C100 Cryomodule Supply/Return Header Design per ASME B31.3  
– An Addendum to JLAB-TN-07-051  
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Introduction

In a previous technical note [1], design of supply/return headers in accordance with ASME B31.3 code has been addressed. The use of B16.9 tees in return header is then questioned because the space between the return header outer diameter (OD) and that of helium vessel is quite narrow, say, less than 2.0 inch. If the tees are used, then there will be a clearance between the B16.9 tees end faces and the helium vessel OD. Welding an extension tube will inevitably introduce the problem of second weld reheating the first weld. Extruding the helium vessel to meet the tees would be a solution, but, fabrication cost will increase and the header and helium vessel will be rigid to rotate during assembly. It is then decided to use branch pipes to bridge the return header and helium vessel. This technical note reflects the changes in B31.3 code analysis related to such a design change.

In the previous technical note, schedule 5 pipes are used for example calculations. Herein, schedule 10 pipes are used instead. The calculations that are affected include the piping system flexibility analysis and welding requirements for the branch pipes. The finite element analysis procedure employed in the previous code analysis is adapted for current code analysis. Note that the design of expansion joints, i.e. the bellows, in headers is subject to very minor influence from this design change and hence is not addressed in this addendum.

I. Piping System Flexibility Analysis

B31.3 para. 304.3.2 Strength of Branch Connections states that “Unless the wall thickness of the run pipe is sufficiently in excess of that required to sustain pressure at an intersection not manufactured in accordance with a listed standard, it may be necessary to provide added material as reinforcement.” For the supply header, 3/4” IPS SCH10 pipes are to be used, the actual wall thickness of 0.083" is 0.083/0.00231>35 times of required minimum wall thickness. For the return header, 5” IPS SCH10 pipes are used. The actual return header wall thickness is 0.134", which is 0.134/0.012 > 11 times of required minimum wall thickness. Therefore, the reinforcement area calculations are waived for both supply and return headers.

B31.3 para 319.4 requires flexibility analysis for piping systems that cannot be excluded by para. 319.4.1, in which Eq. (16) is used as a criterion. In the previous technical note, this equation was used. In fact, it is not applicable to piping system with expansion joints in it. In other words, for the supply/return headers, piping system flexibility analysis has to be performed. The following steps show the analyses reflecting the change in return header design.

I.1 Allowable stress (316L stainless steel)

Material is 316L stainless steel
Thermal expansion coefficient of 316L at 2K (NIST): 
\[ e_{316L} := 300.4 \times 10^{-5} \text{ in/in}\]
Thermal cycles < 7,000  
Sc for 316L at 2K<100F  
Sh for 316L at 300K<200F  
SA for the system is (302.3.5 Eq. (1b))  

\[ f := 1.0 \]
\[ Sc := 16700 \text{psi} \]
\[ Sh := 16700 \text{psi} \]
\[ SA := f \cdot (1.25 \cdot Sc + 0.25 \cdot Sh) \]
\[ SA = 25050 \text{psi} \]

1.2 Sustained load stresses induced by pressure & weight

1.2.1 Supply header Sustained Load Stress

Outer diameter of supply line pipe:  
Wall thickness of supply line pipe:  
Inner diameter of supply line pipe:  
Center to center distance between tees  
Bellows O.D. (HYSPAN part# 7513G):  
Bellows I.D. (HYSPAN part# 7513G):  
Bellows wall thickness (HYSPAN part# 7513G):  
Spring rate of the bellows (HYSPAN part# 7513G):  

Supply header hoop stress:  
Supply header bellows spring force:  
Supply header bellows pressure force  

\[ \sigma_{h_{sup}} := \frac{P \cdot OD_{sup}}{2 \cdot t_{sup}} \]
\[ Sf_{sup} := L_{sup} \cdot e_{316L} \cdot k_{sup\_bellows} \]
\[ Ae_{sup} := \frac{\pi \cdot [1 \cdot ID_{sup\_blw} + 0.5 \cdot (OD_{sup\_blw} \cdot ID_{sup\_blw})]^2}{4} \]
\[ Pf_{sup} := Ae_{sup} \cdot P \]

\[ h_{sup} := 3.1 \cdot \frac{t_{sup}}{(OD_{sup} + ID_{sup})} \]
\[ h_{sup} = 0.532 \]

Then the out-of-plane stress intensification factor (SIF) is evaluated as:  

\[ io_{sup} := \frac{0.9}{h_{sup}^{2/3}} \]
\[ io_{sup} = 1.37 \]

In-plane SIF:  

\[ ii_{sup} := \frac{3}{4} \cdot io_{sup} + \frac{1}{4} \]
\[ ii_{sup} = 1.28 \]

The hoop stress is much lower than the allowable stress of 16,700 psi.

The peak stress in supply header is found to occur at the tee next to the end tee. The axial force and bending and torsional moments at this critical tee’s interface to helium vessel calculated
from ANSYS FEA model:

\[ Fa_{\text{sup}} := 3.23 \text{ lb} \]
\[ Mi_{\text{sup}} := 105.1 \text{ in-lb} \]
\[ Mo_{\text{sup}} := 0.03 \text{ in-lb} \]
\[ Mt_{\text{sup}} := 0.014 \text{ in-lb} \]

Axial stress due to axial force:

\[ Sa_{\text{sup}} := \frac{Fa_{\text{sup}}}{\frac{\pi}{4} \left(OD_{\text{sup}}^2 - ID_{\text{sup}}^2\right)} \]
\[ Sa_{\text{sup}} = 12.8 \text{ psi} \]

Section modulus of tees:

\[ Z_{\text{sup}} := \left(\frac{\pi}{32 \cdot OD_{\text{sup}}}\right) \left(OD_{\text{sup}}^4 - ID_{\text{sup}}^4\right) \]
\[ Z_{\text{sup}} = 0.057 \text{ in}^3 \]

Per para. 319.4.4, the bending (Eq. (18)) and torsional stresses in supply header tees are:

\[ Sb_{\text{sup}} := \frac{\sqrt{(ii_{\text{sup}} \cdot Mi_{\text{sup}})^2 + (io_{\text{sup}} \cdot Mo_{\text{sup}})^2}}{Z_{\text{sup}}} \]
\[ Sb_{\text{sup}} = 2,375 \text{ psi} \]

\[ St_{\text{sup}} := \frac{Mt_{\text{sup}}}{2 \cdot Z_{\text{sup}}} \]
\[ St_{\text{sup}} = 0.124 \text{ psi} \]

Sustained load stress in supply header end tees is evaluated as (para 319.4.4 Eq. (17)):

\[ SL_{\text{sup}} := \sqrt{(|Sa_{\text{sup}}| + Sb_{\text{sup}})^2 + 4St_{\text{sup}}^2} \]
\[ SL_{\text{sup}} = 2,388 \text{ psi} \]

Para. 302.3.5 states that when \( S_h \) is greater than \( S_L \), the allowable stress shall be calculated using Eq. (1b) as follows:

\[ SA_{\text{sup}} := 1.0 \times [1.25(Sc + Sh) - SL_{\text{sup}}] \]
\[ SA_{\text{sup}} = 39,362 \text{ psi} \]

>>> Para 302.3.5(c) requires that “the sum of the longitudinal stresses, \( S_h \) in any component of a piping system, due to sustained loads such as pressure and weight, shall not exceed the product \( S_h \cdot W \dots $$ For seamless pipes, the weld joint strength reduction factor \( W \) is 1.0.  It is found that the sustained load resulted stress in supply header, \( SL_{\text{sup}} = 2,388 \text{ psi} \), is far less than the code allowable stress of \( Sh = 16,700 \text{ psi} \).

### 1.2.2 Sustained Load Stress in Return header

O.D of return header: \( OD_{\text{ret}} := 5.563 \text{ in} \)
Wall thickness of return header: \( t_{\text{ret}} := 0.134 \text{ in} \)
I.D. of return header: \( ID_{\text{ret}} := OD_{\text{ret}} - 2 \cdot t_{\text{ret}} \)
O.D. of branch pipe: \( OD_{\text{branch}} := 3.5 \text{ in} \)
Wall thickness of branch pipe: \( t_{\text{branch}} := 0.12 \text{ in} \)
I.D. of reduced branch: \( ID_{\text{branch}} := OD_{\text{branch}} - 2 \cdot t_{\text{branch}} \)
Center to center distance between branches: \( L_{\text{ret}} := (31.37 + 8.0) \text{ in} \)
Bellows O.D. (HYSPAN part# 7549N): \( OD_{\text{ret \_ blw}} := 5.63 \text{ in} \)
Bellows I.D. (HYSPAN part# 7549N): \( ID_{\text{ret \_ blw}} := 4.625 \text{ in} \)
Bellows wall thickness (HYSPAN part# 7549N): \( t_{\text{ret \_ blw}} := 0.018 \text{ in} \)
Spring rate of the bellows (HYSPAN part# 7549N): \( k_{\text{ret \_ bellows}} := \frac{2627}{3.0} \text{ lbf \_ in} \)
Return header hoop stress: 
\[ \sigma_{h_{\text{ret}}} := \frac{P \cdot OD_{\text{ret}}}{2 \cdot t_{\text{ret}}} \]
\[ \sigma_{h_{\text{ret}}} = 1526 \text{psi} \]

>>> The hoop stress is much lower than the code allowable stress of 16,700 psi.

Return header bellows spring force:
\[ S_{f_{\text{ret}}} := L_{\text{ret-e 316L}} \cdot k_{\text{ret-bellows}} \]
\[ S_{f_{\text{ret}}} = 104 \text{lbf} \]

Return header bellows pressure force
\[ A_{e_{\text{ret}}} := \pi \left[ \left( \frac{ID_{\text{ret-blw}}}{2} + 0.5(OD_{\text{ret-blw}} - ID_{\text{ret-blw}}) \right)^2 \right] \]
\[ A_{e_{\text{ret}}} = 20.6 \text{in}^2 \]
\[ P_{f_{\text{ret}}} := A_{e_{\text{ret}}} \cdot P \]
\[ P_{f_{\text{ret}}} = 1518 \text{lbf} \]

The branch connection between return header and helium vessel resembles the unreinforced fabricated tee in B31.3 App D Table D300. The flexibility characteristic is thus evaluated as:
\[ h_{\text{ret}} := \frac{t_{\text{ret}}}{(OD_{\text{ret}}+ID_{\text{ret}})/4} \]
\[ h_{\text{ret}} = 0.049 \]

The out-of-plane SIF is:
\[ i_{o_{\text{ret}}} := \frac{0.9}{2} \left( \frac{h_{\text{ret}}}{3} \right) \]
\[ i_{o_{\text{ret}}} = 6.69 \]

In-plane SIF:
\[ i_{i_{\text{ret}}} := \frac{3}{4} \cdot i_{o_{\text{ret}}} + \frac{1}{4} \]
\[ i_{i_{\text{ret}}} = 5.27 \]

The peak stress in return header occurs to be at the end tee. The axial force and bending and torsional moments at return header end tee’s interface to helium vessel are calculated from ANSYS FEA model:
\[ F_{a_{\text{branch}}} := 49.78 \text{lbf} \]
\[ M_{i_{\text{branch}}} := 3176.1 \text{in-lbf} \]
\[ M_{o_{\text{branch}}} := 0.38 \text{in-lbf} \]
\[ M_{t_{\text{branch}}} := 18.35 \text{in-lbf} \]

Axial stress at reducing tee small end due to axial force:
\[ S_{a_{\text{ret}}} := \frac{F_{a_{\text{branch}}}}{\pi \left( \frac{(OD_{\text{ret}}+ID_{\text{ret}})^2}{4} \right)} \]
\[ S_{a_{\text{ret}}} = 39.1 \text{psi} \]

Section modulus of reducing outlet branch:
\[ r_2 := \frac{OD_{\text{ret}}+ID_{\text{ret}}}{4} \]
\[ T_b := t_{\text{branch}} \quad T_h := t_{\text{ret}} \quad T_s := \min \left( T_h, i_{i_{\text{ret}}} \cdot T_b \right) \]
\[ T_s = 0.134 \text{in} \]
\[ Z_e := \pi \cdot r_2^2 \cdot T_s \]
\[ Z_e = 3.102 \text{in}^3 \]

Bending stress in return header reducing branch per para 319.4.4 Eq. (20):
\[ S_{b_{\text{ret}}} := \sqrt{\left( i_{i_{\text{ret}}} \cdot M_{i_{\text{branch}}} \right)^2 + \left( i_{o_{\text{ret}}} \cdot M_{o_{\text{branch}}} \right)^2} \]
\[ Z_e \]
\[ S_{b_{\text{ret}}} = 5,392 \text{ psi} \]

Stress at return header end tees is evaluated as (para 319.4.4 Eq. (17)):
\[ SL_{\text{ret}} := \sqrt{(|S\text{a}_{\text{ret}}| + S\text{b}_{\text{ret}})^2 + 4S\text{t}_{\text{ret}}^2} \]

The adjusted allowable stress for supply header is (see Eq (1b) of B31.3 para 302.3.5(d)):

\[ SA_{\text{ret}} := 1.0 \left[ 1.25 (S\text{c} + S\text{h}) - SL_{\text{ret}} \right] \]

\[ SL_{\text{ret}} = 5,431 \text{ psi} \]

\[ SA_{\text{ret}} = 36,319 \text{ psi} \]

>>> The peak sustained load caused stress in return header, \( SL_{\text{ret}} = 5,431 \text{ psi} \), is found to be much lower than the code allowable stress of \( S_h = 16,700 \text{ psi} \).

II. Branch Pipe Welding Requirements

ASME B31.3-2006 para. 328.5.4 Welded Branch Connections subparagraph (d) requires that “Branch connections, including branch connection fittings, which abut the outside of the run or which are inserted in an opening in the run shall be attached by fully penetrated groove welds. The welds shall be finished with cover fillet welds having a throat dimension not less than \( t_c \).” The branch pipes used in between return header and helium vessel shall be welded per B31.3-2006 Fig. 328.5.4D sketch (1) at the junctions between branches and helium vessel, and, per Fig. 328.5.4D sketch (2) at the welding interfaces between branches and the return header. Bevel welds shall be performed at both ends of a branch pipe and covered by fillet welds. The minimum throat thickness \( t_c \) for the covering fillet welds can be calculated as follows (see B31.3 Figure 328.5.4D for definitions of parameters):

For 3” IPS SCH 10S: \( \bar{T}_b = 0.12 \text{ in} \) \[ t_c = 0.7\bar{T}_b = 0.084 \text{ in} \]

Weld leg size of 0.12 in will satisfy this requirement.

REFERENCES
