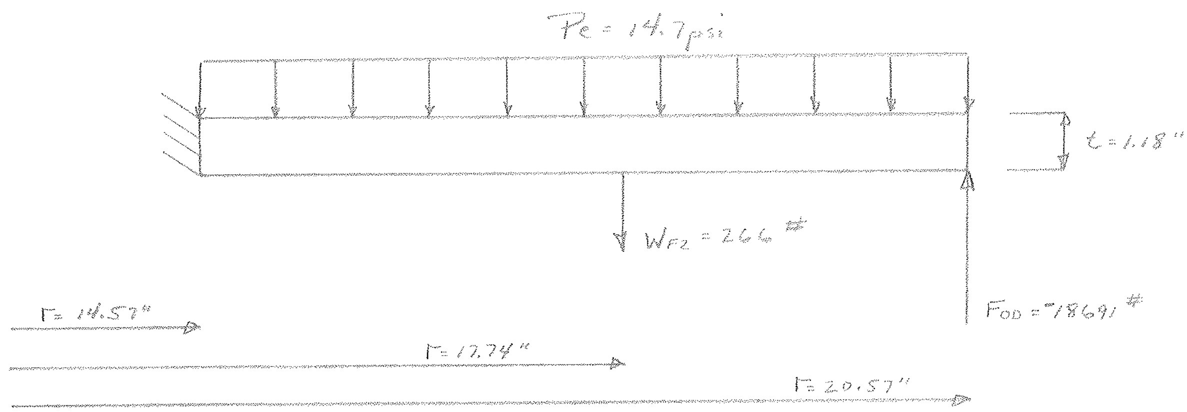


Figure 1: Free Body Diagram for the Annular Flange



PROBLEM 1

FREE INNER EDGE, FIXED OUTER EDGE



PROBLEM 2

FIXED INNER EDGE, FREE OUTER EDGE

Figure 2: Free Body Diagrams for Annular Flange Subproblems

Table 5: Loads on the Annular Flange.

Load	
W_C	277 *lb.*
W_{He}	116 *lb.*
$F_{p_i}(r = 11.87'')$	20671 *lb.*
F_{ID}	21064 *lb.*
P_i	46.7 *psi*
P_e	14.7 *psi*
F_G	500 *lb.*
W_F	341 *lb.*
W_{F1}	75 *lb.*
W_{F2}	266 *lb.*
W_D	1584 *lb.*
$F_{p_i}(r = 14.13'')$	29292 *lb.*
W_V	850 *lb.*
$F_{P_e}(r = 20.57'')$	−19541 *lb.*
F_{OD}	−18691 *lb.*

$$
\begin{aligned}
C_7 &= \frac{(1-\nu^2)}{2}\left[\frac{a}{b} - \frac{b}{a}\right] \\
L_6 &= \frac{r_0}{4a}\left[\left(\frac{r_0}{a}\right)^2 - 1 + 2ln\frac{a}{r_0}\right] \\
L_9 &= \frac{r_0}{a}\left\{\frac{(1+\nu)}{2}ln\frac{a}{r_o} + \frac{(1-\nu)}{4}\left[1 - \left(\frac{r_0}{a}\right)^2\right]\right\}
\end{aligned}
$$

For pressure

$$
M_a^P = Pa^2\left[L_{17} - \frac{C_7}{C_4}L_{14}\right] \tag{2}
$$

where

$$
\begin{aligned}
L_{14} &= \frac{1}{16}\left[1 - \left(\frac{r_0}{a}\right)^4 - 4\left(\frac{r_0}{a}\right)^2 ln\frac{a}{r_0}\right] \\
L_{17} &= \frac{1}{4}\left\{1 - \frac{(1-\nu)}{4}\left[1 - \left(\frac{r_0}{a}\right)^4\right] - \left(\frac{r_0}{a}\right)^2\left[1 + (1+\nu)ln\frac{a}{r_0}\right]\right\}
\end{aligned}
$$

We are interested in the moment at the fixed edge, since this will be the point of maximum stress for the subproblem, and since the stress is directly proportional to the bending moment.

The general solutions given above are solutions to linearized differential equations and, hence, since they have the same boundary conditions, may be superimposed (added together) to form a new and unique solution. We shall use this principle of superposition to solve Problem 1 (and Problem 2). We first use eq. (1) to solve the three individual problems of finding the moment at the plate's fixed edge resulting from the individual line loads of the forces F_{ID}, W_{F1} and F_G. We then utilize eq. (2) to find the moment at the fixed edge caused by a pressure equivalent to P_i, distributed over the entire plate. Again utilizing eq. (2), we find the moment at the fixed edge caused by a pressure equivalent to the difference $P_i - P_e$, distributed over the area between the outer edge of the plate and the O-ring. It should be clear that the difference in the two pressure distributions just described will result in the pressure distribution of Problem 1. Once we find these five values for moment, we add the first four together and subtract the fifth. These operations will give us the moment at the fixed edge caused by the load condition of Problem 1. The results of these calculations are presented in Table 6. We see from Table 6 that the maximum moment at the fixed outer edge of the annular plate of Problem 1 (fixed outer edge) is

$$M_a^T = -783.1 \; in.lb./in.$$

where the minus sign indicates that the moment creates compression on the bottom surface of the plate. Once we have solved Problem 2, we shall sum the magnitude of the two moments, and then calculate the stress at the bolt circle for our original problem of the annular flange.

We shall now use the same basic approach that we used for Problem 1 to solve Problem 2. Referring to Figure 2, Problem 2 consists of an annular plate with a fixed inner edge and a free outer edge, two line loads, and one distributed load (pressure). Again referring to Roark and Young [1], Table 24, solutions for this set of boundary conditions and loads are covered by Cases 1*l* and 2*l*. We are interested in the bending moment at the fixed inner edge. Recall that this corresponds to the location of the bolt circle of the annular flange: the point of maximum stress. The general solution given by Case 1*l* for the bending moment at the fixed inner edge, resulting from an applied line load is

$$M_b^w = -\frac{wa}{C_8}\left[\frac{r_0 C_9}{b} - L_9\right] \tag{3}$$

where

$$\begin{aligned}
C_8 &= \frac{1}{2}\left[1 + \nu + (1-\nu)\left(\frac{b}{a}\right)^2\right] \\
C_9 &= \frac{b}{a}\left\{\frac{(1+\nu)}{2} ln\frac{a}{b} + \frac{(1-\nu)}{4}\left[1 - \left(\frac{b}{a}\right)^2\right]\right\} \\
L_9 &= \frac{r_0}{a}\left\{\frac{(1+\nu)}{2} ln\frac{a}{r_0} + \frac{(1-\nu)}{4}\left[1 - \left(\frac{r_0}{a}\right)^2\right]\right\}
\end{aligned}$$

For the special case of a line load applied at the outer edge of the plate, eq. 3 reduces to

$$M_b^w = -\frac{wa^2}{b}\frac{C_9}{C_8} \tag{4}$$

The general solution given by Case 2*l* for the bending moment at the fixed inner edge of an annular plate resulting from a pressure applied over the entire plate is

$$M_b^P = K_{Mb}Pa^2 \tag{5}$$

where K_{Mb} is found by interpolating between values that are functions of the plate's aspect ratio, b/a, and are presented in a table in Case 2*l*. The table is applicable to materials with a Poisson's Ratio of .3. The Poisson Ratio for our material is taken to be .305 [2], and hence the table may be used without introducing a large error. The results obtained from performing these calculations are given in Table 7. From Table 7 we see that , for the annular plate of Problem 2, the bending moment at the fixed inner edge is

$$M_b^T = 788.2\frac{in\ lb.}{in.}$$

where a positive moment implies compression along the top of the plate, and hence, in this case, is counterclockwise.

We now wish to take the results of Problems 1 and 2, and apply them to our original problem of the annular flange. Recall that the fixed outer edge of Problem 1 and the fixed inner edge of Problem 2 correspond to the same radius of the annular flange, that of the bolt circle. Hence, moments M_a^T and M_b^T are applied at the same radius of the annular flange. The two moments are in the counterclockwise direction, and so their magnitudes are summed to obtain the total moment, M^T, at the bolt circle. Therefore,

$$\begin{aligned} M^T &= |M_a^T| + |M_b^T| \\ &= (783.1 + 788.2)\frac{in\ lb.}{in.} \\ M^T &= 1571\frac{in\ lb.}{in.} \end{aligned}$$

This moment may be used to calculate the maximum stress in the annular flange. The stress in the annular flange is related to the moment by the equation

$$\sigma = \frac{6M^T}{t^2}.$$

The thickness at the bolt circle of the flange is 1.18 inches. Hence,

Table 6: Moment Calculation Results, Problem 1, Free Inner Edge, Fixed Outer Edge

Load	Magnitude and Direction	Case Roark & Young	w lb./in.	r_0 in.	C_4	C_7	L_6	L_9	L_{14}	L_{17}	Superposition Operation	M_a in lb./in.
F_{ID}	21064 lb.	1e	282.4	11.87	.9580	.1870	.01484	.1563	—	—	+	-631.2
W_{F1}	75 lb.	1e	.9	13.26	.9580	.1870	.003796	.08309	—	—	+	-1.08
F_G	500 lb.	1e	5.63	14.13	.9580	.1870	.0004468	.02943	—	—	+	-2.41
P_i	46.7 psi	2e	—	11.87	.9580	.1870	—	—	.001020	.01547	+	-151.4
$P_i - P_e$	32 psi	2e	—	14.13	.9580	.1870	—	—	$4.521 * 10^{-6}$	.0004483	—	-3.04
											$M_a^T = -783.1$	

Table 7: Moment Calculation Results, Problem 2, Fixed Inner Edge, Free Outer Edge

Load	Magnitude and Direction	Case Roark & Young	w lb./in.	r_0 in.	C_8	C_9	L_9	b/a	K_{Mb}	Superposition Operation	M_b in lb./in.
W_{F2}	266 lb.	1*l*	2.386	17.74	.8268	.2207	.1217	.7083	—	+	-8.727
F_{OD}	-18691 lb.	1*l*	-144.6	20.57	.8268	.2207	—	.7083	—	+	1121
P_e	14.7 psi	2*l*	—	14.57	—	—	—	.7083	-.0521	+	-324.1
										$M_b^T = 788.2$	

$$\sigma = 6\frac{(1571\ in\ lb./in.)}{(1.18\ in.)^2}$$
$$\sigma = 6771 psi\ .$$

Since the maximum allowable stress for the flange material is 12560 psi, the flange is adequate for its projected service application.

4.5 Evaluation of the Coupling Weld Between the Annular Flange and the Cryostat's Neck

In Section 2a of this report, we briefly discuss the fact that the edge weld joining the annular flange to the cryostat's neck is not included in the code's design recommendations for a coupling of this type. However, since the weld type for this application is not forbidden by the code, its use requires a demonstration that the weld is as safe as those provided by the rules of the code. In this section, we shall analytically demonstrate that the stress levels in the weld will never exceed the maximum allowable stress of the vessel material. Note that the edge weld is a fusion weld, and hence is of the same material as the vessel.

The stresses in the edge weld are a result of two major load conditions; axial loads and radial loads. The axial loads are the cryostat weight, W_c, the weight of the cryogen, W_{He}, and the hydrostatic end force, $F_{p_i}(r = 11.87'')$. The sum of these three forces is F_{ID}, which was defined in the previous section. The magnitude of F_{ID} is given in Table 5 to be

$$F_{ID} = 21064\ lb.$$

The direction of F_{ID} is shown in Figure 3. F_{ID} is the total axial load on the weld. The axial force per linear inch is therefore

$$w_{ID} = \frac{F_{ID}}{2\pi r} = \frac{21064\ lb.}{2\pi(11.87\ in.)}$$
$$w_{ID} = 282\ lb./in.$$

The radial loads on the edge weld result from the application of moments about the point designated A in Figure 3. These moments are caused by the hydrostatic pressure load on the cryostat's neck. We shall consider two moments in this analysis; that moment applied about A by the hydrostatic pressure to the neck between point A and the weld, and the moment applied about A by hydrostatic pressure below point A. Considering the later moment first, this moment may be found by applying the Elastic Foundation approach to the neck. Solutions using this approach for various loads and boundary conditions for semi-infinite beams have been collected by Roark and Young [1] and are presented in their Table 8. These solutions are

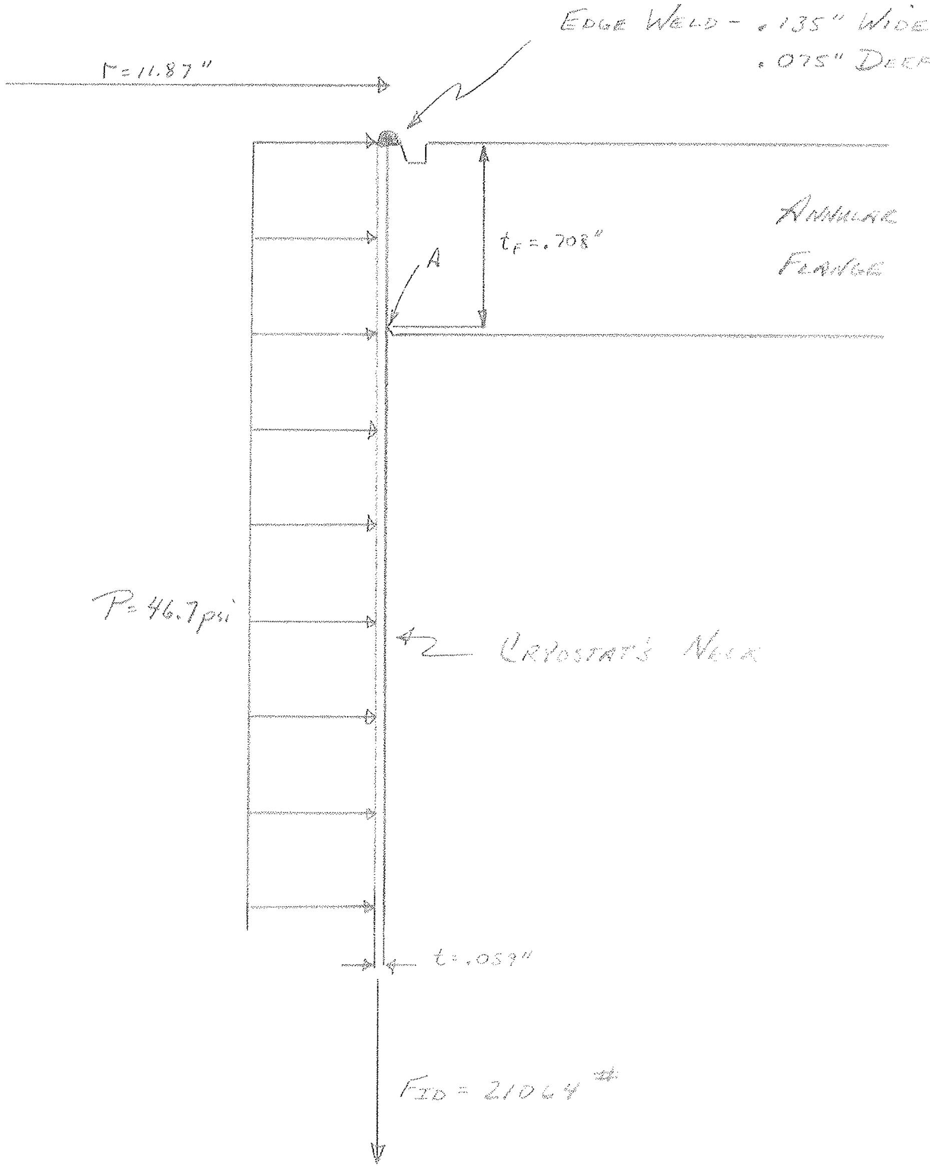


FIGURE 3

Figure 3: Sketch of the Joint Between The Cryostat's Neck and Annular Flange

directly applicable to cylinders upon substitution of λ for β and D for EI in the equations of Table 8 where

$$\lambda = \left[\frac{3(1-\nu^2)}{r^2t^2}\right]^{1/4}$$
$$D = \frac{Et^3}{12(1-\nu^2)} .$$

Before continuing further, we must determine whether the loads on the lower end of the cryostat's neck, where it mates with the conical reducer, have any effect on the moment at point A. From Roark and Young [1], Paragraph 7.5, if the inequality

$$\lambda l > 6$$

holds, then the loads at the lower end of the neck are at a sufficient distance from point A so that they need not be considered in the analysis. Therefore, if end loads are to be neglected, we require

$$l > \frac{6}{\lambda} = 6\left[\frac{3(1-\nu^2)}{r^2t^2}\right]^{-1/4}$$
$$l > 6\left[\frac{3(1-.305^2)}{(11.87in.)^2(.059in.)^2}\right]^{-1/4}$$
$$l > 3.91\ in.$$

The length of the cryostat's neck, l, is 31.85 inches and, hence, any end loads occurring at its lower end may be neglected in our analysis. Additionally, since the pressure is distributed over a length greater than 3.91 inches, we may view the neck as being semi-infinite in length and we need only to concern ourselves with the pressure distribution over the 3.91 inches nearest the weld.

For our situation, Case 2 of Table 8 of Roark and Young [1] is applicable. This case considers a uniformly distributed load between two points. Figure 4 illustrates the geometric parameters for this solution. The general solution for the moment at point A, which is considered to be fixed, is given by Case 2 to be

$$M_A = \frac{P}{\lambda^2}(B_4 - A_4) ,$$

where

$$A_4 = .5e^{-\lambda m}(\sin\lambda m + \cos\lambda m)$$
$$B_4 = .5e^{-\lambda n}(\sin\lambda n + \cos\lambda n) .$$

The results of performing these calculations are given in Table 8. From Table 8 we see that the moment at A is

$$M_A = -9.89\frac{in\ lb.}{in.} .$$

Table 8: Variable Values and Results for the Moment About Point A in Figure 3 Resulting From the Pressure Load Below Point A

P psi	λ $in.^{-1}$	m $in.$	n $in.$	A_4	B_4	M_A $in.lb./in.$
46.7	1.535	0	3.91	.5	$8.44 * 10^{-4}$	−9.89

This moment is the reaction to the applied moment. The minus sign implies that the reaction moment is clockwise about the point A of Figure 3.

We now consider the reaction to the moment applied by the pressure along the area of the dewar neck between the weld in question and the point A. This reaction moment is counterclockwise, and hence will be in the opposite direction to the moment given in Table 8. Since the neck is restricted (stiffened) by the flange over the area in question, the Elastic Foundation Theory will not be applied. Instead we shall segment the neck into 1″ wide beams. The reaction moment about A to a pressure of 32 *psi*, distributed over such a beam with a length of .708″, is equivalent to the reaction moment to a force with magnitude 32 *psi* * .708″ applied at the beam's midpoint. Hence,

$$\begin{aligned} M_A &= (32\ psi * .708'') * \frac{.708''}{2} \\ M_A &= 8.02 \frac{in\ lb.}{in.} \end{aligned}$$

Since the reaction moment is counterclockwise, it is positive. Summing with the moment presented in Table 8, we have

$$\begin{aligned} M_A^T &= (8.02 - 9.89) \frac{in\ lb.}{in.} \\ M_A^T &= -1.87 \frac{in\ lb.}{in.}\ . \end{aligned}$$

The applied radial force on the weld resulting from the moments about A is

$$\begin{aligned} w_r &= \frac{-M_A^T}{t_F} = \frac{1.87\ in\ lb./in.}{.708\ in.} \\ w_r &= 2.64 \frac{lb.}{in.} \end{aligned}$$

directed radially inward.

Summarizing briefly, the forces per linear inch applied to the edge weld coupling the annular flange to the cryostat's neck due to axial and radial loads are

$$w_{ID} = 282\ lb./in. \qquad \text{Directed Axially Downward}$$

and

$$w_r = 2.64\ lb./in. \qquad \text{Directed Radially Inward}\ .$$

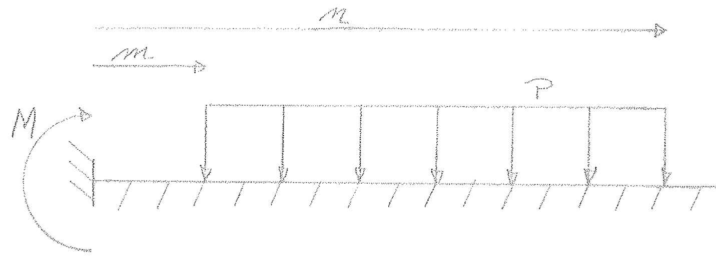


Figure 4: Geometric Parameters for the General Solution from Case 2, Table 8, from Roark and Young[1]

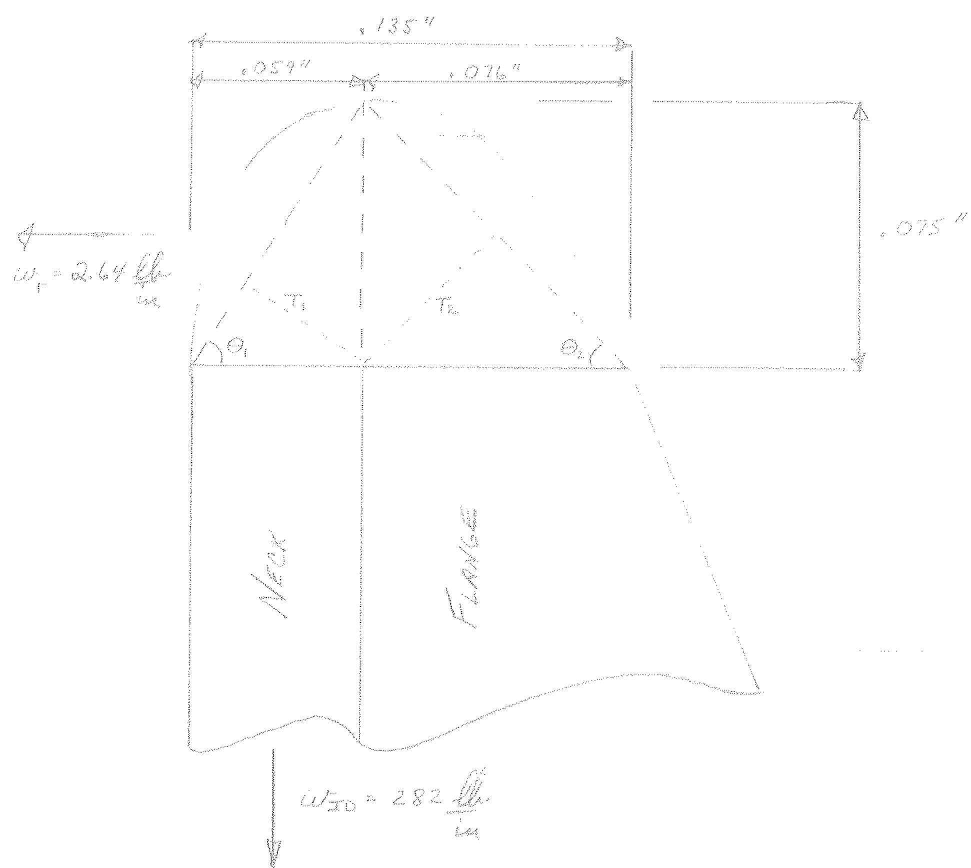


Figure 5: Dimensions and Forces on the Cryostat's Edge Weld

We now wish to determine the stress levels resulting from the loads w_{ID} and w_r upon the edge weld. We shall do this by treating the edge weld as the two inscribed fillet welds shown in Figure 5. In general, the stress in a fillet weld is taken to be the force externally applied to the weld divided by the area of the throat of the weld. For our situation this may be written

$$\sigma = \frac{w}{T} ,$$

where T is the throat of the weld. For axial loads, we shall consider the inscribed weld with throat T_1 as shown in Figure 5. For radial loads, we consider the weld with throat T_2. Values for T_1 and T_2 are trigonometrically obtained. The results of these calculations are presented in Table 9. As we can see, the highest stress levels

Table 9: Stresses in the Cryostat's Edge Weld

Load	w *lb./in.*	Θ	T *in.*	σ *psi*
Radial	14	44.62°	.053	262
Axial	282	51.81°	.046	6130

are caused by the axial loading with the value

$$\sigma = 6130 psi .$$

The radial stresses comparatively are negligible, having a value of 49.8 *psi*. The weld is a fusion weld, and hence is of the same material as the vessel. The maximum allowable stress for the vessel's material is 12560 *psi*. Applying a joint efficiency of .55 required by the BPVC, para. UW-18, and a weld efficiency of .9 for a 100% radiographed fillet weld, our maximum allowable stress for the weld is

$$\begin{aligned} \sigma_{max} &= .9 * .55 * 12560 \\ \sigma_m &= 6217 \ psi \end{aligned}$$

Hence, our weld is adequate.

4.6 Discussion of the Flat Head's Hydrostatic Test

The flat head of the cryostat is another item that has no set code rules governing design. Indeed, a cursory inspection of the drawing for the head (Appendix B, CERN Dwg#314001) would lead to the conclusion that the head's geometry is too complex for analytical analysis. Hence, our colleagues at CERN elected to test their design by experimentally evaluating the head and making any necessary modifications. From conversations with Michel Marquet, the dewar's designer, the head without the stiffening stays was instrumented with strain gauges. Without the stays, the stresses exceeded those allowed by the SNCT Code (19553 *psi* which corresponds to 1/4 of a tensile strength of 78210 *psi* allowed by this code), well before the maximum desired test pressure was reached. Addition of the stays, however, allowed the head to easily reach the desired test pressure of 5.75 bar (83.34 *psid*) without approaching the maximum allowable stress for the material. Indeed, the maximum recorded stress was 6.5 kg/mm^2(9246 *psi*), a fact that is documented in CERN Safety Document RP156. A copy of this document with a translation is included in Appendix A.

Since pressure and stress scale linearly, we can predict what the maximum stress will be in the head at our chosen MAWP of 32 *psig*. Hence

$$\begin{aligned}\sigma_{MAWP} &= \frac{P_{MAWP}}{P_H}\sigma_H \\ &= \frac{32\ psi}{83.34\ psi} * 9246\ psi \\ \sigma_{MAWP} &= 3550\ psi\ .\end{aligned}$$

This value is much less than the maximum allowable stress of 12560 *psi* for the head's material. Hence, the flat head is suitable for the proposed service.

5 Evaluation of the Flat Head's Bolts

There are 22 M12 bolts coupling the cryostat's flat head to the annular flange. The bolt material is type 304 stainless steel. The BPVC permits a maximum allowable stress of 18800 *psi* for this material. Applying the factor of .8 to this stress as required by Fermilab's Engineering Standard SD-37B we have

$$\begin{aligned}S_b &= .8(18800\ psi) \\ S_b &= 15040\ psi\end{aligned}$$

This is our maximum allowable stress in each bolt. The total load on the 22 bolts, L_b^T, is the sum of the loads W_D and $F_{P_i}(r = 14.13'')$. Values for these two loads are given in Table 5. The loads are depicted in Figure 1. Hence,

$$\begin{aligned}L_b^T &= W_D + F_{P_i}(r = 14.13'') = (1584 + 29292)lb. \\ L_b^T &= 30876\ lb.\end{aligned}$$

The load per bolt, L_b, is therefore

$$\begin{aligned}L_b &= \frac{L_b^T}{22} \\ L_b &= 1403\ lb.\end{aligned}$$

The minor diameter of an M12 bolt is .376″ (9.54 mm). Its minor area is therefore

$$A_b = \pi\frac{(.376'')^2}{4}$$
$$A_b = .111\ in.^2$$

The stress per bolt is

$$\sigma_b = \frac{L_b}{A_b} = \frac{1403\ lb.}{.111\ in.^2}$$
$$\sigma_b = 12640\ psi$$

This value is less than our maximum allowable stress, S_b, and hence the bolts are adequate.

6 Vent System Analysis

The LHe pump dewar's cryostat is protected against overpressurization by three separate devices. The first protection device is a 3.25″ID ball valve with a pneumatic actuator, PV-002-H, shown on FNAL Drawing #2753.700-ME-157052, pg. 6. During operations, valve PV-002-H is closed unless the pressure in the cryostat raises above 2.5 *bar abs.* (21.55 *psig*). When the cryostat's pressure exceeds 2.5 *bar abs.*, the valve opens and vents helium gas through the check valve CV-071-H and into the high bay area of the New Muon Laboratory. Note that, if the power or air supplied to the valve is lost, the actuator is spring-loaded to open the valve. The second protection device is a set of six Circle Seal Relief Valves (CC-K5120-10MP-32), which open at 30 *psig*. Each has a capacity of 165 SCFM air at the cracking pressure, resulting in a total capacity of 990 SCFM air. The final relief device is a 4″ Fike Rupture Disc. These last two devices also empty into the High Bay area. All devices vent at a height greater than 20 ft. above the floor of the High Bay and are directed away from areas occupied by personnel and equipment.

It is the intent of this section to demonstrate that the six Circle Seal Relief Valves and the 4″ Fike Rupture Disc are sufficient to adequately protect the cryostat from overpressurization. The following three conditions are discussed or analyzed:

- Condensation or conduction load on the cryostat due to loss of vacuum.
- Heat load from a fire that engulfs the dewar.
- A quench of the magnet driving liquid from the coils back into the dewar.

6.1 Venting Requirements for a Heat Load on the Cryostat from a Fire or Loss of Vacuum

A loss of vacuum can be the result of a helium leak through the cryostat wall or an air leak through the vacuum jacket. In the former case, heat transfer to the cryostat is enhanced as a result of conduction through the gas saturated insulation. In the later case, heat transfer increases as a result of air condensation. The heat transferred in these two situations shall be found and compared with that for a fire to determine the worst case heat load to the cryostat. We shall then demonstrate that the six Circle Seal relief valves will adequately protect the vessel from any possible overpressurization due to the worst case situation.

To first order, the problem of heat conduction through the vacuum space, when it is saturated with helium gas, may be treated one-dimensionally. Using this assumption, the conductive heat load to the cryostat is written

$$Q = -A\overline{K}\frac{\Delta T}{\Delta X} \,. \tag{6}$$

According to Glaser, *et al.* [3], the apparent thermal conductivity of saturated multilayer insulation approaches the conductivity of the interstitial gas. To maximize our answer, we shall take $\overline{K}$ to be the conductivity of GHe at $100°F$ ($311K$ or $560R$). Hence,

$$\overline{K} = .09171 \frac{BTU}{hr.ft.°F} \,.$$

The area that is used in the calculation, 52.91 ft.^{2}, is the area of the entire cryostat surface neglecting the area of the flat head. This will exaggerate the conduction heat load, since the portion of the cryostat containing LHe has a surface area that is about 1/2 that of the cryostat. Three inches (.25 ft.) of multilayer insulation (ΔX) covers the surface of that portion of the cryostat containing LHe. The temperature difference, ΔT, is taken to be between $100°F(560R)$ and LHe at $8R$. Hence,

$$\Delta T = (560 - 8)R = 552R \,.$$

Solving equation (6)

$$\begin{aligned} Q &= -\frac{(52.91ft^2)(.09171\ BTU/hr.ft.°R)(552R)}{(.25ft.)} \\ Q &= -10714\ BTU/hr. \end{aligned}$$

where the minus sign implies heat flow into the cryostat.

We shall now obtain values for the heat load to the cryostat for a loss of vacuum to air (air condensation) and for an engulfing fire. Long and Loveday [4] offer a figure which presents the heat load to multilayer insulated helium containers for air condensation and fire conditions as a function of vessel area. This figure is presented as our Figure 6. Since there is no information presented for air condensation on a container with 3″ of multilayer insulation we shall use, as a worse case, the heat load for 1″ of insulation. For the fire condition, we shall use the curve for 3″ of multilayer insulation. The heat loads are summarized in Table 10. As should be

Table 10: Heat Loads on the Cryostat Due to Loss of Vacuum and Fire

Condition		Insulation Thickness	Heat Load into Cryostat BTU/Hr.
Loss of Vacuum	GHe Conduction	3″	10714
	Air Condensation	1″	22000
Fire		3″	63000

expected, the fire condition produces the worst case heat load to the cryostat.

The Compressed Gas Association's Standard, CGA S-1.3 presents rules to be used for calculating the minimum required flow capacity of a pressure relief device for vessels containing liquified compressed gas. For a fire condition, a relief device must be sized to provide a volumetric flowrate of

$$V = G_i U A^{.82} \quad SCFMair \; , \tag{7}$$

where G_i has a value, for LHe, of 52.5 and is obtained from Table 1 of the CGA Standard previously cited. The value U is the thermal conductivity of lading-saturated insulation per unit thickness of insulation. This is obtained by dividing the thermal conductivity of GHe at 900 R (the average temperature between 1200F and 5K) and 1 $atm.$ by the insulation thickness, .25 ft. (3″). Hence, if

$$\overline{K}(900R,\ 1\ atm) = .128 \frac{BTU}{hr.ft.^\circ F} \; ,$$

then

$$U = \frac{.128 BTU/hr.ft^\circ F}{.25\ ft.} \; ,$$

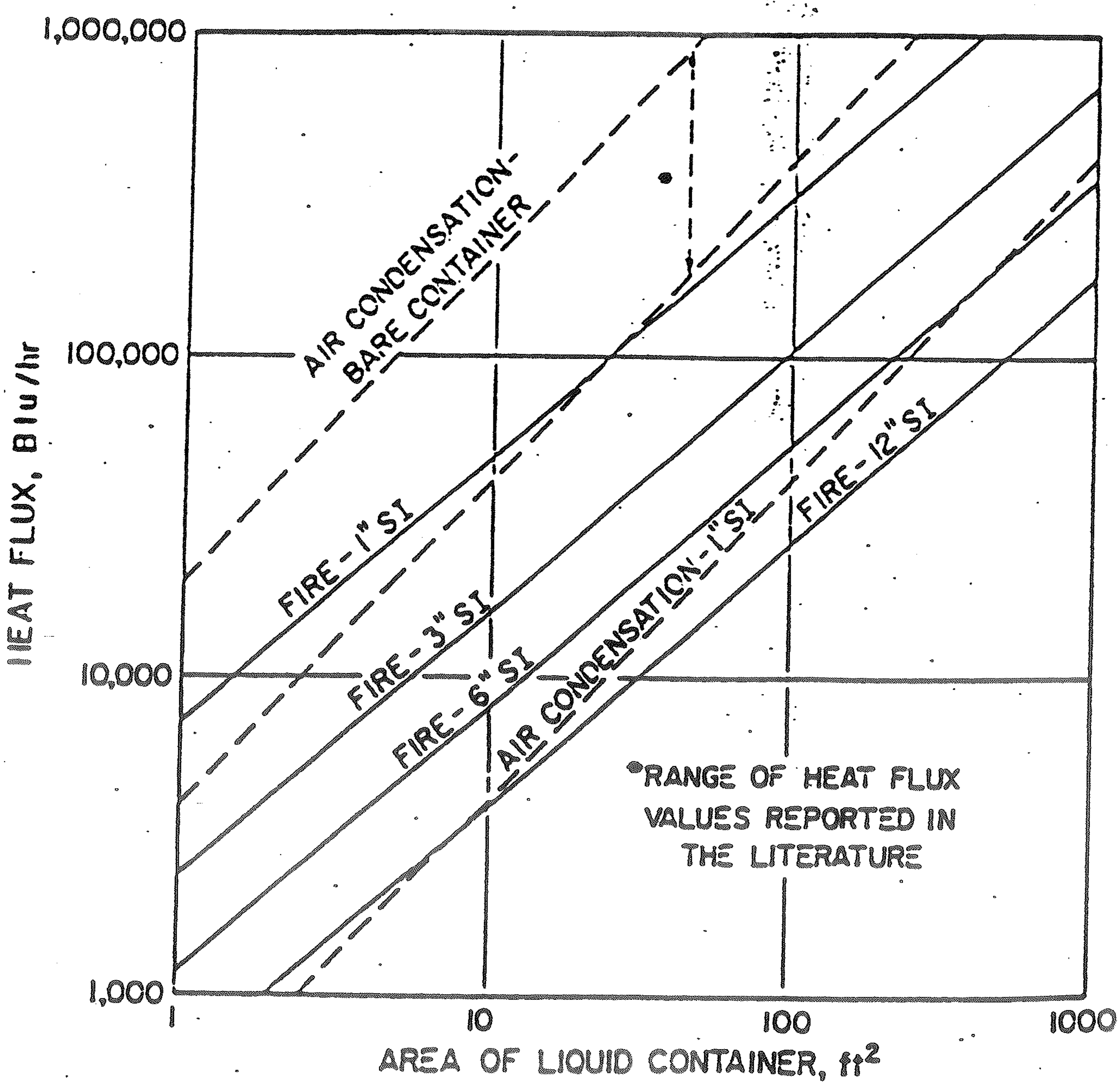
$$U = .512 \frac{BTU}{hr.ft.^{2\circ}F} \; .$$

Using Eq. (7), our required volumetric flowrate is

$$V = 52.5(.512)(52.91)^{.82} \; ,$$

$$V = 696\ SCFM\ air \; .$$

There are six Circle Seal K5120-10MP-32 relief valves on the cryostat. These valves have a measured cracking pressure of 30 $psig$. Presented in Appendix I is a chart



Estimated total heat flux versus area for air condensation and fire conditions in multilayer (SI) insulated liquid helium containers.

Figure 6: Heat Loads to Multilayer Insulated Helium Containers Resulting From a Fire or from Air Condensation.

and figure giving the flow capacity *vs.* cracking pressure for the Circle Seal 5100 series relief valve with an 8M-type inlet (1″ *vs.* the 1-1/4″ inlet for a 10M-type valve and .444 in. *vs.* .57 in. effective square edge orifice diameter for the 10 MP type valve [8]). No values are given for the flow capacity at 30 *psig*. We see, however, that the flow capacity behaves linearly with cracking pressure. We also have values for the flow capacity at 100 and 200 *psig*. Extrapolating to 30 *psig*, we have

$$V_{cs} = \left[\frac{(811-431) SCFM\ air}{(200-100) psig}\right](30-100) psig + 431\ SCFM\ air\ ,$$
$$V_{cs} = 165\ SCFM\ air\ .$$

The total capacity of the six Circle Seal relief valves is therefore

$$V_{cs}^{T} = 6\ V_{cs} = 6(165\ SCFM\ air)\ ,$$
$$V_{cs}^{T} = 990\ SCFM\ air\ .$$

Hence, since our required flow capacity for a fire is 696 SCFM air, the vessel is adequately protected for a fire condition. Note that, since the cryostat experiences the largest heat loads during a fire, the vessel is also adequately protected for either loss of vacuum conditions.

6.2 Overpressurization Protection for a Quench

To accurately predict flow rates and pressures during a quench of the CVM's coils is extremely difficult and will not be attempted here. Instead, we shall demonstrate that our vent system will provide, as a minimum, the same protection against a quench caused overpressurization as the system used at CERN. This is significant since the vent system at CERN has successfully protected the cryostat during a quench [5].

A schematic of the CERN vent system is given in Figure 7a. This vent system includes a pneumatically-operated ball valve identical to our PV-002-H, with a check valve identical to our CV-071-H downstream of the ball valve. CERN's system also includes the same type and number of Circle Seal relief valves as our system. These valves are positioned upstream of the ball valve. The ball valve and the Circle Seal relief valves are set to open at the same values as those in our system, 2.5 bar abs. (21.55 *psig*) and 30 *psig* (cracking), respectively. The check valves in both systems open at approximately 2.1 *psig*. Note that the internal diameter of the ball valve is 3.25 inches. At CERN, during a quench event, all helium is recovered. For this purpose, a gas bag was installed in the roof of their experimental. The author estimates that the distance between the CERN check valve and the gas bag is between 200 and 300 ft. With this system, the maximum recorded pressure in the cryostat during a quench of the magnet was 2.8 bars abs. (40.6 *psia*) [5].

A schematic of the Fermilab vent system is given in Figure 7b. An isometric drawing of the system, Fermilab Dwg #2753.700-MD-193502, is included in Appendix B. There are two major differences between the CERN and the Fermilab system. The first is the addition of a Fike Rupture Disc, set to burst at 32 *psig*, in parallel to the line which consists of the pneumatically-operated ball valve and the check valve. Note that this line was added to the existing equipment so that the ball and check valves are in the same relative position to the cryostat as those valves of the CERN system. The second difference between the two systems is that both legs of the parallel network are vented to atmosphere within 25 ft. of leaving the cryostat.

In comparing the relative ability of the two systems to protect the cryostat from overpressurization, we consider the resistance to flow offered by the CERN system with respect to the flow resistance of the leg of the Fermilab system which holds the rupture disc. Qualitatively, it should be obvious that the pipe runs of the CERN system, being more extensive that those of the Fermilab system and of a slightly smaller diameter (3.94″ *vs.* 4.26″) must offer a greater resistance to flow. We must therefore demonstrate that the rupture disc of the Fermilab system offers less resistance to flow than do the ball and check valves of the CERN system to conclusively demonstrate our hypothesis. To do this, wc shall examine the resistance coefficients (K factors) for the individual components.

The resistance coefficient, K, is defined as

$$K = f_T \frac{L_e}{d} , \tag{8}$$

and is related to the pressure drop and flow velocity by the equation

$$\Delta P = \frac{\rho v^2}{2g} K . \tag{9}$$

Values of K for many valves and fitting are tabulated in sources such as Marks [2] and Crane [6]. We may obtain the resistance coefficient for one of our three components of interest from such a source.

The CERN check valve is a lift-type check valve. A copy of the CERN engineer's sketch of this valve is given in Appendix I. Crane [6] gives a resistance coefficient for a lift check valve of

$$K_{cv} = 600\ f_T \tag{10}$$

The inlet and outlet diameters of the check valve are 100 mm(3.94″). For fully turbulent flow in a 4″ clean commercial steel pipe, the friction factor is [6]

$$f_T = .017 .$$

Substituting this valve into Eq. (10), gives

$$K_{cv} = 10.2 .$$

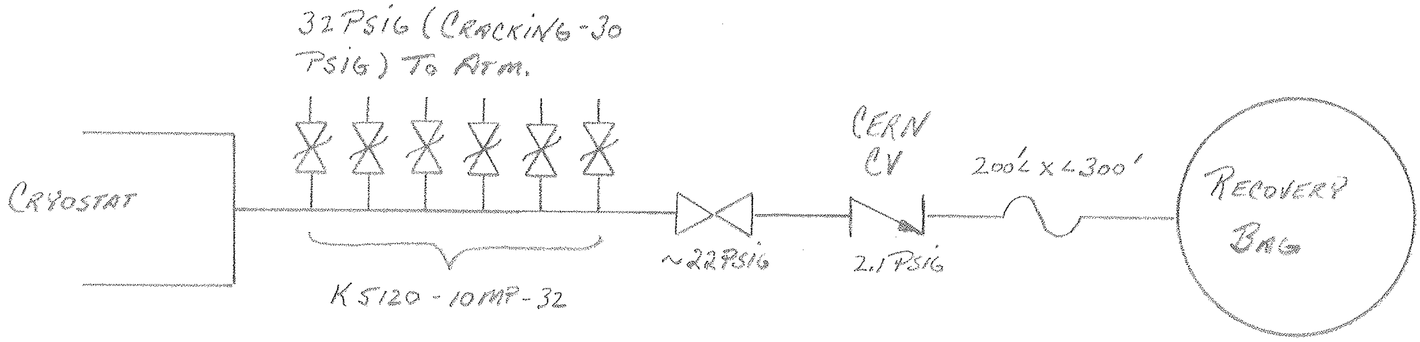


FIGURE 7a
CERN VENT SYSTEM

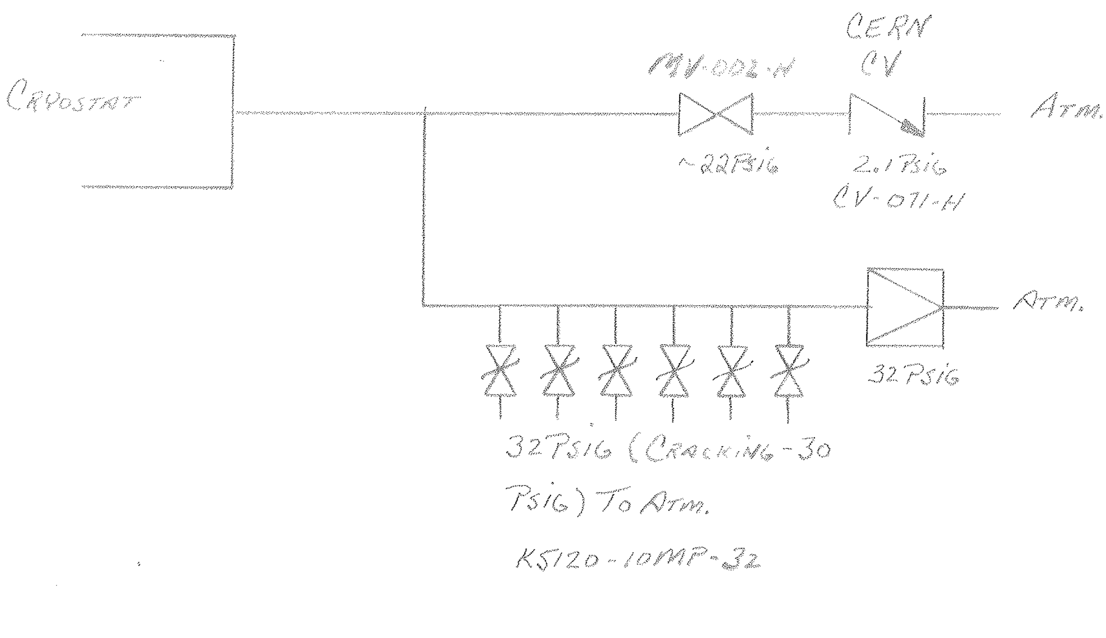


FIGURE 7b
FERMILAB VENT SYSTEM

Figure 7: Schematics of the CERN and Fermilab Vent Systems

This is our K factor for the CERN check valve.

We shall now attempt to find a K factor for the Fermilab rupture discs. There are no tabulate values of K factors for the rupture disc. Hence, a K factor must be calculated. Equations for the general sizing of a rupture disc are obtained by assuming the disc to be a flat plate orifice, and applying a factor of .62 required by the ASME [7]. The equation for the volumetric flowrate of compressible flow through a square-edged orifice is given by Eq. 2-15 of Crane [6] to be

$$V = YCA\left\{\frac{2g\Delta P}{\rho}\right\}^{1/2} .$$

Incorporating the factor of .62 as a reduction in area, we have

$$V' = YCA'\left\{\frac{2g\Delta P}{\rho}\right\}^{1/2} .$$

This is our equation for the volumetric flowrate through a rupture disc. Solving for ΔP we have

$$\Delta P = \frac{\rho}{2g}\left\{\frac{V'}{YCA'}\right\}^2 = \frac{\rho v^2}{2g}\left[\frac{1}{YC}\right]^2 .$$

Comparing this expression with Eq. (9), we find

$$K_{RD} = \frac{1}{(YC)^2} \tag{11}$$

for a rupture disc. The values for Y and C are obtained from figures presented in Crane [6], which are reproduced here as Figure 8. The variable C is a function of the ratio of the orifice to inlet diameters and also of the Reynolds number. The ratio of the diameters, d_0/d_1, is equal to the square root of the ratio of the areas. Hence,

$$\frac{d_0}{d_1} = \left[\frac{A'}{A}\right]^{1/2} \cong (.62)^{1/2} = .79 .$$

Therefore

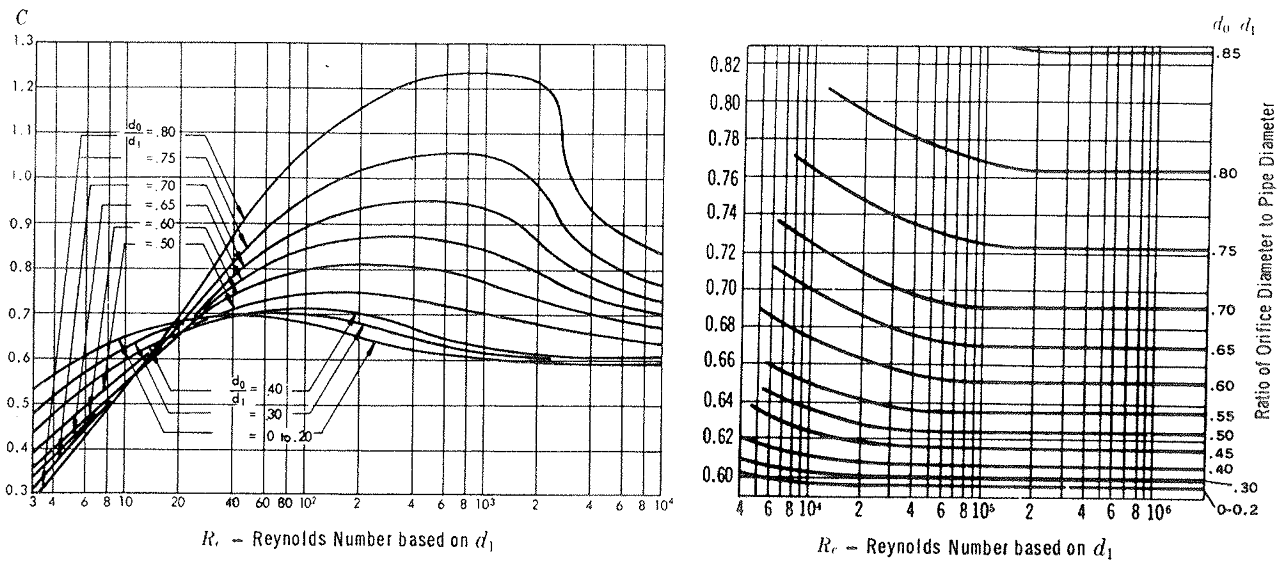
$$\frac{d_0}{d_1} \cong .8 .$$

Figure 8 indicates that assuming the Reynolds number to be greater than 2×10^5, where C behaves linearly (quite realistic), will minimize C and hence maximize K. Therefore, we take C to have the value

$$C = .764$$

The net expansion factor, Y, is a function of the ratio of the pressure difference over the disc, ΔP, and the absolute upstream pressure, P_1'. It is also a function of the ratio of the diameters and the ratio of the specific heats, k. Taking ΔP to be

Flow Coefficient C for Square Edged Orifices



Net Expansion Factor, Y

For Compressible Flow through Nozzles and Orifices[9, 10]

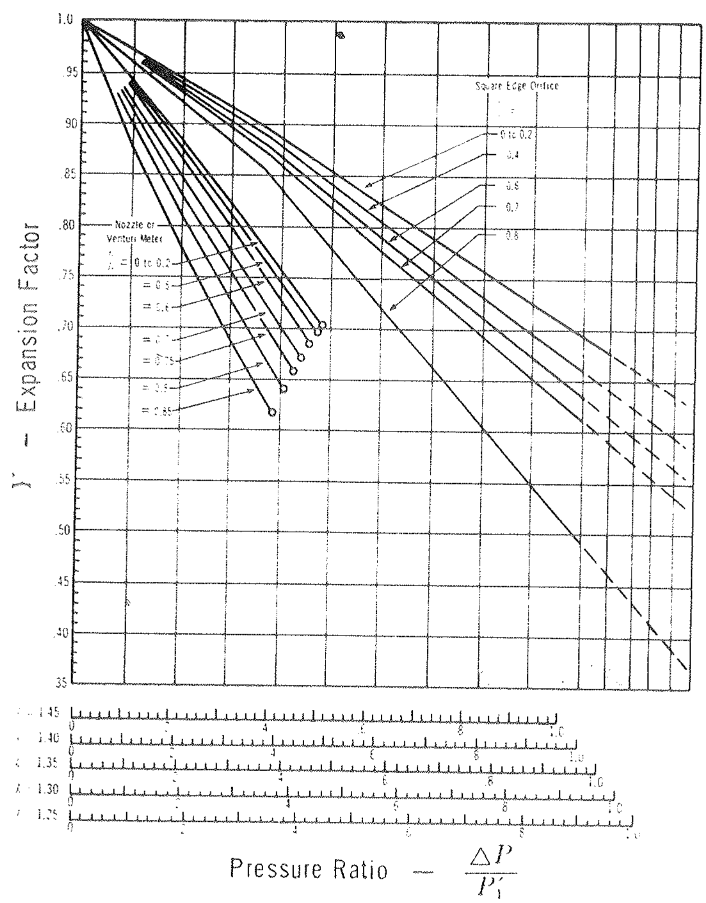


Figure 8: Charts for the Flow Coefficient, C, and Net Expansion Factor, Y, for Orifice (Rupture Disc) Flow Calculations.

32 *psig* (actually the pressure drop over the whole vent) and the upstream pressure to be 46.7 *psia*, we have

$$\frac{\Delta P}{P_1'} = \frac{32\ psi}{46.7\ psia} = .69\ .$$

Linearly extrapolating the scales for K and $\Delta P / P_1'$ in Figure 8 leads us to a value for Y of

$$Y = .74\ .$$

Substituting the values for Y and C into Eq. (11) gives

$$\begin{aligned} K_{RD} &= \frac{1}{(YC)^2} = \frac{1}{(.74 * .764)^2}\ , \\ K_{RD} &= 3.13\ . \end{aligned}$$

This is our K factor for the Fermilab rupture disc.

Comparing the K factor for the Fermilab rupture disc with that for the CERN check valve, we see that the K factor for the CERN check valve is larger by a factor greater than 3. Our task is therefore complete. We have demonstrated that the leg added to the system at Fermilab has less resistance to flow than does the system that successfully protected the cryostat from overpressurization during a quench at CERN. Hence, our system at Fermilab will protect our cryostat during a quench.

7 Summary

Adhering to the demands of Fermilab's Engineering Standard SD-37B, this paper has demonstrated that the cryostat of the CERN *LHe* Pump Dewar can safely withstand an internal pressure of 32 *psig* with its external vacuum vessel evacuated. Hence, the maximum allowable working pressure of the cryostat is 46.7 *psia*. This paper has also demonstrated that the vent system for the cryostat will protect the vessel from an overpressurization due to loss of vacuum, engulfing fire, or a quench of the associated magnet. The author therefore recommends that permission be granted to operate the vessel as part of the Muon Cryogenic System.

Bibliography

1. Roark, Raymond J. and Young, Warren C., "Formulas for Stress and Strain," 5th Ed., McGraw Hill Book Co., New York, 1975.

2. "Mark's Standard Handbook for Mechanical Engineers," 8th Ed., Baumeister, T., Avallone, E.A., and Baumeister, T. III, Editors, McGraw Hill Book Co., New York, 1978.

3. Glaser, Peter E., Black, Igor A., Lindstrom, Richard S., Ruccia, Frank E., Wechsler, Alfred E., "Thermal Insulation Systems—A Survey", NASA Publication NASA SP-5027, 1969, pg.55.

4. Long, Hugh M., and Loveday, Paul E., "Safe and Efficient Use of Liquid Helium," published in "Technology of Liquid Helium", NBS Monogram 111, ed. by Kropschot, R.H., Birmingham, B.W., and Mann, D.B., NBS Boulder Laboratories, Boulder, Colorado, 80302, October, 1968.

5. Kelley, John Patrick, "Foreign Trip Report," Muon Cryosystem Design Note 31 (CVM), Fermilab, Batavia, IL 60510, May, 1986.

6. Crane Technical Paper No. 410, "Flow of Fluids through Valves, Fittings, and Pipe", Crane Co., Chicago, IL, 1978.

7. Fike Metal Products Corp. Catalog No. 7384, "Rupture Discs Explosion Vents and Other Pressure Relief Devices," Fike Metal Products Corp., Blue Springs, MO 64015, 1983.

8. Haupt, Richard, Circle Seal Midwest Region Manager, private conversation.

A CERN Safety Document for the CVM's Pump Dewar, RP 156

DATE : 22 JUIN 1977.

CC : MM. MURATORI - EP
GYVOCT - EP

ANNEXE 1.

A : MR. M. MARQUET. EP

DE : GROUPE SECURITE DU TRAVAIL - B. P. 't HART

FICHE DE CONTROLE MECANIQUE POUR RESERVOIR A PRESSION

TYPE RESERVOIR : CRYOSTAT POUR AIMANT DIPOLE

DATE DU CONTROLE : 21 JUIN 1977 — ANNEE MISE EN SERVICE : 1977.

DESSIN No. : EP 303391 G — CONSTRUCTEUR : CRYODIFFUSION

VOLUME : 600 LITTRES — RADIOGRAPHIE : OUI/~~NON~~

No. D'EQUIPEMENT : [redacted] 156

LIEU D'UTILISATION : EHN 2

FLUIDE : He LIQUIDE — TEMPERATURE : 4 ~~°C~~ °K

PRESSION DE CALCUL : 4,5 BARS ABS.

PRESSION DE TRAVAIL : 1,5 BARS ABS.

PRESSION D'EPREUVE : 5,75 BARS

ACCEPTE POUR LE VIDE : OUI/~~NON~~

RECEPTION/~~INSPECTION APRES MODIFICATION~~.

MODIFICATIONS APPORTEES :

EPREUVE HYDROSTATIQUE / ~~PNEUMATIQUE~~ DE L' INTERIEUR / ~~EXTERIEUR~~ A : 5,75 BARS

RESULTAT ~~NON~~ CONCLUANT. CONTRAINTE DANS LA COUVERCLE À LA PRESSION D'ESSAI: 6,5 KG/MM², MESURÉE AVEC JAUGE DE CONTRAINTE.

OBSERVATIONS : VEUILLEZ FAIRE PEINDRE LE NO. RP156 ET LES COULEURS D'IDENTIFICATION SUR LE RESERVOIR

FENETRES DE FAISCEAU.

PLOMBEES : OUI/NON

MATIERE : EPAISSEUR:

NOMBRES DE FEUILLES :

SOUPAPE DE SECURITE : PSV TARAGE BARS

LE RESERVOIR PEUT / ~~NE PEUT PAS~~ ETRE MIS EN SERVICE ~~MOYENNANT LE REMPLISSAGE DE LA LISTE DE CONTROLE (ANNEXE 2 ou 3 DU CODE D.3)~~

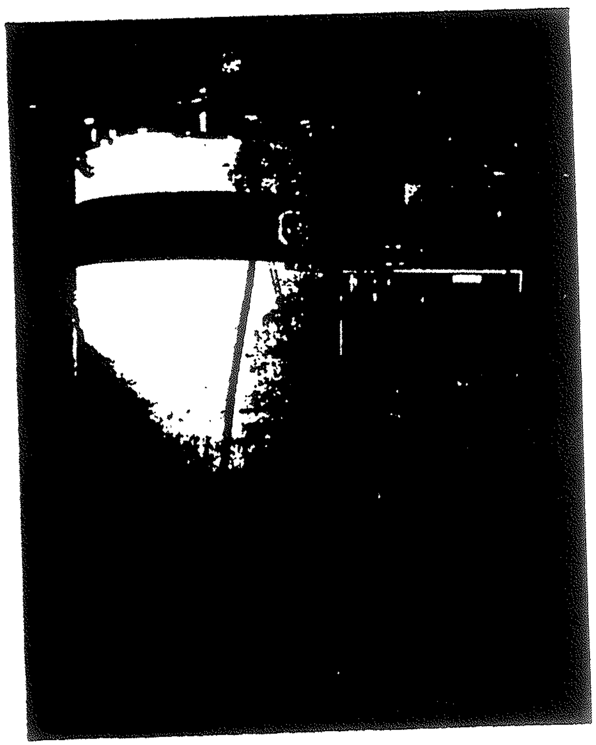
B.P't HART

Ce rapport est valable jusqu'au........JUIN 1980................d'après

SERIE :

DATE : 21 JUIN 1977

BATIMENT : EHN 2



RESERVOIR A PRESSION

No. d'EQUIPEMENT RP- 156

DESCRIPTION : Cryostat pour aimant dipole

Année 1977

DESSIN Nb : E 303391 G

VOLUME APPROX : 600 litres

DIMENSIONS : Ø 1100 x hauteur 2180 mm

TROU D'HOMME : OUI/~~NON~~

CONSTRUCTEUR : Cryodiffusion

PRESSION DE CALCUL : 4,5 BARS ABS.

PRESSION DE TRAVAIL : 1,5 BARS ABS.

PRESSION D'EPREUVE : 5,75 BARS

SUPPORTE LE VIDE : OUI/~~NON~~

FLUIDE : He liquide

TEMPERATURE : 4 ~~°C~~ °K

SOUPAPE DE SECURITE : PSV- ....

TARAGE .... BARS

CONSTRUCTION :

	MATERIAUX	EPAISSEURS
CYLINDRE	304 L	2,0 mm
FONDS	-DO-	4,0 mm
Cône	-DO-	mm
Cylindre Ø 600	-DO-	1,5 mm

OBSERVATIONS : Resp. Mr. Marquet/EP

June 22, 1977

TO: Mr. M. Marquet, EP

FROM: Working Safety Group: B.P. Thart

SUBJECT: Mechanical Inspection Memo for the Pressure Tank

TANK TYPE:	Cryostat for Dipole Magnet		
INSPECTION DATE:	June 21, 1977	STARTING YEAR:	1977
DRAWING NUMBER:	EP 303391 G	MANUFACTURER:	Cryodiffusion
CAPACITY:	600 Litres	RADIOGRAPHY:	Yes/~~No~~
EQUIPMENT NUMBER:	156		
SITE:	EHN 2		
FLUID:	Liquid Helium	TEMPERATURE:	4 K
CALCULATION PRESSURE:	4.5	BARS ABS	
WORKING PRESSURE:	1.5	BARS ABS	
TESTING PRESSURE:	5.75	BARS	
ACCEPTED FOR VACUUM:		Yes/~~No~~	

RECEIVED/~~INSPECTION-AFTER-MODIFICATION~~

MODIFICATIONS DONE:

INTERNAL/~~EXTERNAL~~ HYDROSTATIC/~~PNEUMATIC~~ TEST: 5.75 BARS

POSITIVE RESULT: Stress in the cover under testing pressure: 6.5 kg/mm^2 measured with a pressure gage.

REMARKS: Have Nr RP 156 and the identifying colors painted on the tank

<u>COMPOUND MAGNET WINDOWS</u>

LEADED: Yes/No

MATERIAL: Thickness

NUMBER OF SHEETS:

SAFETY VALVE: PSV Adjusted to Bars

The tank can/~~CANNOT~~ operate ~~USING THE OPERATING PROCEDURES (SECTION2 OR 3 OF CODE D-3)~~

This memo is valid till June 1980, according to the terms of the document: "CERN POLICY TOWARDS SAFETY MATTERS" - Appendix V - Paragraph 11.1.

PRESSURE TANK
Equipment Number RP 156

SERIAL:			
DATE:	June 21, 1977		
BUILDING:	EHN 2		
DESCRIPTION	Cryostat for Dipole Magnet		
YEAR:	1977		
DRAWING NUMBER:	EP 303391 G		
APPROXIMATE CAPACITY:	600 litres		
DIMENSIONS:	Ø 1100 x height 2180 mm		
INSPECTION HOLE:	Yes/~~NO~~		
MANUFACTURER	Cryodiffusion		
CALCULATION PRESSURE:	4.5	BARS	ABS
WORKING PRESSURE:	1.5	BARS	ABS
TESTING PRESSURE:	5.75	BARS	
TAKE VACUUM:		Yes/~~NO~~	
FLUID:	Liquid He		
TEMPERATURE:	4 K		
SAFETY VALVE:	PSV	ADJUSTED TO	BARS

DESIGNING:

	MATERIALS	THICKNESSES
CYLINDER	304 L	2.0
BOTTOM	"	4.0
CONE	"	
CYLINDER Ø 600	"	1.5

REMARKS	Mr. Marquet/EP

B Referenced Blueprints

CERN Dwg. # 30 36 05

CERN Dwg. # 30 33 91

CERN Dwg. # 31 40 01

CERN Dwg. # 31 39 99

FNAL Dwg. # 2753-700-MD-193502

FNAL Dwg. # 2753-700-ME-157052, #6 & 7

C Muon Cryosystem Design Note No. 29

D Personal Radiography Certifications

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

ROGER B. MASSOW

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL III RADIOGRAPHY

BASED ON SNT TC-1A

AWARDED THIS DATE

JULY 18, 1985

[redacted] DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. BUSSE
NDT LEVEL III EXAMINER

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

CHARLES VULYAK JR.

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL II - RADIOGRAPHY

BASED ON SNT TC-1A

AWARDED THIS DATE

JULY 7, 1984

D. N. Bounelis

D. N. BOUNELIS, DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. Busse

T. H. BUSSE
NDT LEVEL III EXAMINER

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

JOSEPH LUCAS

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL - II - RADIOGRAPHY

BASED ON SNT TC-1A

AWARDED THIS DATE

APRIL 1, 1984

D. N. Bounelis

D. N. BOUNELIS, DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. Busse

T. H. BUSSE
NDT LEVEL III EXAMINER

E Individual Weld Radiography Records

NDT-500	QUALITY ASSURANCE DIVISION – Nondestructive Testing RADIOGRAPHIC TECHNIQUE RECORD	PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: FERMI LAB | PERSON: J.P. KELLEY | JOB NO.: 750-10404

INSPECTION CODE: ASME SECTION VIII | ACCEPTANCE CRITERIA: ASME SECTION VIII DIV. I - UW 57 | MATERIAL TYPE: S.S./CU/AL

MATL. THICKNESS:

PART NAME: CERN LAr CRYOSTAT INNER TANK | JCP # ——— | DWG. NO.: 30-36-05

PART NUMBER(S):

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-1
LONGITUDINAL WELD
SHOT #1 - #4

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-1

INSPECTION DATE: 1/29-30/86

PROCEDURE: NDT/500-REV-7-

☐ IR-192 | ☐ CO-60 | SOURCE STRENGTH: C. | SOURCE SIZE: mm

☒ X-RAY MACHINE: DOA 250 SCAN-RAY | FOCAL SPOT SIZE: 3.5 mm | KV: 180 | MA: 5

EXPOSURE TIME: * NOTED | PENETRAMETER(S)/SHIM(S): #7 S.S. / .020", .040" PART ITSELF

SFD: 36"	
SCREENS: Pb .005/.010	
FILM TYPE(S): M	
FILM SIZE(S): 7" X 17"	
NUMBER OF FILMS: 4	
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE	

FILM LOCATION STATUS	DATE
FILED WITH QAD/NDT	
SUBMITTED TO CUSTOMER	
SUBMITTED TO MATL. REVIEW	
RETURNED TO QAD/NDT	
SENT TO CENTRAL STORAGE	

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

IRREGULAR LINEAR DARKER DENSITY IN MIDDLE OF WELD IS DUE TO CROWNS MEETING.

* NOTED: SHOT #1 + #2 - 50 SEC.
SHOT #3 + #4 - 1½ MIN.

RADIOGRAPHER (signature) [signature] [signature] | CERT. LEVEL: II | DATE: 1/30/86

INTERPRETER (signature) [signature] | CERT. LEVEL: II | DATE: 1/30/86

SHOT SKETCH

P. KELLEY / FERMI

JOB# 750-10404

1/30/86

INNER TANK

R.T.

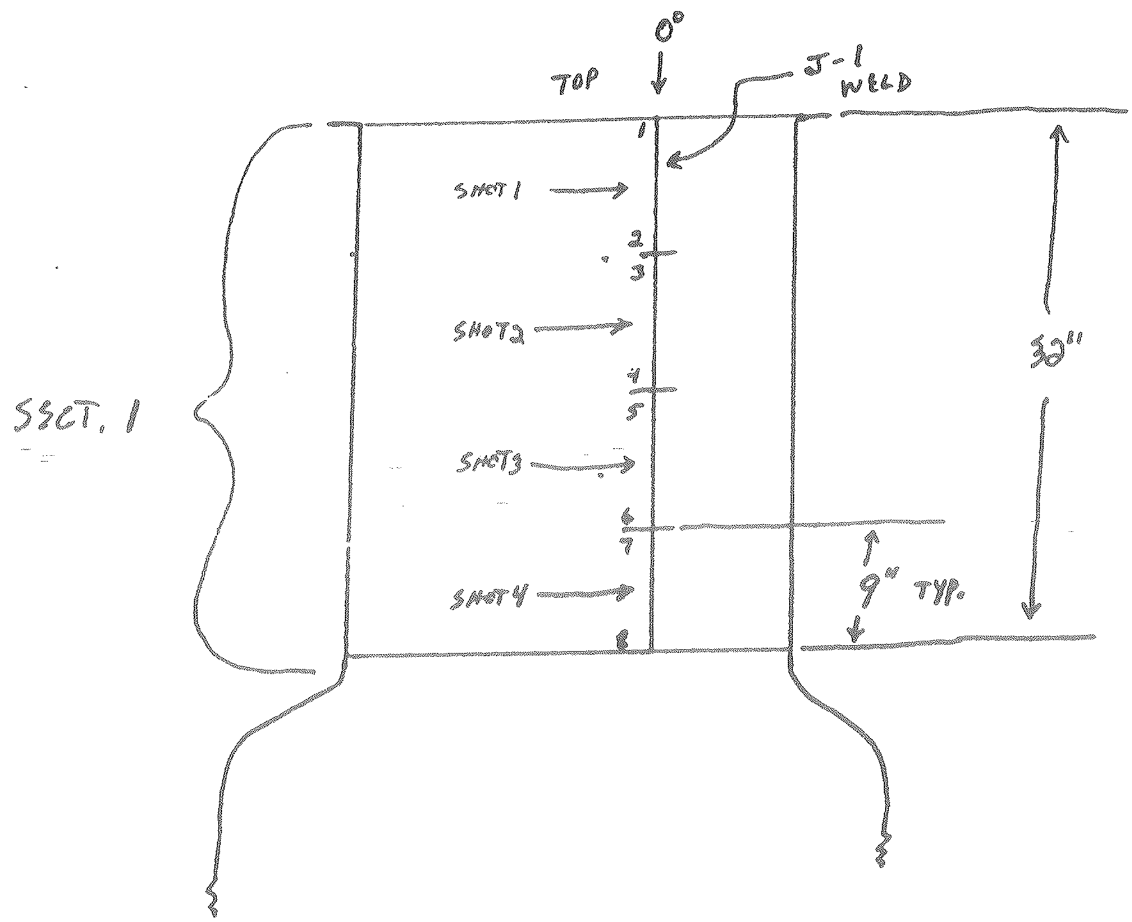
I LONG. WELD : J-1 LENGTH 32"

BUTT WELD

THICKNESS OF INNER TANK ≈ .059" (SECT. 1)

4 ea. - 9" LENGTH OF WELD (AREA OF INTEREST)

TOTAL OF 4 SHOTS (TOTAL LENGTH 32")



RADIOGRAPHIC TECHNIQUE RECORD

INSPECTION REQUIREMENTS

DIVISION: FERMI	PERSON: P. KELLEY	JOB NO.: 750-10404
INSPECTION CODE: ASME SECT. VIII	ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I UW 52	MATERIAL TYPE: S.S.
		MATL. THICKNESS: .079"
PART NAME: He CRYOSTAT (INNER TANK)	JCP #	DWG. NO.: 30-36-05
PART NUMBER(S): INNER TANK		

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-2 LONG. WELD

SHOT # 1, 2, 3

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-2 WELD (LONG.)		INSPECTION DATE: 1/31/86	
		PROCEDURE: NDT500/REV. 7	
☐ IR-192	☐ CO-60	SOURCE STRENGTH: C.	SOURCE SIZE: mm
☐ X-RAY MACHINE: DOA SCAN-RAY 250	FOCAL SPOT SIZE: 3.5 mm	KV: 180	MA: 5
EXPOSURE TIME: 2 min.	PENETRAMETER(S)/SHIM(S): #7 S.S. / .020", .040" PART ITSELF		

	FILM LOCATION STATUS	DATE
SFD: 36"	FILED WITH QAD/NDT	
SCREENS: Pb .005"F / .010"B	SUBMITTED TO CUSTOMER	
FILM TYPE(S): "M"	SUBMITTED TO MATL. REVIEW	
FILM SIZE(S): 7"X17"	RETURNED TO QAD/NDT	
NUMBER OF FILMS: 3	SENT TO CENTRAL STORAGE	
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE		

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

RADIOGRAPHER (signature) [signature] / J.W. Lucas	CERT. LEVEL: II	DATE: 2/14/86
INTERPRETER (signature) J.W. Lucas	CERT. LEVEL: II	DATE: 2/14/86

SHOT SKETCH

P. KELLEY / FERMI

JOB# 750-10404

1/30/86

INNER TANK

R.L.

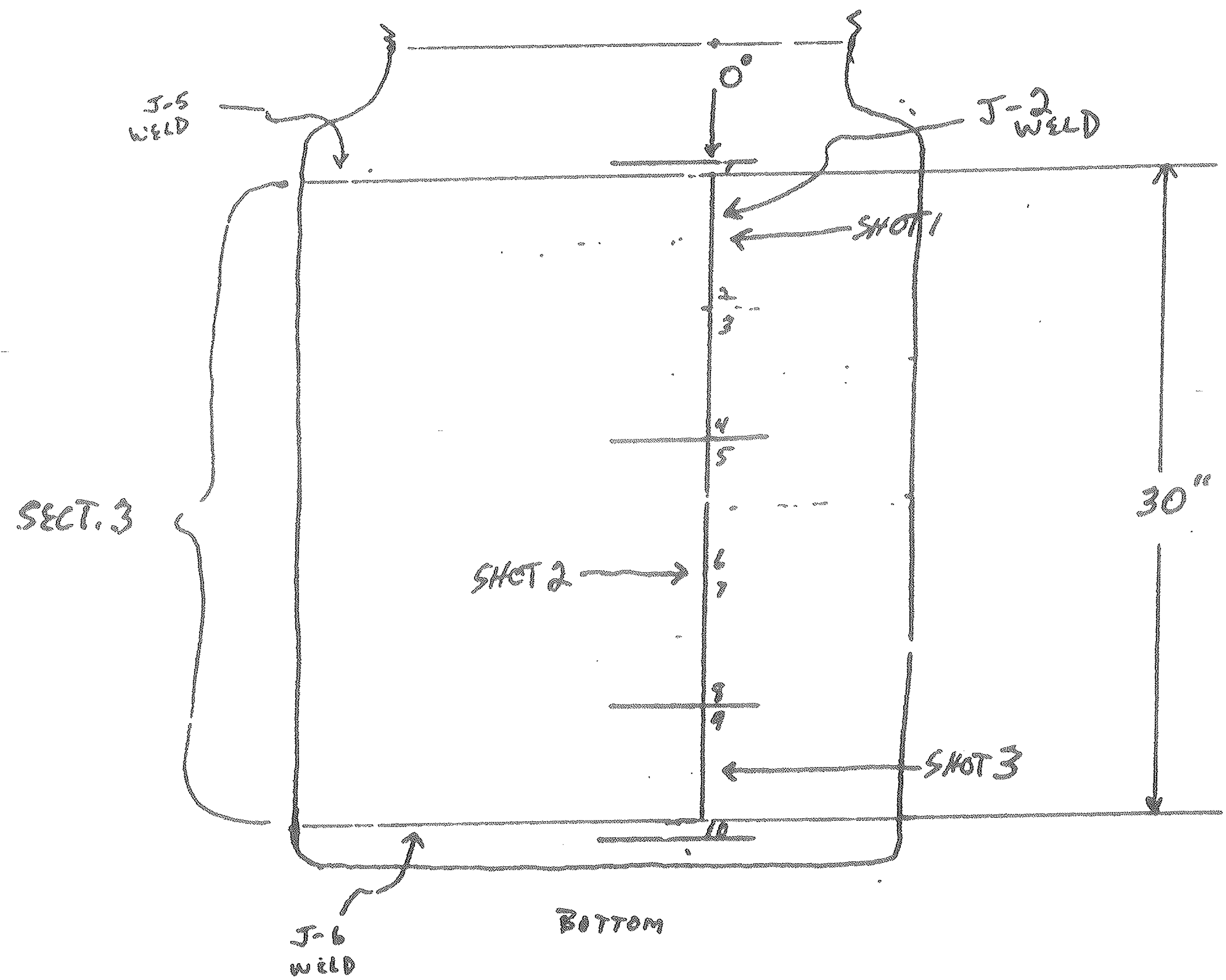
II. LONG. WELD J-2 LENGTH 30"

BUTT WELD

THICKNESS OF INNER TANK ≈ .078" (SECT. 3)

2 ea - 14" LONG, 1 ea. ≈ 7" — LENGTHS OF WELD (AREA OF INTEREST)

TOTAL OF 3 SHOTS (TOTAL LENGTH 30")



NDT-500	QUALITY ASSURANCE DIVISION — Nondestructive Testing RADIOGRAPHIC TECHNIQUE RECORD	PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: FERMI | PERSON: P. KELLEY | JOB NO.: 75C-1C4C4

INSPECTION CODE: ASME SECT. VIII | ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I UW-51 | MATERIAL TYPE: 304L S.S.

MATL. THICKNESS: Z .1562

PART NAME: He CRYOSTAT | JCP # —— | DWG. NO.: 30-36-05

PART NUMBER(S): INNER TANK

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-3 WELD 100%

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-3 WELD

INSPECTION DATE: 2/11-2/13/86

PROCEDURE: NDT 500/REV. 7

☐ IR-192 | ☐ CO-60 | SOURCE STRENGTH: C. | SOURCE SIZE: mm

☒ X-RAY MACHINE: TFI 110 (HOT SHOT) | FOCAL SPOT SIZE: 0.5 mm | KV: 110 | MA: 5

EXPOSURE TIME: (*) SEE COMMENTS | PENETRAMETER(S)/SHIM(S): #10 S.S. / 3 ea. = .140"

SFD: (*) SEE COMMENTS

SCREENS: F .005"/B .010" Pb

FILM TYPE(S): "M" KODAK

FILM SIZE(S): 8" X 10"

NUMBER OF FILMS: 15

VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE

FILM LOCATION STATUS	DATE
FILED WITH QAD/NDT	
SUBMITTED TO CUSTOMER	
SUBMITTED TO MATL. REVIEW	
RETURNED TO QAD/NDT	
SENT TO CENTRAL STORAGE	

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

	SFD	TIME		SFD	TIME
SHOT 1	30"	8 min.	SHOT 8	40"	14.5 min
SHOT 2	36"	10.5 min.	SHOT 9	40"	14.5 min
SHOT 3	37"	13 min.	SHOT 10	34"	10 min.
SHOT 4	35"	11 min.	SHOT 11	34"	12 min.
SHOT 5	34"	10 min.	SHOT 12	38"	12 min.
SHOT 6	37"	13 min.	SHOT 13	36"	10.5 min.
SHOT 6A	33"	14 min.	SHOT 14	33"	9 min.
SHOT 7	30"	8 min.			

RADIOGRAPHER (signature) C.W. Vukolic / J.W. Lucas | CERT. LEVEL: II | DATE: 2/14/86

INTERPRETER (signature) J.W. Lucas | CERT. LEVEL: II | DATE: 2/14/86

SHOT SKETCH

R. KELLEY/Fermi:

JOB # 750-10404

1/30/86

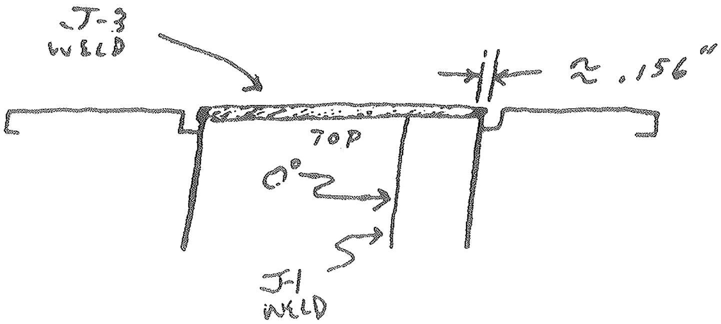
INNER TANK

R.T.

J-3 CIRCUM. ≈ 75.4"

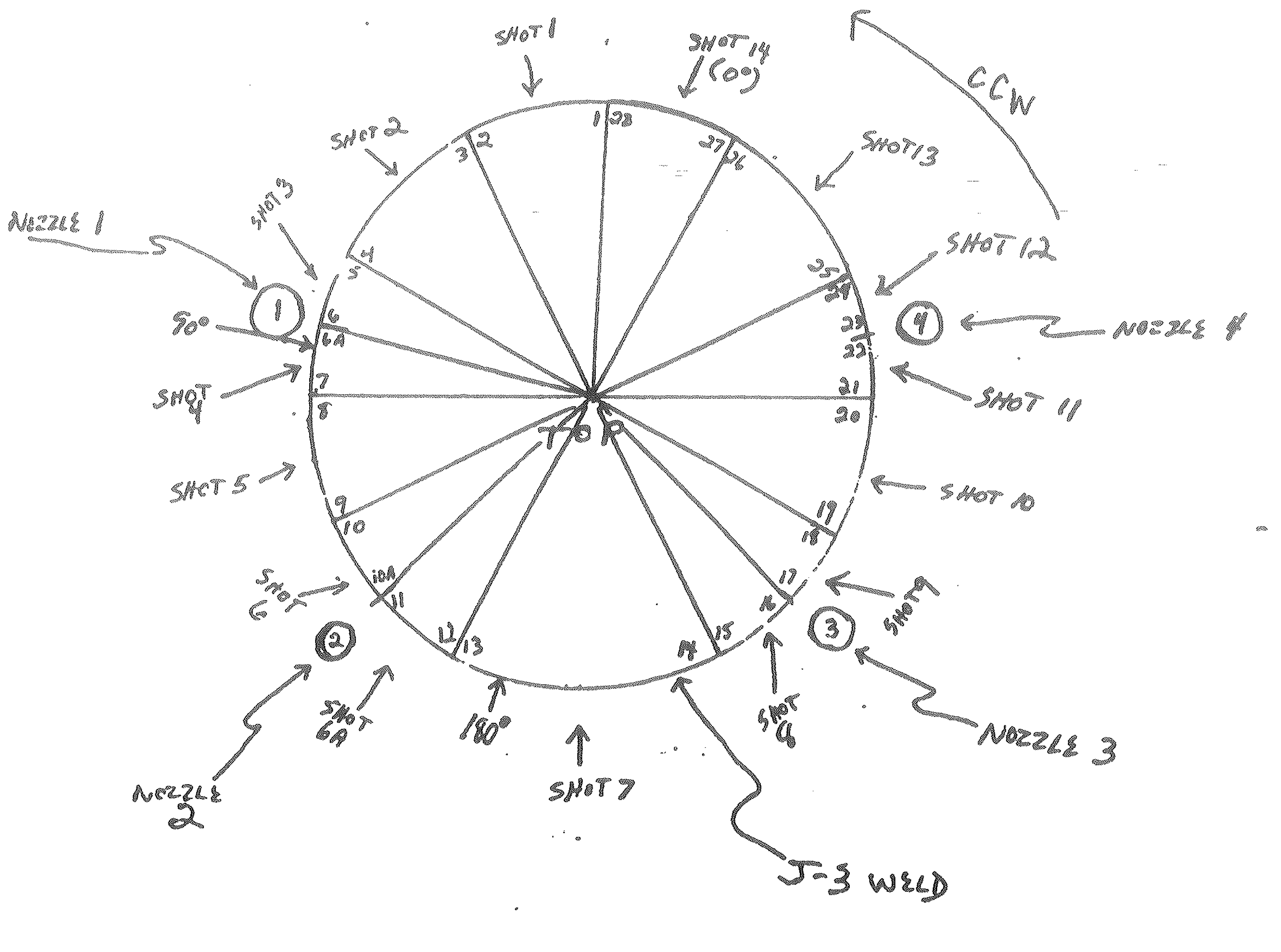
THICKNESS OF INNER TANK ≈ .059"

100% X-RAY OF J-3



7 ea. – 6.283" ≈ LENGTH OF WELD (AREA OF INTEREST)

8 ea. – 3 3/4" ≈ LENGTH OF WELD (AREA OF INTEREST), TO RIGHT AND LEFT OF NOZZLES.



NDT-500	QUALITY ASSURANCE DIVISION – Nondestructive Testing RADIOGRAPHIC TECHNIQUE RECORD	PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: FERMI
PERSON: P. KELLEY
JOB NO.: 750-10404
INSPECTION CODE: ASME SECT. VIII
ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I - UW-52
MATERIAL TYPE: S.S./Cu/Al.
MATL. THICKNESS: ≈ .059"
PART NAME: He CRYOSTAT (CERN)
JCP # —
DWG. NO.: 30-36-05
PART NUMBER(S): INNER TANK

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-4 WELD (CIRCUM.)

SHOT # 1, 2.

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-4 WELD
INSPECTION DATE: 2/3/86
PROCEDURE: NDT 500/REV. 7
☐ IR-192 ☐ CO-60 SOURCE STRENGTH: C.
SOURCE SIZE: mm
☒ X-RAY MACHINE: SCAN RAY 250
FOCAL SPOT SIZE: 3.5 mm
KV: 180
MA: 5
EXPOSURE TIME: 2.5 min.
PENETRAMETER(S)/SHIM(S): #7, .020", .040", PART ITSELF
SFD: 36"
SCREENS: F .005"/B .010" Pb
FILM TYPE(S): "M" KODAK
FILM SIZE(S): 7" X 17"
NUMBER OF FILMS: 2
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE

FILM LOCATION STATUS	DATE
FILED WITH QAD/NDT	
SUBMITTED TO CUSTOMER	
SUBMITTED TO MATL. REVIEW	
RETURNED TO QAD/NDT	
SENT TO CENTRAL STORAGE	

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

RADIOGRAPHER (signature) C.W. [signature] / J.W. Lucas CERT. LEVEL: II DATE: 2/3/86

INTERPRETER (signature) J.W. Lucas CERT. LEVEL: II DATE: 2/14/86

SHOT SKETCH

P. KELLEY/FERMI: JOB# 750-10404
1/30/86

INNER TANK • R.T.

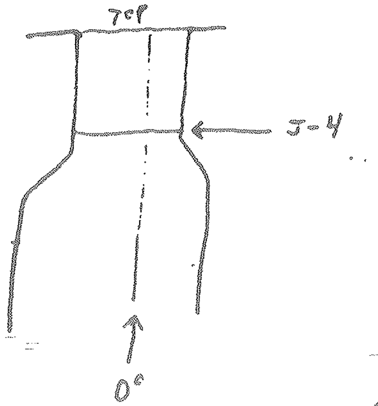
J-4 CIRCUM ≈ 75.4" BUTT WELD

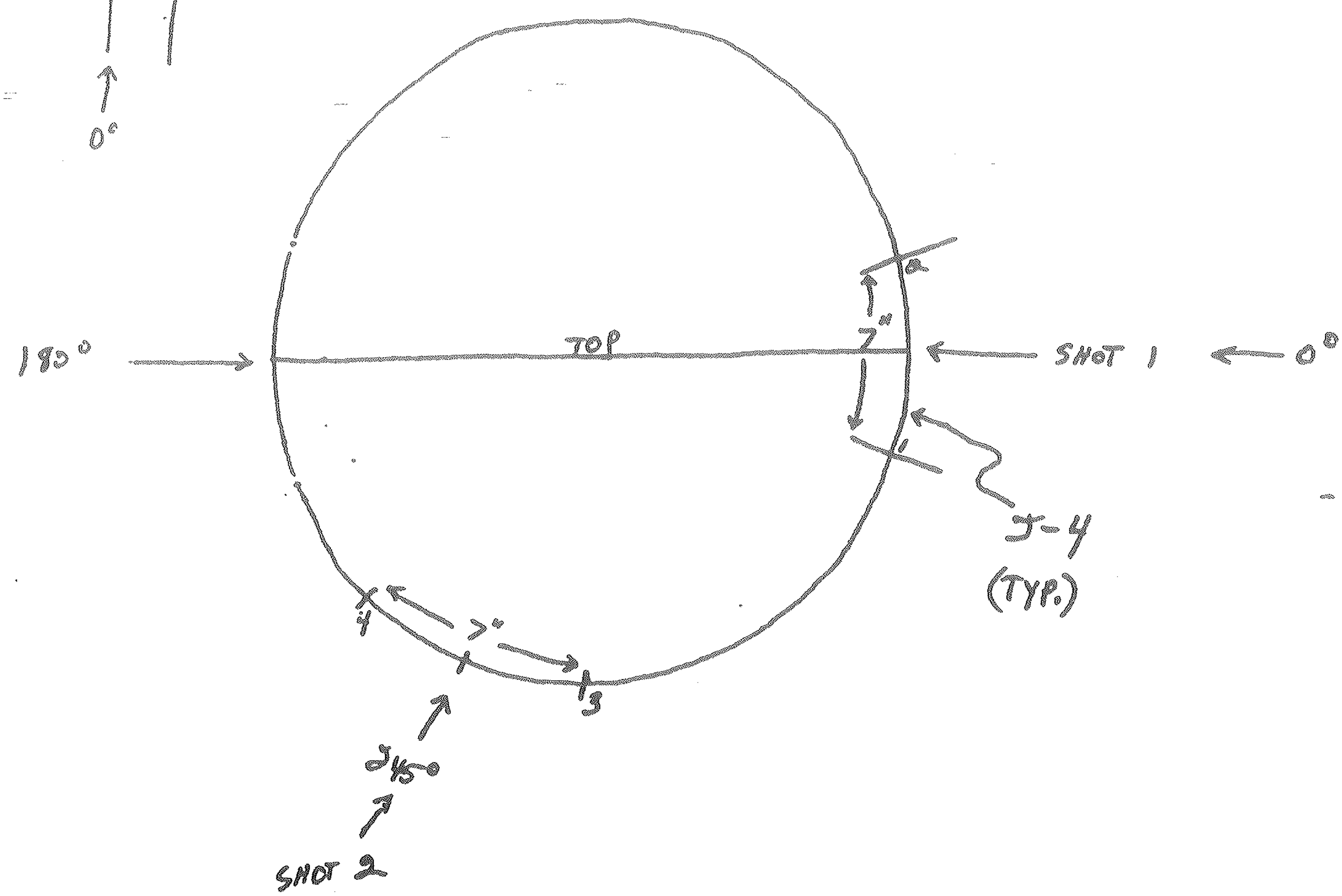
THICKNESS OF INNER TANK ≈ .059"

10% OF CIRCUM. TO BE X-RAYED, 18.5% OF CIRCUM. ACTUALLY X-RAYED.

2 ea. - 7" LENGTH OF WELD (AREA OF INTEREST)

TOTAL OF 2 SHOTS (TOTAL LENGTH ≈ 14")





NDT-500

QUALITY ASSURANCE DIVISION — Nondestructive Testing

RADIOGRAPHIC TECHNIQUE RECORD

PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: FERMi	PERSON: P. KELLEY	JOB NO.: 750-10404
INSPECTION CODE: ASME SECT. VIII	ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I - UW-52	MATERIAL TYPE: S.S./Cu/Al.
		MATL. THICKNESS: ≈.119"
PART NAME: He CRYOSTAT (CERN)	JCP #	DWG. NO.: 30-36-05
PART NUMBER(S): INNER TANK		

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-5 WELD (CIRCUM.)
SHOT #1, #2

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-5 WELD			INSPECTION DATE: 2/3/86
			PROCEDURE: NDT 500/REV. 7
☐ IR-192	☐ CO-60	SOURCE STRENGTH: C.	SOURCE SIZE: mm
☒ X-RAY MACHINE: SCAN RAY 250	FOCAL SPOT SIZE: 3.5 mm	KV: 180	MA: 5
EXPOSURE TIME: 2.5 min.	PENETRAMETER(S)/SHIM(S): #7SS/.020", .040", PART ITSELF		

	FILM LOCATION STATUS	DATE
SFD: 36"	FILED WITH QAD/NDT	
SCREENS: F.005"/B.010" Pb	SUBMITTED TO CUSTOMER	
FILM TYPE(S): "M" KODAK	SUBMITTED TO MATL. REVIEW	
FILM SIZE(S): 7"X17"	RETURNED TO QAD/NDT	
NUMBER OF FILMS: 2	SENT TO CENTRAL STORAGE	
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE		

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

RADIOGRAPHER (signature) C.W. Vialyak Jr. / J.W. Lucas	CERT. LEVEL: —	DATE: 2/14/86
INTERPRETER (signature) J.W. Lucas	CERT. LEVEL: II	DATE: 2/14/86

SHOT SKETCH

P. KELLEY/FERMI

JOB # 750-10464
2/3/86

INNER TANK

R.T.

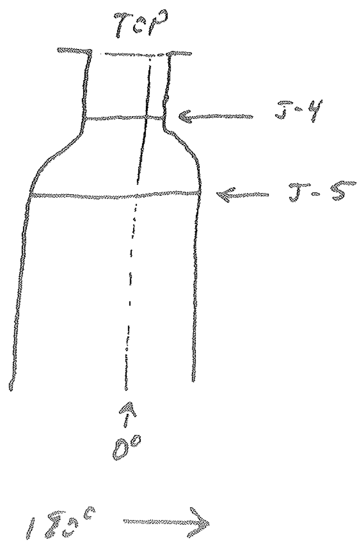
J-5 CIRCUM ≈ 94.25" BUTT WELD

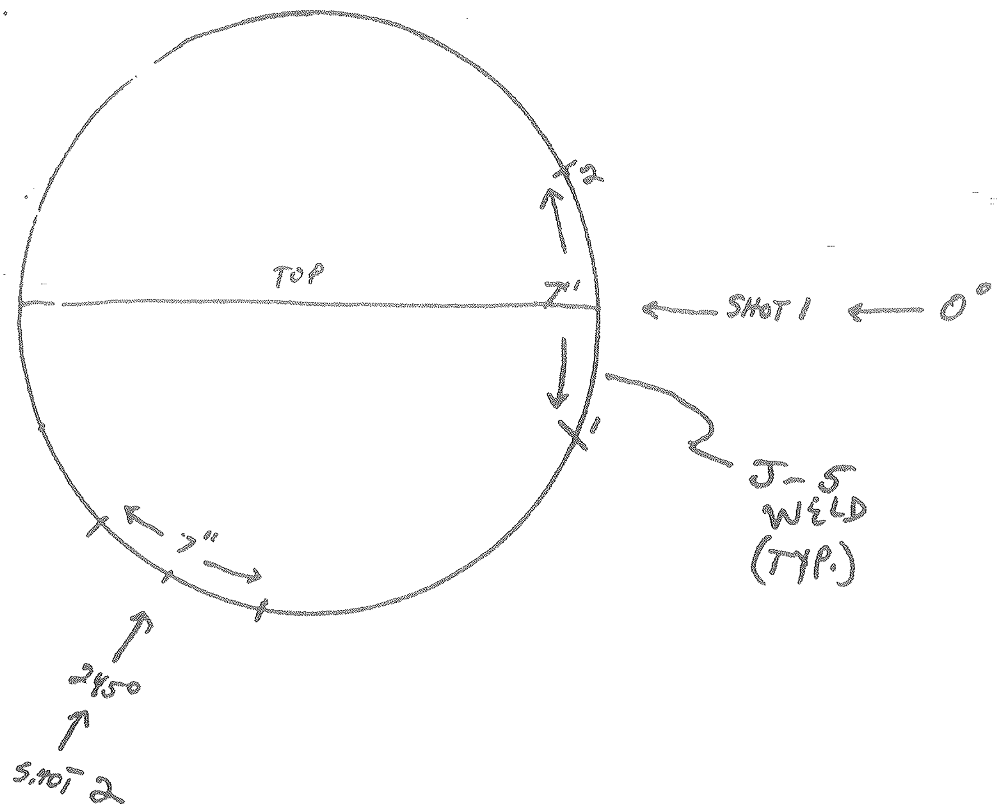
THICKNESS OF INNER TANK ≈ .079"

10% OF CIRCUM TO BE X-RAYED, 14.8% OF CIRCUM ACTUALLY X-RAYED.

2 EA. - 7" LENGTH OF WELD (AREA OF INTEREST)

TOTAL OF 2 SHOTS (TOTAL LENGTH ≈ 14")





NDT-500	QUALITY ASSURANCE DIVISION – Nondestructive Testing RADIOGRAPHIC TECHNIQUE RECORD	PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: Fermi	PERSON: P. Kelley	JOB NO.: 750 - 10404
INSPECTION CODE: ASME SECT. VIII	ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I - UW-52	MATERIAL TYPE: S.S./Cu/Al.
		MATL. THICKNESS: ~.079"/.129"
PART NAME: He CRYOSTAT (CERN)	JCP #	DWG. NO.: 30-36-05
PART NUMBER(S): INNER TANK		

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-6 WELD (CIRCUM.)
SHOT #1, #2

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-6 WELD			INSPECTION DATE: 2/3/86
			PROCEDURE: NDT500/REV.7
☐ IR-192	☐ CO-60	SOURCE STRENGTH: C.	SOURCE SIZE: mm
☐ X-RAY MACHINE: SCAN RAY 250	FOCAL SPOT SIZE: 3.5 mm	KV: 180	MA: 5
EXPOSURE TIME: 2.5 min.	PENETRAMETER(S)/SHIM(S): #7 S.S./.020", .040"; PART ITSELF		

	FILM LOCATION STATUS	DATE
SFD: 36"	FILED WITH QAD/NDT	
SCREENS: F.005"/B.010" Pb	SUBMITTED TO CUSTOMER	
FILM TYPE(S): "M" KODAK	SUBMITTED TO MATL. REVIEW	
FILM SIZE(S): 7"x17"	RETURNED TO QAD/NDT	
NUMBER OF FILMS: 2	SENT TO CENTRAL STORAGE	
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE		

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

RADIOGRAPHER (signature) C.W. [signature] / J.W. Lucas	CERT. LEVEL: II	DATE: 2/3/86
INTERPRETER (signature) J.W. Lucas	CERT. LEVEL: II	DATE: 2/14/86

SHOT SKETCH

P. KELLEY/FERMI

JOB# 750-10404
2/3/86

INNER TANK

R.T.

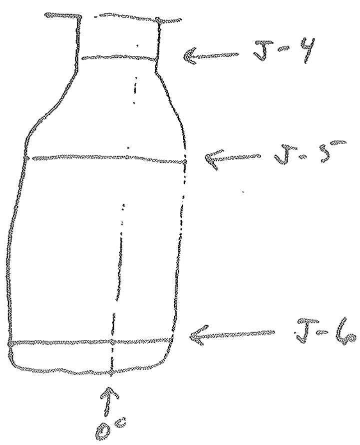
J-6 CIRCUM. ≈ 94.25″ BUTT WELD

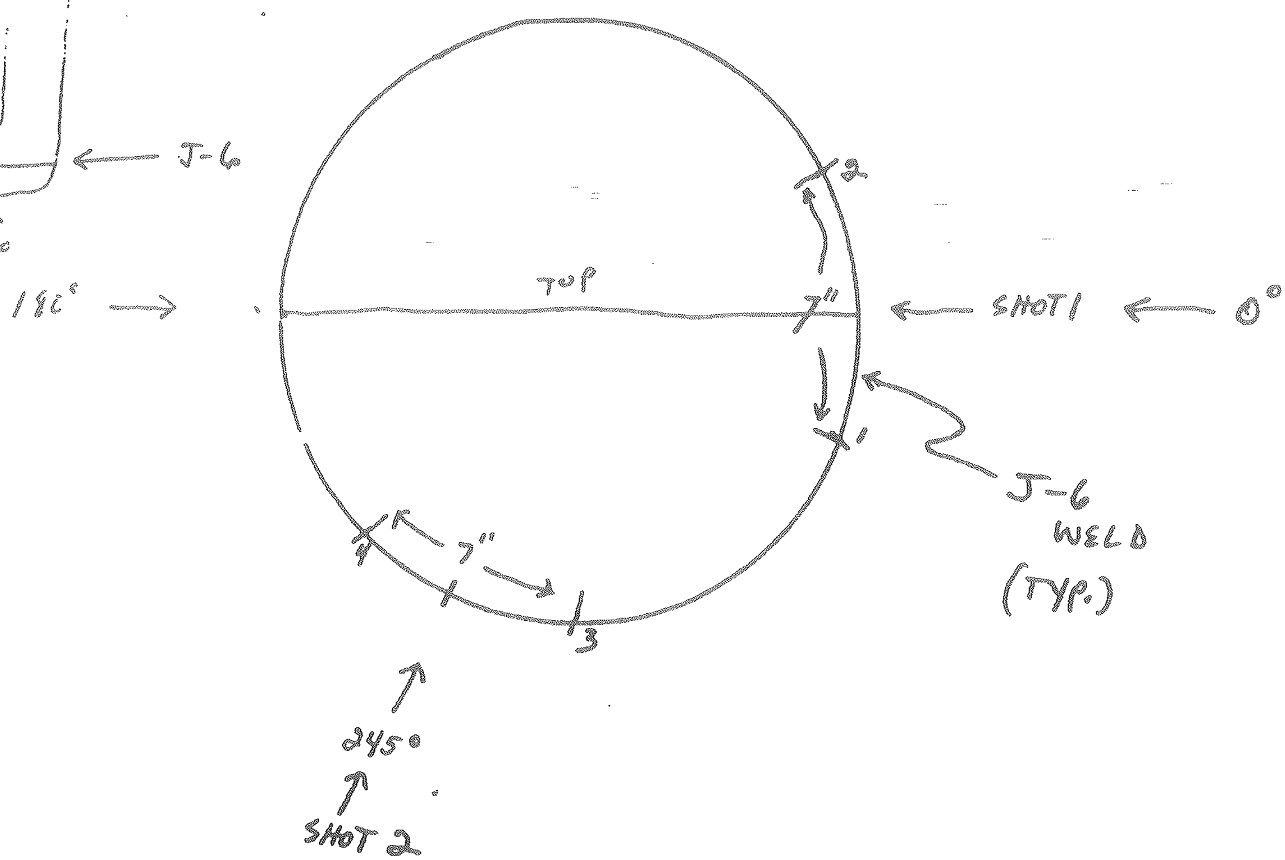
THICKNESS OF INNER TANK ≈ .079″ TO .236″

10% OF CIRCUM. TO BE X-RAYED, 14.8% OF CIRCUM. ACTUALLY X-RAYED.

2 ea. – 7″ LENGTH OF WELD (AREA OF INTEREST)

TOTAL OF 2 SHOTS (TOTAL LENGTH ≈ 14″)





NDT-500

QUALITY ASSURANCE DIVISION – Nondestructive Testing

RADIOGRAPHIC TECHNIQUE RECORD

INSPECTION REQUIREMENTS

DIVISION: Fermi
PERSON: P. Kelley
JOB NO.: 750 - 10404

INSPECTION CODE: ASME SECT. VIII
ACCEPTANCE CRITERIA: ASME SECT. VIII DIV. I - UW-52
MATERIAL TYPE: 304L S.S.
MATL. THICKNESS: 1/2"

PART NAME: He CRYOSTAT
JCP #
DWG. NO.: 30-36-05

PART NUMBER(S): INNER TANK

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS:
(raw material, weld type, weld joint, specific part area, etc.):

J-7 WELD 10% (circum.)

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☐ OTHER:

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: J-7 WELD (circum) (INNER / OUTER) WELDS
INSPECTION DATE: 2/10/86
PROCEDURE: NDT 500/REV. 7

☒ IR-192 ☐ CO-60 SOURCE STRENGTH: 68 C. SOURCE SIZE: .1 X .1 mm

☐ X-RAY MACHINE: FOCAL SPOT SIZE: mm KV: MA:

EXPOSURE TIME: 2.5 min.
PENETRAMETER(S)/SHIM(S): #7 / .020", .040" (Film side)

SFD: 21"
SCREENS: .010" F/B Pb
FILM TYPE(S): "M" KODAK
FILM SIZE(S): 8" X 10"
NUMBER OF FILMS: 2
VIEWING TECH.: ☒ SINGLE ☐ COMPOSITE

FILM LOCATION STATUS	DATE
FILED WITH QAD/NDT	
SUBMITTED TO CUSTOMER	
SUBMITTED TO MATL. REVIEW	
RETURNED TO QAD/NDT	
SENT TO CENTRAL STORAGE	

INSPECTION RESULTS: ☒ ACCEPT ☐ UNACCEPT ☐ OTHER*: I/DR NO.:

COMMENTS (masks, filters, etc.*):

RADIOGRAPHER (signature) J. W. Lucas CERT. LEVEL: II DATE: 2/14/86

INTERPRETER (signature) CERT. LEVEL: II DATE: 2/14/86

SHOT SKETCH

P. KELLEY/ FERMI

JOB# 750-10404

2/17/86

INNER TANK

R.T.

(OUTER) J-7 CIRCUM ≈ 37.68" BUTT WELD

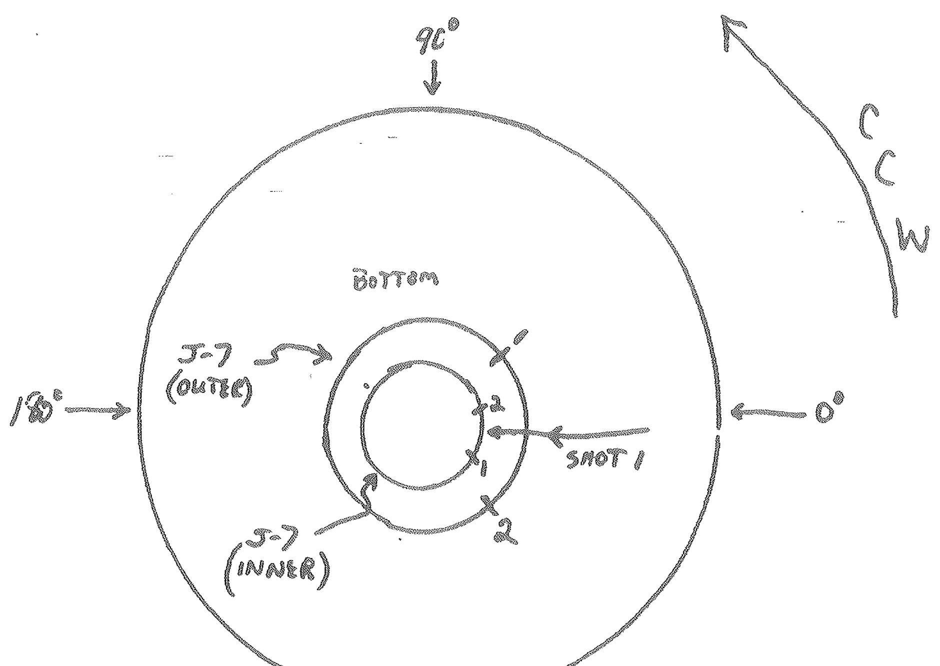
(INNER) J-7 CIRCUM. ≈ 12.56" BUTT WELD

THICKNESS OF INNER TANK ≈ .159"

10% OF CIRCUM TOBE X-RAYED.

(OUTER) 1ea. – 7" LENGTH OF WELD (AREA OF INTEREST)

(INNER) 1ea. – 1½" LENGTH OF WELD (AREA OF INTEREST)



F Personal Ultrasonic Testing Certificates

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

ROGER B. MASSOW

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL III — ULTRASONIC

BASED ON SNT TC-1A

AWARDED THIS DATE

JULY 28, 1985

D. N. Bounelis

D. N. BOUNELIS, DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. Busse

T. H. BUSSE
NDT LEVEL III EXAMINER

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

CHARLES VULYAK JR

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL II ULTRASONIC

BASED ON SNT TC-1A

AWARDED THIS DATE

MAY 2, 1984

D. N. Bounelis

D. N. BOUNELIS, DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. Busse

T. H. BUSSE
NDT LEVEL III EXAMINER

ARGONNE NATIONAL LABORATORY

CERTIFICATE AWARDED TO

JOSEPH W. LUCAS

WHO HAS SUCCESSFULLY MET THE REQUIREMENTS STATED IN ARGONNE NATIONAL LABORATORY'S NON-DESTRUCTIVE TESTING PERSONNEL QUALIFICATION AND CERTIFICATION PROGRAM FOR

LEVEL II – ULTRASONIC

BASED ON SNT TC-1A

AWARDED THIS DATE

APRIL 1, 1985

D. N. Bounelis

D. N. BOUNELIS, DIRECTOR
QUALITY ASSURANCE DIVISION

T. H. Busse

T. H. BUSSE
NDT LEVEL III EXAMINER

G Ultrasonic Technique Records and Grid Sketches

NDT-600	QUALITY ASSURANCE DIVISION — Nondestructive Testing SSD-IN ULTRASONIC TECHNIQUE RECORD	PAGE 1 OF 1

RBM 1/30/86

INSPECTION REQUIREMENTS

DIVISION: Fermi | PERSON: P. KELLEY | JOB NO.: 750-10404

INSPECTION CODE: N/A | ACCEPTANCE CRITERIA: CUSTOMER EVALUATION | MATERIAL TYPE: 304L S.S. | MATL. THICKNESS: SEE ⊛ COMMENTS

PART NAME: He CRYOSTAT (INNER TANK) | JCP # | DWG. NO.: 30-36-05

PART NUMBER(S) INNER TANK

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS: (material, weld type, weld joint no., specific part area, etc.): "CERN"

THICKNESS MEASUREMENT EVERY 60° INCREMENTS

144 READINGS ON (INSIDE) CYLINDER (TANK)

48 READINGS ON (INSIDE) BOTTOM OF CYLINDER (TANK)

ATTACHMENTS: ☒ SKETCH ☐ DRAWING ☒ OTHER: THICKNESS MEASUREMENT RECORDINGS

FOR QAD/NDT USE ONLY

PART IDENTIFICATION: He CRYOSTAT (INNER TANK) | INSPECTION DATE: 1/23/86 | PROCEDURE: NDT 605

EQUIPMENT MODEL: KBI MOD. CL 204 THICKNESS GAUGE | P.R.R.: 1 K Pulse/sec.

TRANSDUCER TYPE: DELAY LINE AEROTECH ALPHA-2, SER. # E-18774 | FREQUENCY: 15 MHz

TRANSDUCER SIZE & SHAPE: 1/4" DIA.

SCANNING EQUIPMENT MODEL: MANUAL | SCAN SPEED: N/A In./sec.

METHOD: ☐ IMMERSION ☒ CONTACT ☐ OTHER:

TECHNIQUE: ☒ PULSE ECHO ☐ THROUGH TRANSMISSION ☐ OTHER:

MODE: ☒ STRAIGHT BEAM ☐ ANGLE BEAM ☐ OTHER:

COUPLANT: ULTRAGEL II | REFRACTED ANGLE: N/A Deg.

REFERENCE STANDARD: U3-SS8 | DISCONTINUITY: N/A

REFERENCE STANDARD ACOUSTIC SIMILARITY: — % REFLECTION OF REFERENCE STD.

DATA PRESENTATION: ☐ VISUAL CRT ☐ GATE ALARM ☒ OTHER: DIGITAL READOUT ☐ STRIP CHART RECORDING ☐ C — SCAN RECORDING

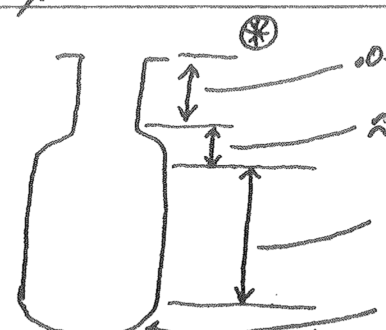
INSPECTION RESULTS: ☐ ACCEPT ☐ UNACCEPT ☒ OTHER*: | I/DR NO.:

COMMENTS (reportable indications, etc.*):

CUSTOMER EVALUATION

RESOLUTION: ± .0001"

ACCURACY OF INSPECTION: ± .0005"



INSPECTOR (signature) [signatures] | CERT. LEVEL II/II | DATE: 1/30/86

RBM 1/30/86

NDT - 01	QUALITY ASSURANCE DIVISION - Nondestructive Testing "STANDARD" VERIFICATION	PAGE 1 OF 1

DESCRIPTION: Step wedge 1.5" x 7.5"

MATERIAL FABRICATOR:

STANDARD FABRICATOR: ANL/CS

STANDARD No.: U 3-558

MATERIAL: 304 SS

HEAT:

INSPECTOR: RB Massey

DATE: 9/19/78

DIMENSIONS

NO.	TYPE	LOCATION	ORIENTATION	LENGTH	WIDTH/DIA.	DEPTH*
1	Step	.040		1.5"	1.5"	.0400"
2	Step	.078		1.5"	1.5"	.0784"
3	Step	.118		1.5"	1.5"	.1179"
4	Step	.158		1.5"	1.5"	.1580"
5	Step	.197		1.5"	1.5"	.1967"

☐ LP-10 PROFILE PROJECTOR (ANL # 160438) and PROJECTOR STANDARD (Gage Code # 2-OCS-1)

☒ MICROMETER SERIAL No.(s): 2-M-0-1-14
& MIC. STANDARD GAGE CODE No.(s): 2-SB-.5-1

☐ OTHER MEASURING EQUIP.:

These measurements were made with above equipment and are traceable to the N.B.S.

SKETCH & REMARKS: * Measurements are within ± 0.0001"

SKETCH & RECORDINGS

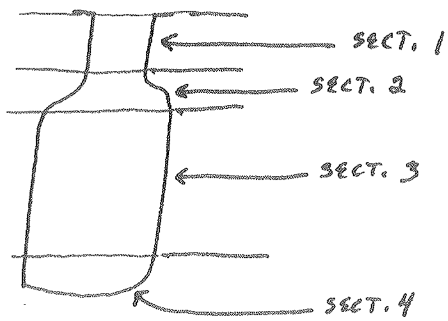
P. KELLEY / FERMI

JOB # 750-10404

1/24/86

INNER TANK (SEC. 1)

1. READINGS NUMBERED FROM # 1 TO # 48.
2. 0° POSITION ALIGNED WITH LONG. SEAM WELD.



LONG. SEAM WELD

3) ROTATIONS OF POSITION CCW. (INSPECTION DIRECTION) FROM TOP OF SEC. TO BOTTOM OF SECTION.

Position	TOP							BOTTOM
0°	#1 .0593	#2 .0595	#3 .0598	#4 .0598	#5 .0598	#6 .0596	#7 .0592	#8 .0587
60°	#9 .0593	#10 .0596	#11 .0598	#12 .0598	#13 .0598	#14 .0597	#15 .0594	#16 .0592
120°	#17 .0593	#18 .0596	#19 .0598	#20 .0598	#21 .0598	#22 .0598	#23 .0594	#24 .0590
180°	#25 .0593	#26 .0598	#27 .0598	#28 .0598	#29 .0599	#30 .0599	#31 .0595	#32 .0592
240°	#33 .0592	#34 .0597	#35 .0599	#36 .0600	#37 .0599	#38 .0598	#39 .0595	#40 .0591
300°	#41 .0593	#42 .0597	#43 .0598	#44 .0598	#45 .0598	#46 .0598	#47 .0594	#48 .0590
0°	LONG. SEAM WELD							

CCW

TRANSDUCER CONTACT POINTS (X) POSITIONED EVERY ≈ 4 in. OF EACH OTHER.

SKETCH & RECORDINGS

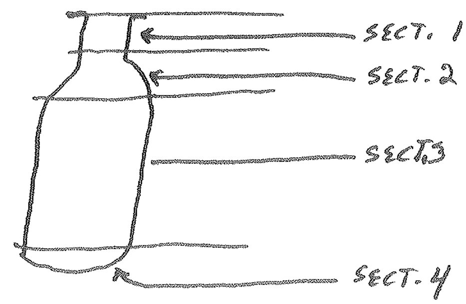
P. KELLEY/FERMI

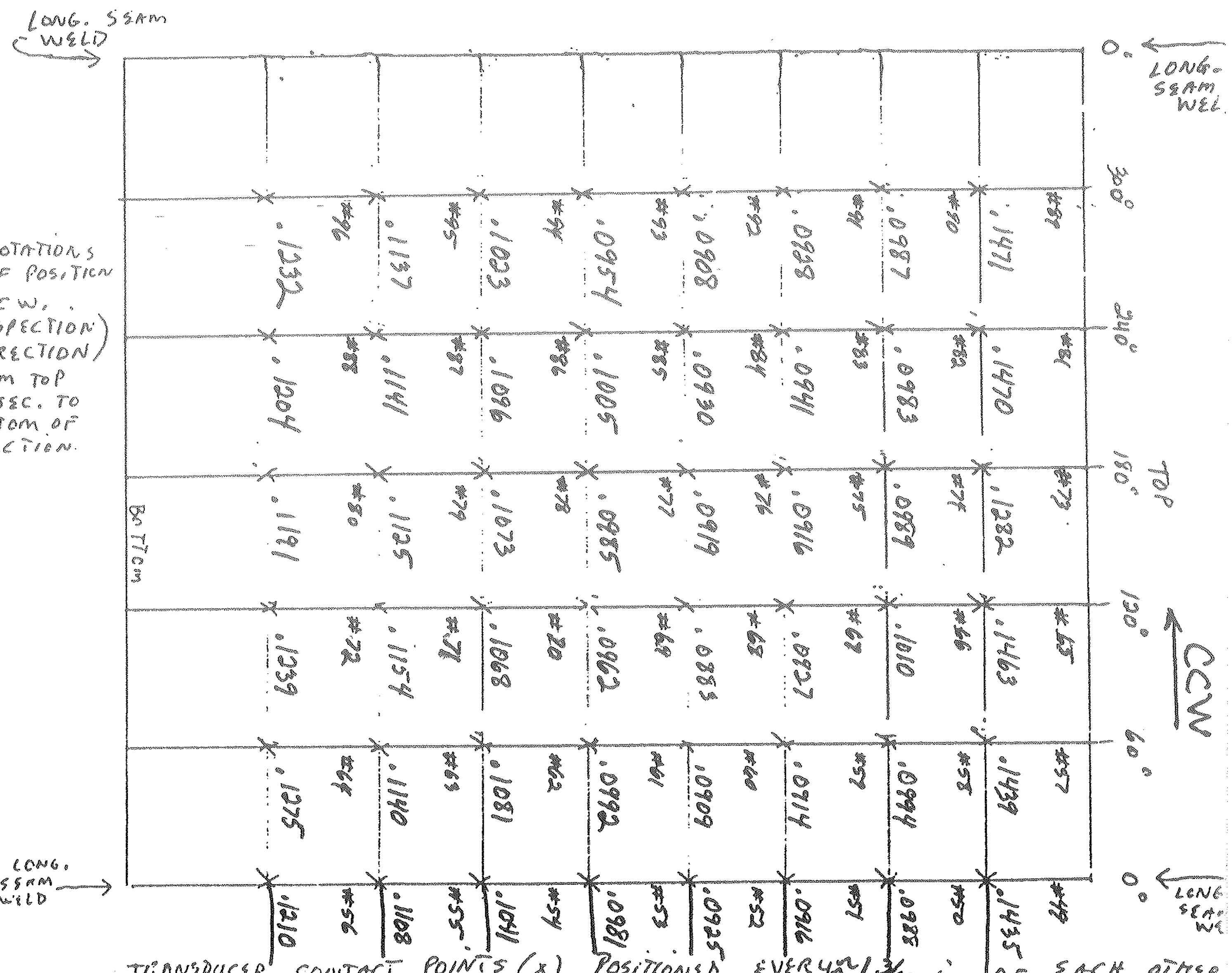
JOB# 750-10404

1/24/86

INNER TANK (SEC 2)

1. READINGS NUMBERED FROM # 49 TO # 96.
2. 0° POSITION ALIGNED WITH LONG. SEAM WELD.





TRANSDUCER CONTACT POINTS (X) POSITIONED EVERY 2 1/32 in. OF EACH OTHER

P. KELLEY / FERMI

SKETCH & RECORDINGS

INNER TANK (SEC. 2)

JOB # 750-10404

2/14/86

INSIDE RADIUS — U.T.

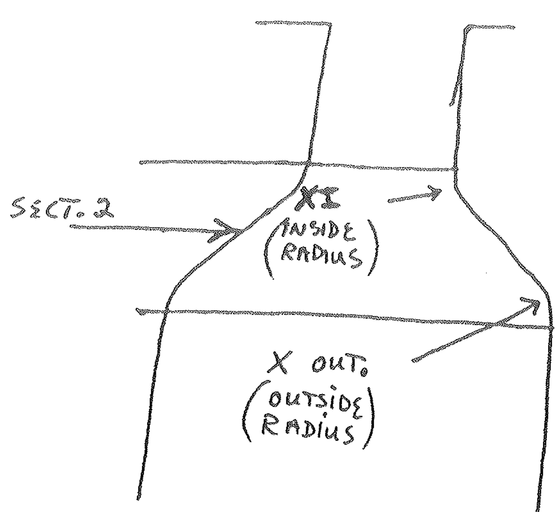
0°		60°		120°		180°	
READING #	READINGS	READING #	READINGS	READING #	READINGS	READING #	READINGS
49	.1435"	57	.1439"	65	.1463	73	.1282
1I	.1151"	2I	.1199	3I	.1118	4I	.1102
50	.0988"	58	.0994	66	.1010	74	.0989

240°		300°	
READING #	READINGS	READING #	READINGS
81	.1470	89	.1471
5I	.1206	6I	.1163
82	.0983	90	.0987

OUTSIDE RADIUS

0°		60°		120°		180°	
READING #	READINGS	READING #	READINGS	READING #	READINGS	READING #	READINGS
55	.1108"	63	.1140	71	.1154	79	.1125
1 OUT.	.1110"	2 OUT.	.1142	3 OUT.	.1147	4 OUT.	.1120
56	.1210"	64	.1275	72	.1239	80	.1191

240°		300°	
READING #	READINGS	READING #	READINGS
87	.1141	95	.1137
5 OUT.	.1149	6 OUT.	.1139
88	.1204	96	.1232



NOTE: OUTSIDE RADIUS READINGS ARE LOWEST READINGS TAKEN AT EACH LOCATION.

RB Massar ANL Level III - UT 2/14/86

SKETCH + RECORDINGS

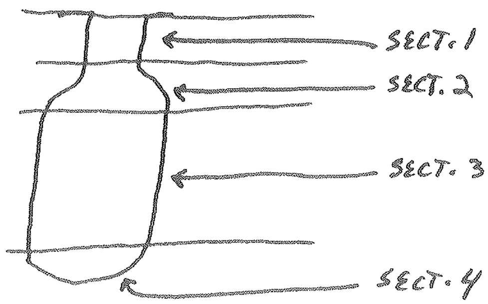
P. KELLEY/FERMI

JOB # 750-10404

1/24/86

INNER TANK (SEC. 3)

1. READINGS NUMBERED FROM # 97 TO # 144.
2. 0° POSITION ALIGNED WITH LONG. SEAM WELD.



LONG. SEAM WELD

TOP / BOTTOM

° ROTATIONS OF POSITION CCW. (INSPECTION DIRECTION) FROM TOP OF SEC. TO BOTTOM OF SECTION

CCW

Position								
300°	.0794 #144	.0794 #143	.0795 #142	.0795 #141	.0796 #140	.0797 #139	.0797 #138	.0799 #137
240°	.0797 #136	.0798 #135	.0799 #134	.0802 #133	.0804 #132	.0804 #131	.0805 #130	.0805 #129
180°	.0797 #128	.0797 #127	.0798 #126	.0800 #125	.0801 #124	.0802 #123	.0803 #122	.0804 #121
120°	.0793 #120	.0794 #119	.0795 #118	.0798 #117	.0797 #116	.0800 #115	.0800 #114	.0800 #113
60°	.0797 #112	.0792 #111	.0794 #110	.0798 #109	.0799 #108	.0800 #107	.0799 #106	.0801 #105
0°	.0798 #104	.0799 #103	.0803 #102	.0802 #101	.0801 #100	.0803 #99	.0801 #98	.0802 #97

TRANSDUCER CONTACT POINTS (X) POSITIONED EVERY 3 13/16 in. OF EACH OTHER.

SKETCH & RECORDINGS

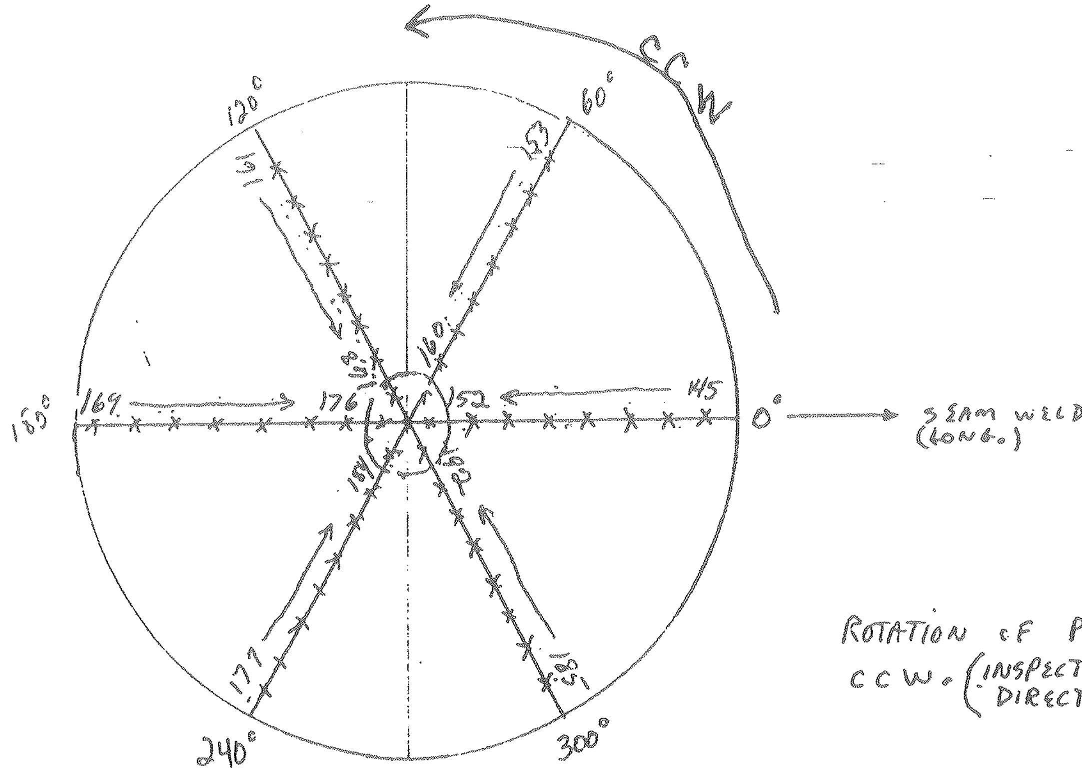
P. KELLEY / FERMI — JOB # 750-10404 — 1/24/86

INNER TANK (BOTTOM) SECT. 4

1) READINGS NUMBERED FROM # 145 TO # 192.
2) 0° POSITION ALIGNED WITH LONG. SEAM WELD

READINGS

0° #		60° #		120° #		180° #		240° #		300° #	
145	.1298	153	.1296	161	.1328	169	.1331	177	.1295	185	.1296
146	.1441	154	.1427	162	.1444	170	.1447	178	.1389	186	.1412
147	.1506	155	.1463	163	.1478	171	.1518	179	.1447	187	.1484
148	.1524	156	.1527	164	.1543	172	.1557	180	.1520	188	.1518
149	.1527	157	.1532	165	.1534	173	.1538	181	.1527	189	.1525
150	.1513	158	.1538	166	.1556	174	.1555	182	.1548	190	.1538
151	.1603	159	.1554	167	.1602	175	.1610	183	.1607	191	.1604
152	.1611	160	.1605	168	.1607	176	.1602	184	.1606	192	.1608



ROTATION OF POSITION CCW. (INSPECTION DIRECTION)

TRANSDUCER CONTACT POINTS (X) POSITIONED EVERY ≈2 IN. OF EACH OTHER IN EACH QUADRANT.

H Finite Element Analysis of CVM Conical Transition—Memo from R. Wands to J.P. Kelley, August 1986.

Fermilab

Cryogenics Department — MS#219
Wilson Hall 11th Floor — Ext: 4882

August 25, 1986

To: Pat Kelley
From: Bob Wands
Subject: **Finite Element Analysis of CVM Conical Transition**

The CVM conical transition has been modeled with ANSYS. The resulting stresses have been evaluated and have been found to be within the limits set by the ASME Section VIII, Div. 2 , Appendix 4, which a maximum allowable membrane stress intensity (S_M) of 12560 *psi* is assumed.

The transition was modeled axisymmetrically with STIF42 4-node quadrilateral elements. An internal pressure of 47 *psid* was applied. Ten inches of cylindrical shell was included at each end of the transition to eliminate end effects, and the end pressure effects were simulated with nodal forces at the bottom of the large diameter cylindrical shell, and a vertical constrain at the top of the small diameter shell. A sketch of the geometry and boundary conditions is shown in Fig. 1. Due to the high length to thickness ratio in most sections, the mesh does not plot in an easily interpreted manner. Therefore the number of elements along the length and through the thickness of a section are noted on the figure.

The thicknesses used in the model are based on your ultrasound testing data, and use the minimum thickness found in each end radius and the conical portion of the transition. Variation of thickness between these values is linear (see Fig. 1).

Maximum stresses in each end radius and the center of the conical portion are given in Table 1. The stresses are categorized according to Section VIII, Div. 2, App. 4. The allowable S_M of 12560 *psi* is derived by applying a factor of 0.80 to the maximum allowable stress for 304L as given in Section VIII, Div. 1. As can be seen, all stresses are within the allowable values.

Stresses were extracted by the ANSYS post-processor POST11, which is used exclusively for calculating linearized stress distributions in axisymmetric pressure vessel analyses to aid in Code evaluation. The POST11 output is appended for your information.

Table 1. Stress Summary

Location (Fig. 2)	Stress Category[1]	Actual Stress	Allowable Stress[1]
1	P_L	16000	18840
	$P_L + Q$	20700	37680
2	P_M	9000	12560
	$P_M + P_b$	9200	18840
3	P_L	11600	18840
	$P_L + Q$	29600	37680

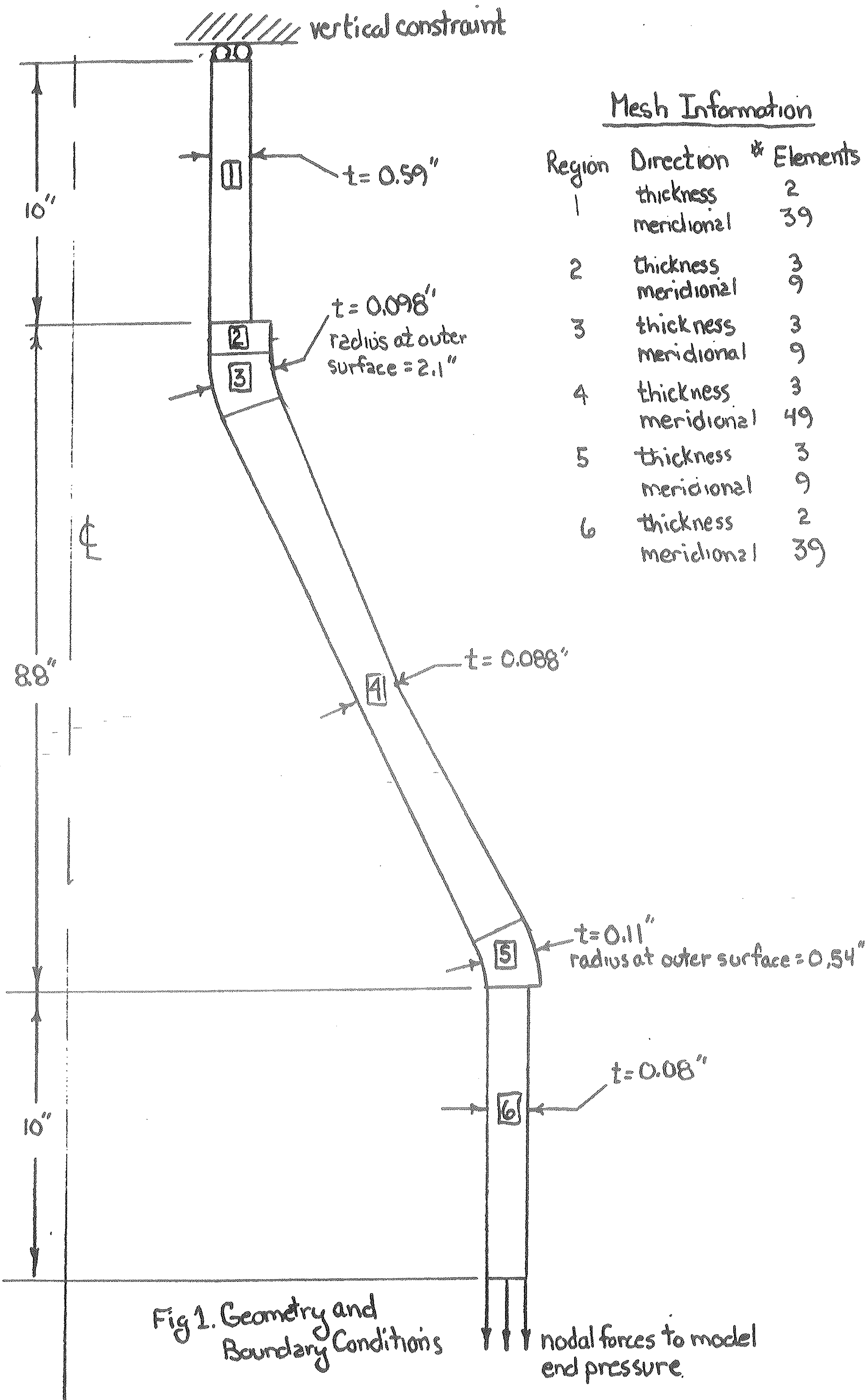
1

P_L = primary local membrane stress. Allowable is $1.5S_M$.

Q = secondary bending stress. Allowable for $P_L + Q$ is $3S_M$.

P_M = primary membrane stress. Allowable is $1.0S_M$.

P_b = primary bending stress. Allowable for $P_M + P_b$ is $1.5S_M$.



Mesh Information

Region	Direction	# Elements
1	thickness	2
	meridional	39
2	thickness	3
	meridional	9
3	thickness	3
	meridional	9
4	thickness	3
	meridional	49
5	thickness	3
	meridional	9
6	thickness	2
	meridional	39

Fig 1. Geometry and Boundary Conditions

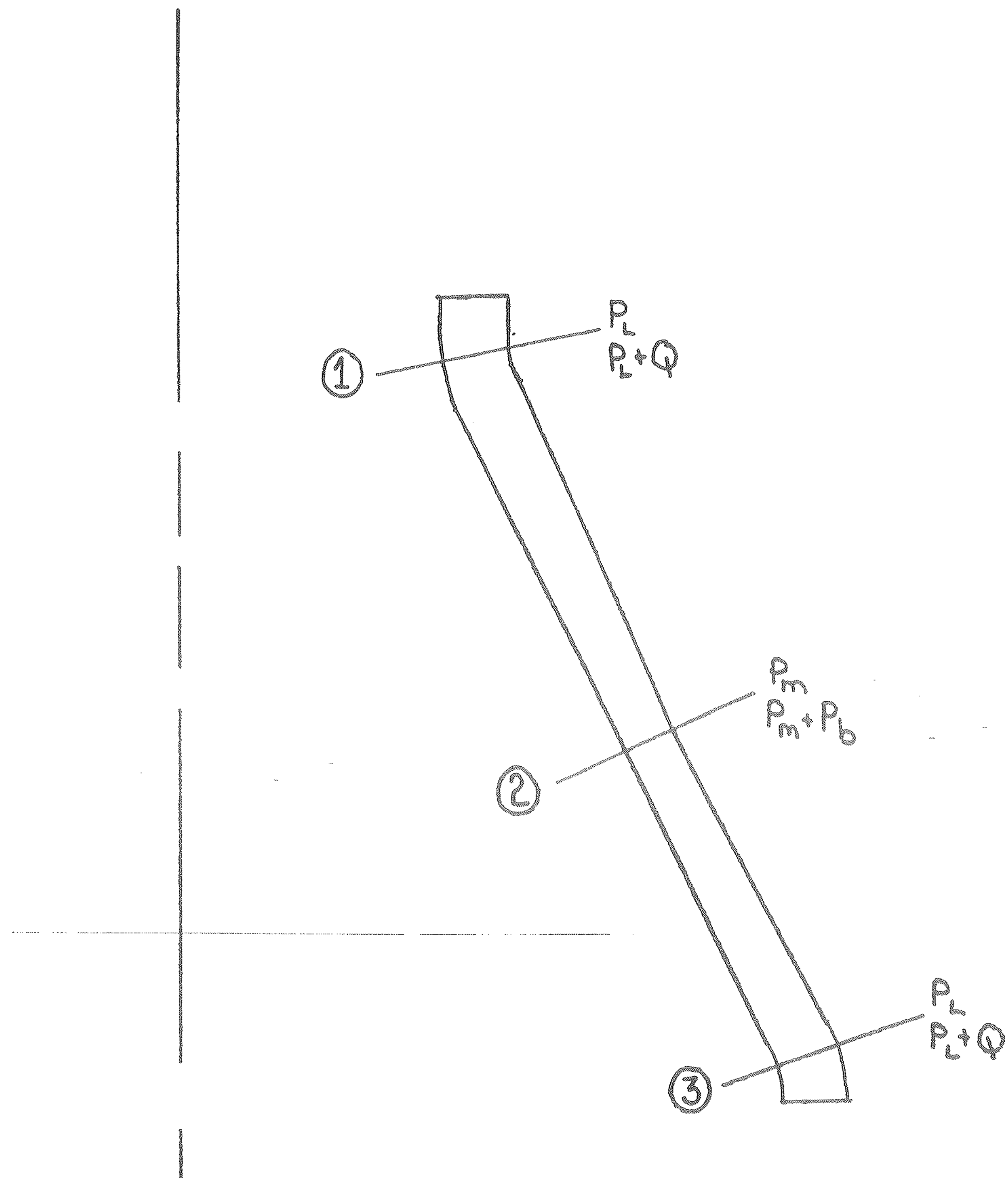


Fig 2. Locations and Stress Categories for Table I

PRIMARY STRESS EVALUATION
****

Location 1 P_L

POS-11 Output 8/20/86

CONICAL TRANSITION FOR CVM CRYOSTAT

SECTION 2 LOADING 1

ELEMENT	CENTROID X	CENTROID Y	STRESSES SIG-X	SIG-Y	SIG-T	TAU-XY
118	11.965	-.54880	832.87	8682.5	17874.	-2301.5
119	11.933	-.55728	427.22	2714.8	16028.	-724.33
120	11.902	-.56576	-75.155	-3060.5	14204.	828.65
		AVERAGE	390.38	2719.4	16017.	-716.51

PRINCIPAL STRESSES		STRESS INTENSITIES	
(S1)	2922.2	(S1-S2)	2734.6
(S2)	187.60	(S2-S3)	15829.
(S3)	16017.	(S3-S1)	13094.
MAXIMUM	16017.		15829.

PRIMARY STRESS EVALUATION
****

Location 2 P_m

CONICAL TRANSITION FOR CVM CRYOSTAT

SECTION 3 LOADING 1

ELEMENT	CENTROID X	CENTROID Y	STRESSES SIG-X	STRESSES SIG-Y	STRESSES SIG-T	STRESSES TAU-XY
202	13.886	-4.1067	1166.3	3605.2	9101.7	-2055.0
203	13.860	-4.1214	1045.0	3167.0	8976.1	-1844.3
204	13.835	-4.1361	883.63	2772.0	8851.2	-1611.6
		AVERAGE	1031.7	3181.4	8976.3	-1837.0

PRINCIPAL STRESSES		STRESS INTENSITIES	
(S1)	4234.9	(S1-S2)	4256.7
(S2)	-21.801	(S2-S3)	8998.1
(S3)	8976.3	(S3-S1)	4741.5
MAXIMUM	8976.3		8998.1

PRIMARY STRESS EVALUATION
****

CONICAL TRANSITION FOR CVM CRYOSTAT

Location 3 P_L

SECTION 4 LOADING 1

ELEMENT	CENTROID X	CENTROID Y	STRESSES SIG-X	SIG-Y	SIG-T	TAU-XY
289	15.737	-7.3657	-728.22	-9936.3	-13145.	3619.9
290	15.702	-7.3773	1037.2	2031.7	-9100.0	7.0585
291	15.666	-7.3889	2338.3	16339.	-4482.2	-5003.2
		AVERAGE	857.55	2560.1	-8990.8	-372.38

PRINCIPAL STRESSES		STRESS INTENSITIES	
(S1)	2638.0	(S1-S2)	1858.3
(S2)	779.66	(S2-S3)	9770.5
(S3)	-8990.8	(S3-S1)	11629.
MAXIMUM	-8990.8		11629.

LINEAR STRESS GRADIENTS
****

CONICAL TRANSITION FOR CVN CRYOSTAT

Location 1 P_L+Q

SECTION 2 LOADING 1

	CENTROID X	CENTROID Y	STRESSES SIG-X	STRESSES SIG-Y	STRESSES SIG-T	STRESSES TAU-XY
REFERENCE SURFACE	11.981	-.54457				
118	11.965	-.54880	832.87	8682.5	17874.	-2301.5
119	11.933	-.55728	427.22	2714.8	16028.	-724.33
120	11.902	-.56576	-75.155	-3060.5	14204.	828.65
SURFACE	11.886	-.57000				

LINEARIZED STRESSES (OPTION 2)

	MERIDIONAL MEMB	MERIDIONAL BEND	MERIDIONAL MEMB+BEND	HOOP MEMB	HOOP BEND	HOOP MEMB+BEND
FIRST SURFACE	2921.6	10857.	13779.	16017.	3166.2	19183.
SECOND SURFACE	2921.6	-10711.	-7789.7	16017.	-3123.7	12893.

****

STRESS SUMMARY(LINEAR GRADIENT)

	FIRST SURFACE	SECOND SURFACE
PRINCIPAL STRESSES		
-PRESSURE (S1)	0.	0.
MERIDIONAL (S2)	13779.	-7789.7
HOOP (S3)	19183.	12893.
STRESS INTENSITIES		
S1-S2	-13779.	7789.7
S2-S3	-5404.1	-20683.
S3-S1	19183.	12893.
MAXIMUM	19183.	-20683.

LINEAR STRESS GRADIENTS
****

CONICAL TRANSITION FOR CVM CRYOSTAT

Location 2 $P_m + P_b$

SECTION 3 LOADING 1

	CENTROID X	CENTROID Y	STRESSES SIG-X	SIG-Y	SIG-T	TAU-XY
REFERENCE SURFACE	13.898	-4.0994				
202	13.886	-4.1067	1166.3	3605.2	9101.7	-2055.0
203	13.860	-4.1214	1045.0	3167.0	8976.1	-1844.3
204	13.835	-4.1361	883.63	2772.0	8851.2	-1611.6
SURFACE	13.822	-4.1435				

LINEARIZED STRESSES (OPTION 2)

	MERIDIONAL MEMB	MERIDIONAL BEND	MERIDIONAL MEMB+BEND	HOOP MEMB	HOOP BEND	HOOP MEMB+BEND
FIRST SURFACE	4234.8	925.41	5160.3	8976.3	214.69	9191.0
SECOND SURFACE	4234.8	-925.41	3309.4	8976.3	-214.69	8761.6

****

STRESS SUMMARY(LINEAR GRADIENT)

	FIRST SURFACE	SECOND SURFACE
PRINCIPAL STRESSES		
-PRESSURE (S1)	0.	0.
MERIDIONAL (S2)	5160.3	3309.4
HOOP (S3)	9191.0	8761.6
STRESS INTENSITIES		
S1-S2	-5160.3	-3309.4
S2-S3	-4030.8	-5452.2
S3-S1	9191.0	8761.6
MAXIMUM	9191.0	8761.6

LINEAR STRESS GRADIENTS
****

CONICAL TRANSITION FOR CVM CRYOSTAT

Location 3 $P_L + Q$

SECTION 4 LOADING 1

REFERENCE SURFACE	CENTROID X	CENTROID Y	STRESSES SIG-X	SIG-Y	SIG-T	TAU-XY
SURFACE	15.753	-7.3600				
289	15.737	-7.3657	-728.22	-9936.3	-13145.	3619.9
290	15.702	-7.3773	1037.2	2031.7	-9100.0	7.0585
291	15.666	-7.3889	2338.3	16339.	-4482.2	-5003.2
SURFACE	15.648	-7.3947				

LINEARIZED STRESSES (OPTION 2)

	MERIDIONAL MEMB	MERIDIONAL BEND	MERIDIONAL MEMB+BEND	HOOP MEMB	HOOP BEND	HOOP MEMB+BEND
FIRST SURFACE	2614.5	-23947.	-21333.	-8990.8	-7122.2	-16113.
SECOND SURFACE	2614.5	25623.	28237.	-8990.8	7620.6	-1370.3

****

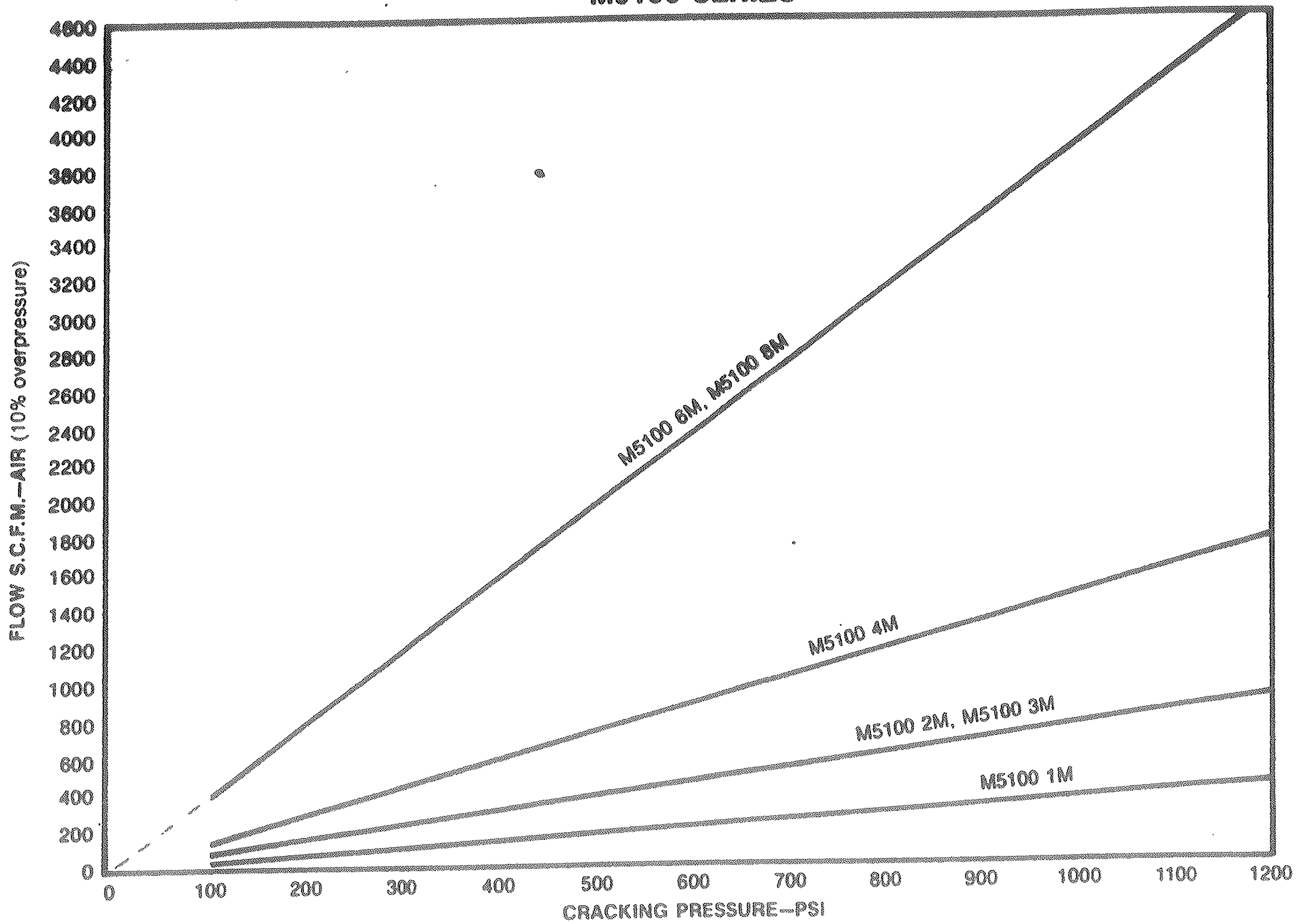
STRESS SUMMARY(LINEAR GRADIENT)

	FIRST SURFACE	SECOND SURFACE
PRINCIPAL STRESSES		
-PRESSURE (S1)	0.	0.
MERIDIONAL (S2)	-21333.	28237.
HOOP (S3)	-16113.	-1370.3
STRESS INTENSITIES		
S1-S2	21333.	-28237.
S2-S3	-5219.6	29608.
S3-S1	-16113.	-1370.3
MAXIMUM	21333.	29608.

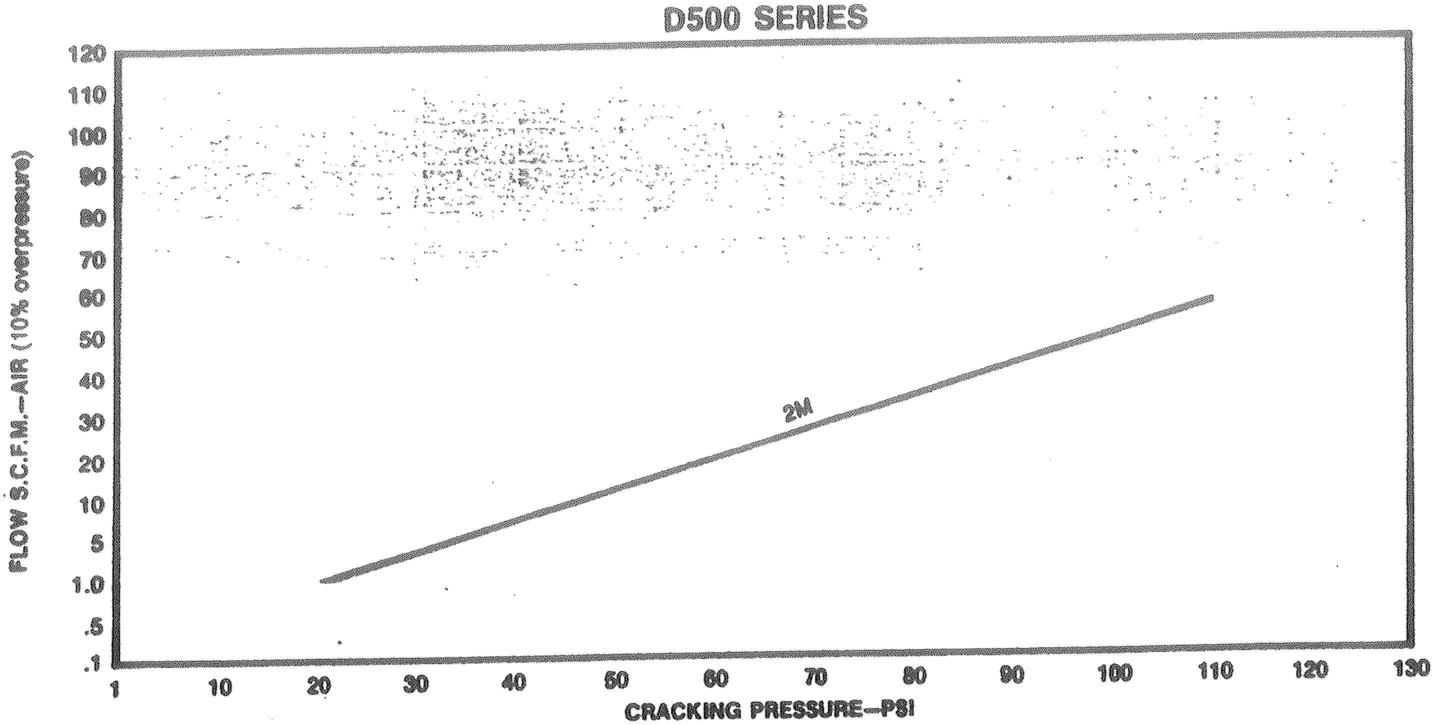
I Circle Seal Relief Valves Relieving Capacities

TYPICAL FLOW CURVES

M5100 SERIES



D500 SERIES



Non-destructive testing, such as individual flow test, testing with fluids other than compressed air or hydraulic oil, hydrostatic testing, x-ray, dye penetrant are not normal to our production processing, but are available at extra costs.

CIRCLE SEAL CONTROLS
BRUNSWICK CORPORATION
POST OFFICE BOX 3666
ANAHEIM • CALIFORNIA • 92803

SAFETY AND SAFETY RELIEF VALVE RELIEVING CAPACITIES

Manufacturer — CIRCLE SEAL CORPORATION, Location — Anaheim, California

SERIES OR CAT. NO. — D-300

CITY TESTS Conducted in Accordance with Sec. VIII at Alliton, Pennsylvania on May 13, 1958

METHOD OF ESTABLISHING RELIEVING CAPACITY — Curve - Slope = .361: TEST MEDIUM — Air: DATE RETESTED — Apr. 8, 1975

Inlet Size .281 in. Seal Dia. .260 in.

Set Pressure PSIG	Capacity S.C.F.M. (Air)
30	13
40	21
60	29
80	37
100	45
120	53
140	61
160	68
180	75

VALVE SERIES OR CAT. NO. — M 5100 (L)

CAPACITY TESTS Conducted in Accordance with Sec. VIII at Phillips Petroleum on Apr. 7, 1967

METHOD OF ESTABLISHING RELIEVING CAPACITY — Curve - Slope (see size): TEST MEDIUM — Nat. Gas: RETESTED — Apr. 8, 1975

Inlet Size 1/8 in. (-1M) Seal Dia. 0.250 in.
Slope = .285 Throat Dia. 0.188 in.

Set Pressure PSIG	Capacity Lift Inches	Capacity S.C.F.M. (Air)
100	0.060	36
200	0.060	67
300	0.060	89
400	0.060	130
500	0.060	162
600	0.060	194
800	0.060	257
1000	0.060	320
1100	0.060	351
1200	0.060	382

Inlet Size 1/4 in. (-2M) & 3/8 in. (-3M) Seal Dia. 0.358 in.
Slope = .665 Throat Dia. 0.358 in.

Set Pressure PSIG	Capacity Lift Inches	Capacity S.C.F.M. (Air)
100	0.080	83
200	0.080	156
300	0.080	224
400	0.080	302
[illegible]	0.080	377
[illegible]	0.080	450
800	0.080	596
1000	0.080	743
1100	0.080	815
1200	0.080	890

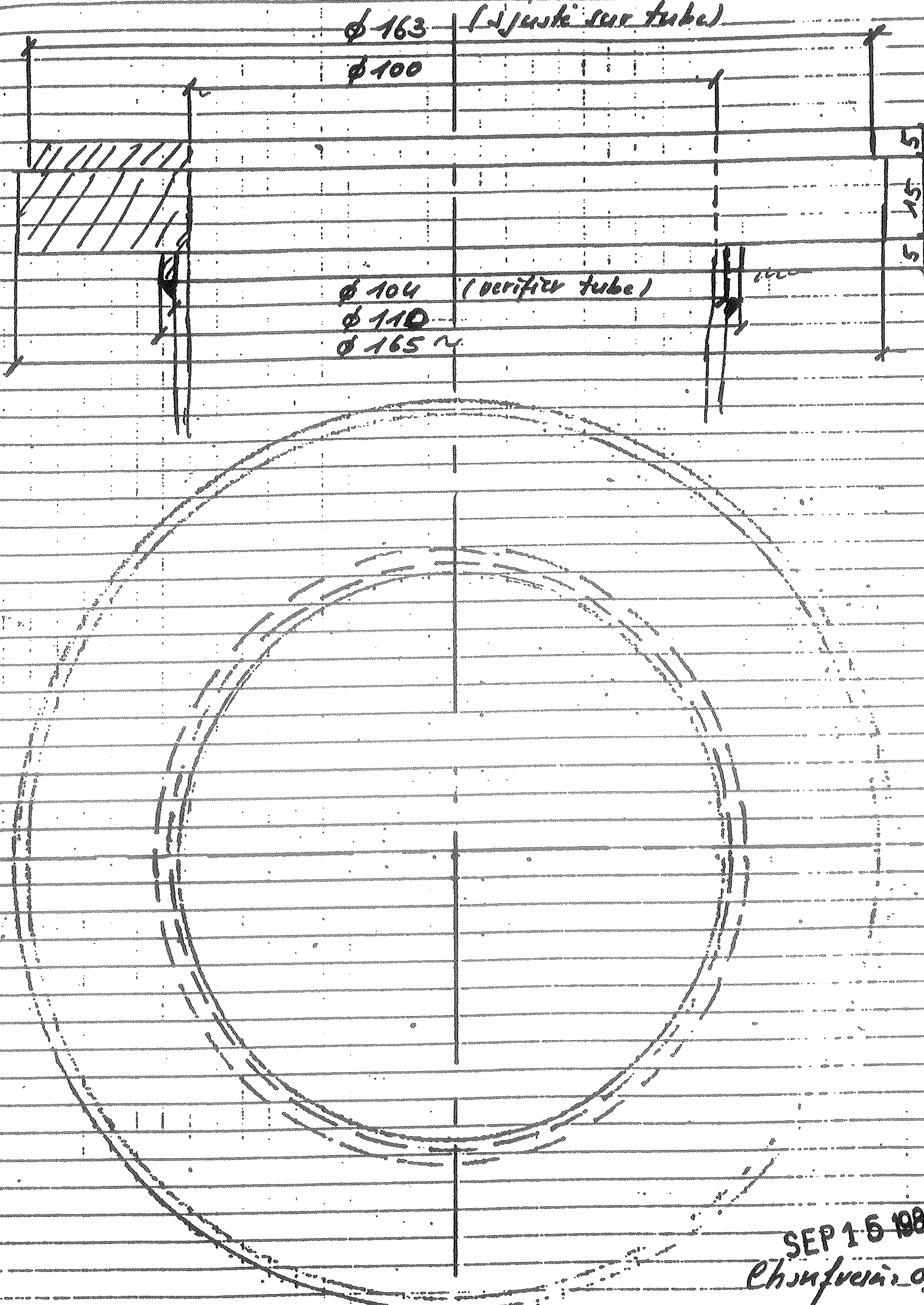
Inlet Size 1/2 in. (-4M) Seat Dia. 0.516 in.
Slope = 1.310 Throat Dia. 0.516 in.

Set Pressure PSIG	Capacity Lift Inches	Capacity S.C.F.M. (Air)
100	0.100	164
200	0.100	308
300	0.100	451
400	0.100	595
500	0.100	740
600	0.100	885
800	0.100	1170
1000	0.100	1460
1100	0.100	1600
1200	0.100	1750

Inlet Size 3/4 in. (-6M) & 1 in. (-8M) Seat Dia. 0.738 in.
Slope = 3.453 Throat Dia. 0.738 in.

Set Pressure PSIG	Capacity Lift Inches	Capacity S.C.F.M. (Air)
100	0.250	431
200	0.250	811
300	0.250	1190
400	0.250	1570
500	0.250	1950
600	0.250	2330
800	0.250	3100
1000	0.250	3850
1100	0.250	4230
1200	0.250	4610

J Sketch of the CERN Check Valve



SEP 16 1986

Chanfreins 0,5

Matière : Ac. inox

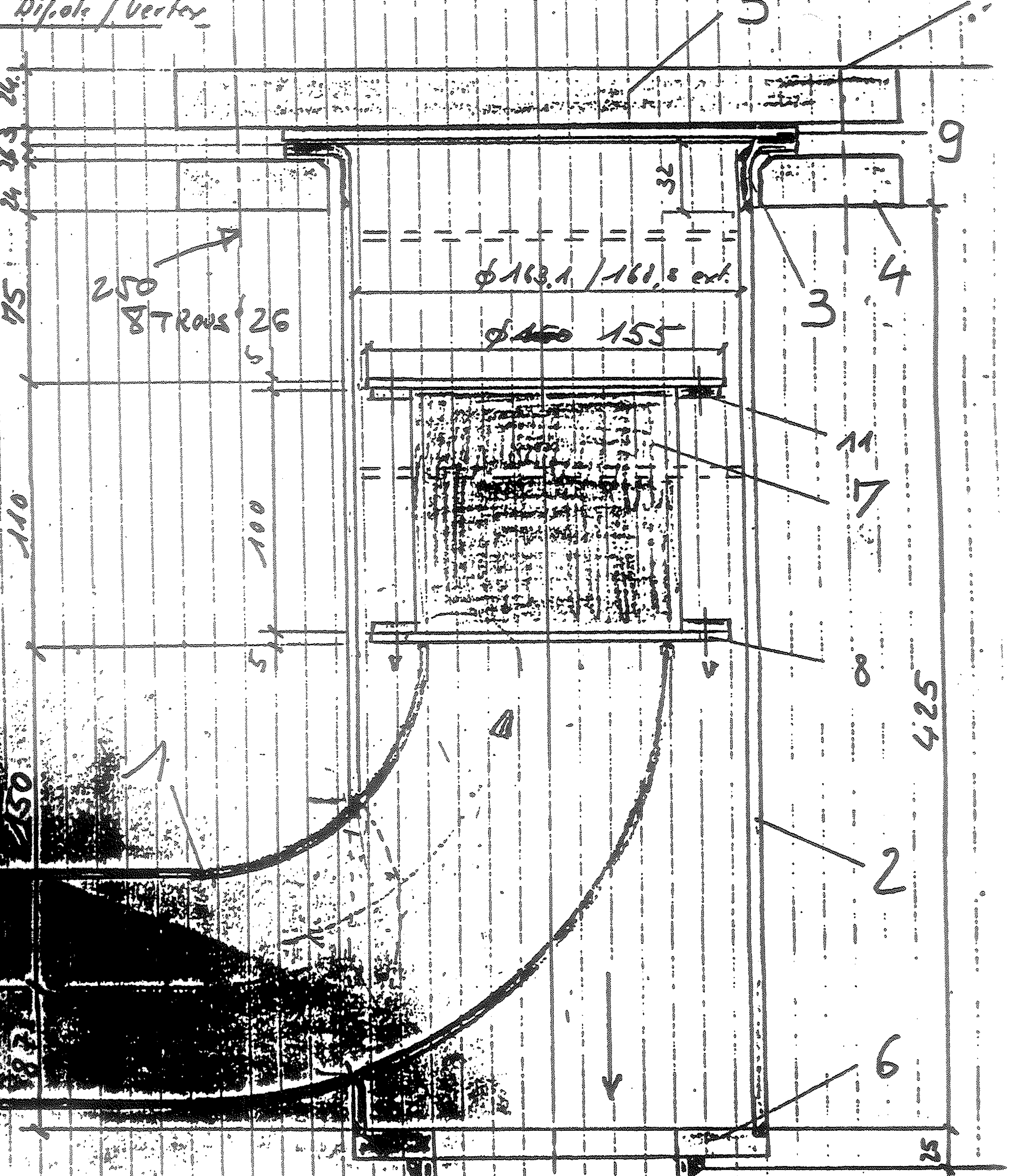
Liste : 409.821

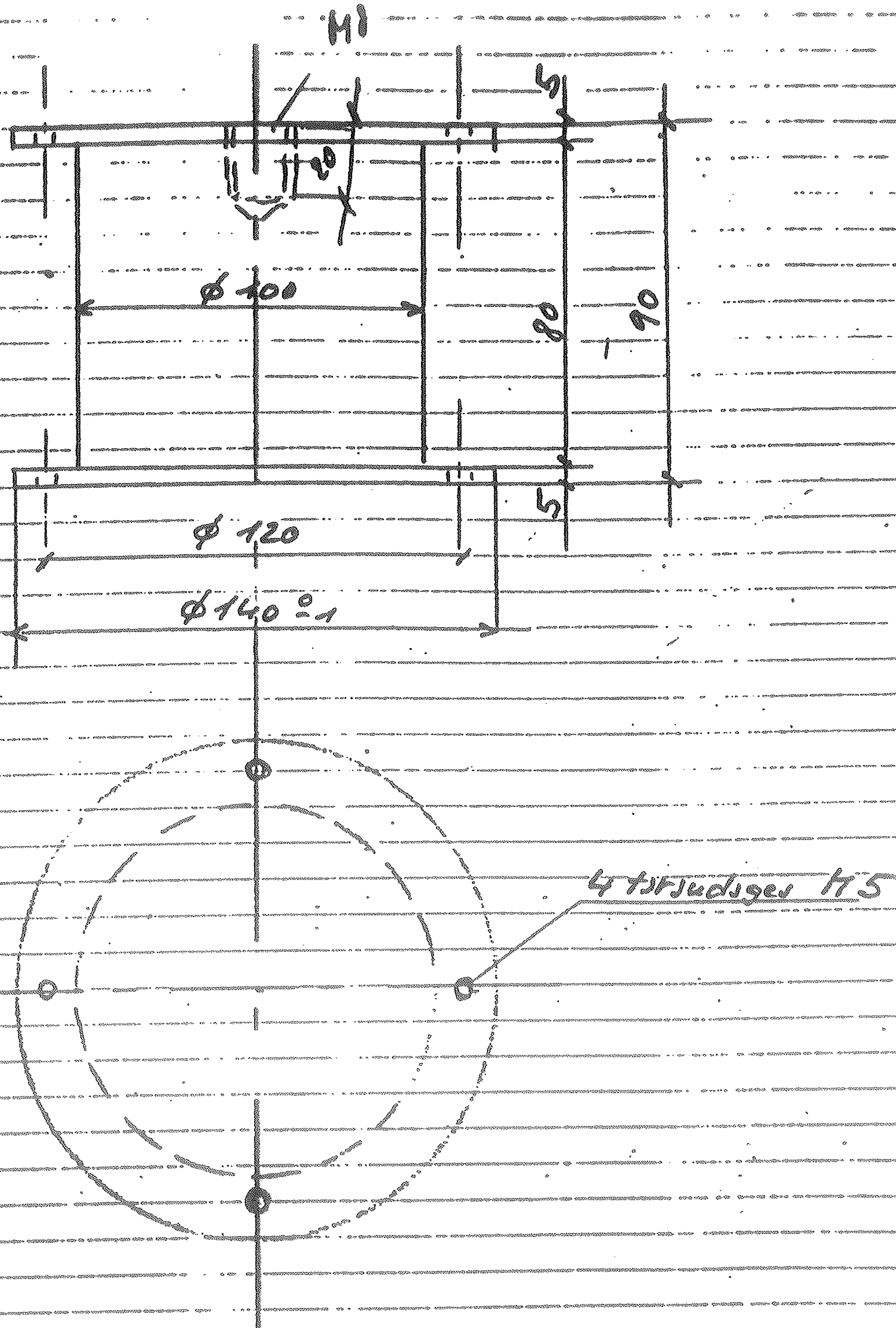
Clapet l. ligne récupération Cryostat

Clapet ligne récupération cryostats Dipole / Vertex

JD / 26.03.80

Pos.	Nbr	[illegible]
11	24	[illegible] M5×12
10	24	Boulon [illegible] M24×100
9	1	[illegible] 225×2
8	1	[illegible] Ø 155×5
7	1	[illegible] Ø 140×100
6	1	[illegible] Ø 160×25
5	1	Bride pleine Anticor Ø 300×24
4	1	Bride folle [illegible] DN 150
3	1	[illegible] Ø 168.3 / 212×32
2	1	Tube [illegible] Ø 168.3×4.25
1	1	Coude ligne récupération





Chanfrein = 0,3 à 45°

Matière = laiton

liste = 409.818

Clapet / ligne récupération [illegible]

JD / 27.03.80