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A+ Filter Cavity Tube, Expansion Joints and Tube Supports: Conceptual Design and Requirements

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1 Introduction

The A+ Project[1] scope includes the addition of an optical Filter Cavity (FC). The vacuum system layout for the 300 m long FC (D1800238 for LLO and D1800241 for LHO) includes a long Filter Cavity Tube (FCT), which extends from vacuum chamber HAM7 to vacuum chamber BSC3, in the corner station LVEA, and then to vacuum chamber HAM8, which is housed in the Filter Cavity End Station (FCES) building. Most of the length of the FCT is housed in the Filter Cavity Tube Enclosure (FCTE) which spans between the corner station and the FCES. *The locations, and numbers, of expansion joints (bellows) and tube supports indicated in the current versions of the layout drawings (D1800238-v13 and D1800241-v10) are notional; The purpose of this document is to establish the conceptual design and requirements for these elements of the A+ FC vacuum system modifications.*

The purpose of expansion joints (bellows) is to:

- accommodate tolerances,
- assist with alignment of UHV-tight (conflat) joints, and
- accommodate thermal expansion/contraction due to temperature variation, especially due to an elevated temperature bake-out process.

The purpose of the tube supports is to:

- hold the filter cavity tube at the proper elevation, and
- align the tube to the bellows and direct axial movements to the bellows,
- prevent excessive bending loads on the conflat joints, and
- resist loads and (if necessary) prevent (column) buckling of the tube.

2 Assumptions/pre-requisites

Installation is into a pre-existing Filter Cavity Tube Enclosure (FCTE). As a result of this assumption wind loads are not an issue during assembly/installation.

3 Requirements

The basic requirements of the Filter Cavity Tube (FCT) are as follows:

1) Layout requirements: The FCT layout drawing (D1900456-~~v4~~v7) captures the basic conceptual design elements for the layout of the FCT, which are taken as requirements for the design of the FCT supports and bellows (see section 4.2~~5~~ for more detail).
2) Straightness: Provide a ~300 meter straight stainless steel pressure boundary with a clear aperture of ? mm, extending from the HAM7 chamber to the BSC3 chamber and from the BSC3 chamber to the HAM8 chamber. The aperture is defined by optical baffling which is beyond the scope of this document. However, the FCT supports and installation should not allow more than ? mm of deviation from straightness.
PDR Action item: What is the allowable straightness deviation of the FCT central axis?
3) Rotatable flange: One flanges of the bellows must be rotatable (to eliminate torsion in the assembly).

[1] LIGO-M1800264, A+ Project Execution Plan

4) Adjustable supports: Provide adjustable supports to allow for the initial tube alignment, and future re-alignments in case of settlement, of ±3 in (±75 mm) horizontally and vertically[2].
5) Insulated supports: The supports must provide insulation so that cold spots don't develop from heat sinking at the supports.
6) Prevent stick-slip: Support the beam tube in a manner which prevents "stick-slip" vibrations and allows vacuum bake-out of the module at temperatures up to 200 C. *PDR Action Item: Is this requirement necessary? The BT interior surface has an oxide layer which can rain particulates if mechanically shocked/disturbed. The FCT will not be air fired (like the BT) in order to reduce hydrogen outgassing, so it will not have a thick oxide layer.*
7) Sustain loads: Sustain seismic loads, (infrequent) 200C thermal bake-out loads, and accommodate loads associated with instrumentation and pumps at 6-way cross locations.
8) Conflat joint support: No conflat joint will be in an unsupported span; Moments on the joint will likely cause opening of the copper gasket seal and lead to leaks (see section 5.1.3).
9) Bellows support: All bellows (expansion joints) shall be near anchor supports and guide supports, in accordance with EJMA guidelines.
10) Thermal insulation: Incorporate insulation at the FCT supports for in situ bakeout.
11) Bellows cyclic loading lifetime: The bellows (expansion joint) shall be capable of sustaining the diurnal temperature cycling, as well as infrequent bake-outs, for a period of at least 20 years.
12) Cost conscious design: due to the relatively large number of instances of the FCT components, some value engineering is in order. As much as possible commercial-off-the-shelf (COTS) items should be chosen.
~~12)~~13) Bellows cover: Include the provision for attaching a cover around the bellows to protect them from accidental impact damage.

4 Expansion joint

4.1 Expansion Joint movement ranges

4.1.1 Axial

4.1.1.1 Fabrication and assembly tolerances

One can intentionally pre-compress, or pre-extend the bellows, during initial installation, in order to bias the bellows axial movement (deflection). As indicated in the layout drawing (D1900456-v7), most bellows (all in sub-assemblies FC-B and FC-C) must be extended in the initial installation to accommodate a nominal 0.40" gap. ~~While we do not plan (need) to intentionally pre-compress (or pre-extend) the bellows,~~In addition, fabrication and assembly tolerances can result in some initial pre-compression or pre-extension:

- the flanged pipe (D1900443-~~v5~~v7) tolerance on length is +.188"/-.000"
- the 6-Way Cross (D1900485-~~v1~~v3) tolerance on length between 10" Conflat Flanges is +/- .03"
- the Bellows length (D# PDR TBD) tolerance is likely +/- .03" (The manufacturer will issue a drawing which should be available at PDR.)

[2] The support adjustment range is taken as equal to the LIGO Beam Tube support range, given in

- the Anchor Support axial position tolerance[3] is likely ~ +/- .118”

These tolerances result in an initial compression of the Bellows of up to .772” or an extension of up to .208”.

Of course one could compensate for these (potentially) cumulative tolerances by using the adjustment range of the supports. However any consistent and systematic errors (e.g. all flanged tubes at the plus extreme of the allowed tolerance) would add over the entire ~300 m FCT assembly and need to be accommodated in the compression or extension of one bellows, or the custom length adjustment of one tube length.

4.1.1.2 Diurnal temperature fluctuations

During operation the environment is well controlled within the LVEA and within the FCES VEA spaces; The VEA temperatures are kept to ~20C (68F) +/- ~1C year round. However the temperature is not controlled within the FCTE. Consequently the bellows in these sections of the FCT will experience diurnal variations in temperature which will cause axial deflection cycling. The bellows fatigue life for these diurnal cycles must exceed 20 years, or 7300 cycles.

The diurnal temperature variation in the FTE is currently unknown (since the FTE has not yet been designed). However the FTE environment is likely to be similar to the BTE environment. The maximum diurnal temperature swing of the LLO BTE[4] is 25C, as indicated in Figure X. If the zero strain temperature of the bellows is set at about nominal room temperature (~20C), then these diurnal temperature variations can occur in both the compression range and expansion range of the bellows (as indicated in Figure 1).

[3] Survey monument tolerance is +/- 3 mm per T1000230, section 5.

[4] LIGO-G1400470-v1, LLO BTE raw data

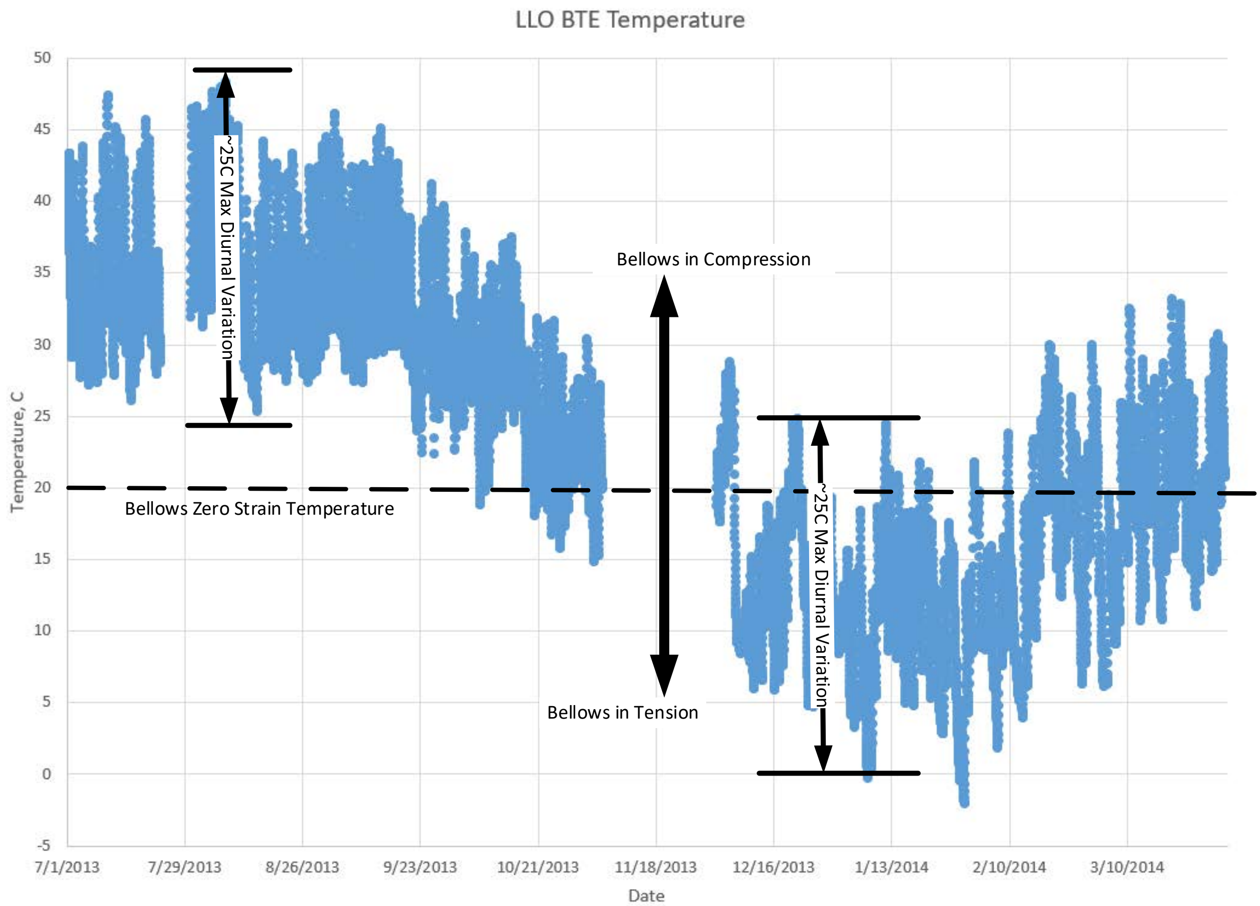


Figure 1 LLO BTE Temperature Variation

The section of the FCT within the FCE (section C) is currently scheduled[5] to be installed in February and March of 2021 at both LHO and LLO. As indicated in Figure 1, this is about the coldest period of the year for LLO. Likewise, February is one of the coldest months for LHO. As a worst case condition/scenario, the zero strain state of the bellows could be assumed to set at ~0C, with a ~55C seasonal, and ~25C diurnal, variation.

4.1.1.3 FCT bake-out

The FTC must also be able to sustain a 200 C bakeout. The bakeout is used to drive water and hydrocarbons off of the internal surfaces in order to obtain a lower vacuum pressure for operation. The bakeout is only planned to occur once (at initial installation). However it would be prudent for the bellows to be capable of sustaining the bakeout for a few cycles at least, say ~10 cycles.

4.1.2 Angular Rotation

The fabrication and assembly tolerances related to angular (bending) deflection of the bellows are as follows:

- Angular (parallel) tolerance on each of the flanged pipe sections (D1900443-v7), ± 1 mrad

[5] LIGO-M1800270-v11, A+ Schedule

- Angular (parallel) tolerance on each of the 6-way crosses (D1900485-v3), ± 1 mrad

Given that each FCT sub-assembly between anchor (fixed) supports can have up to three flanged pipe sections and up to two 6-way crosses, the total potential angular (bending) deflection of the bellows (expansion joint) is ± 5 mrad.

If these angular tolerances were to be all in the same direction (additive), then the lateral deviation of a sub-assembly of three flanged tubes and two 6-way crosses would be 2.16” off laterally from the intended position. This cumulative error can be partially corrected by bending the tube lengths (with a lateral force of 400N for each 1 mrad of error on a 20 ft tube length) so that the tube can more closely match the intended support locations, and match adjacent conflat flanges. The resulting lateral deflection over the entire sub-assembly is 0.40”.

4.1.3 Lateral

The fabrication and assembly tolerances related to lateral deflection of the bellows are as follows:

- Centering tolerance on each of the flanged pipe sections (D1900443-v7), ± 0.063 in
- Centering tolerance on each of the 6-way crosses (D1900485-v3), ± 0.063 in
- Tolerance on the anchor (fixed) support lateral position, ± 0.118 in

Given that each FCT sub-assembly between anchor (fixed) supports can have up to three flanged pipe sections and up to two 6-way crosses, the total potential lateral deflection of the bellows (expansion joint) is ± 0.431 inches. This lateral error can potentially add to the lateral error induced by tube bending to correct angular tolerances, so the total lateral movement that the bellows must compensate is ± 0.831.

4.1.4 Torsional Rotation

A rotatable flange will be required on each bellows (expansion joint) in order to accommodate any potential torsion or clocking of the sub-assemblies. No torsional load should be imposed on the bellows.

4.1.5 Combined, effective rated movement

Using the EJMA guidelines, the effective total (rated) movement of the bellows is:

- Xc = -3.360 in, maximum axial compression - <10 cycles (bake-out)
- Xc = -1.484 in, maximum axial compression – diurnal cycles
- Xe = 0.~~596~~ 996 in, maximum axial extension
- Y = 0.831 in, maximum lateral deflection
- ϴ = 5 mrad, maximum rotation (bending)

(For details of the calculation, see the excel spreadsheet uploaded with this document in the LIGO Document Control Center (DCC).)

4.2 Expansion joint design

Ideally for cost and maintenance considerations the FCT expansion joint would be a commercial-off-the-shelf, formed (not welded) bellows design. We’ve allocated ~20 inches in overall length for the bellows, which might be allocated as follows:

- 1.12” rotatable flange
- 2.00” long neck (cuff): the cuff must be at least as long as the stud used to accommodate 0.5” GV blind hole plus the CF thickness plus 0.5” for two nuts (in case we have to double nut when studs get stuck), or a total of 2 inches.
- 15.26” long section of convolutions
- 0.50” long neck (cuff)
- 1.12” fixed flange

The two cuff sections could be made the same length by reducing the length of the active (convolution) section.

Although no COTS UHV bellows meet all of our parameters Hyspan Type 2509, Part No. 074-5 is close:

- Nominal size (NPS) 10”
- Axial compression: 5.31”
- Axial extension 2.66”
- Lateral off-set: 1.87”
- Axial spring rate: 112 lb/in
- Lateral spring rate: 151 lb/in
- Overall length: 14”
- However the flanges are fixed and not Conflat type flanges, and this is a laminated bellows which may not be appropriate for our UHV application..

Other bellows manufacturers have 10” bellows with shorter convolution lengths. If their designs were modified to incorporate longer convolution length (more convolutions), then they could likely meet our movement requirements:

- MDC model #FB-6571, part number 470024, 10” formed bellows (without flanges, 11.3” OD and .020” thickness) has an axial deflection range of +.60/-1.50 for a 6.00 convolution length. If the convolution length were increased to 13.5” it might meet our requirements.
- Huntington’s part number 6526, 10” formed bellows (without flanes, 11.25” OD and .010” thickness) has an axial deflection range of ±2.00 for a 6.00 convolution length. If the convolution length were increased to 10” it might meet our requirements.

Using the EJMA’s manual a design with the following parameters seems to meet our requirements:

- A240-304 Bellows material
- 10.0” inside diameter
- 11.25” outside diameter
- .010” thick bellows convolutions
- 16 convolutions
- 12.0” convolution length (0.75” per convolution)
- 1.25” cuff (tangent) length

The resulting theoretical spring rates and fatigue life of this bellows design is as follows:

- 98 lbf/in axial spring rate
- 1,900 cycles for full range of required movement
- 14,857 cycles for diurnal compression movement

(For details of the calculation, see the excel spreadsheet uploaded with this document in the LIGO Document Control Center (DCC).)

5 Layout

The A+ Vacuum Equipment top-assembly drawings (sheet 1 of D1800238 for LLO and D1800241 for LHO) designate the following FCT modules:

- FC-A: between chamber HAM7 and chamber BSC3, in the LVEA
- FC-B: from BSC3 extending toward HAM8, limited to within the LVEA
- FC-C: the FCT basically within the FT Enclosure (FCE)
- FC-D: the FCT within the FC End Station (FCES), attached to chamber HAM8

These four modules are further divided into sections in the FCT layout drawing (D1900456-v4). *The locations, and numbers, of expansion joints (bellows) and tube supports indicated in the current version of the FCT layout drawing (D1900456-v4) are notional; The purpose of this document is to establish the conceptual design and requirements for these elements of the A+ FC vacuum system modifications.*

The FCT layout drawing (D1900456-v4) captures the following basic conceptual design elements for the layout of the FCT, which are taken as requirements for the design of the FCT supports and bellows:

- Stainless steel (304L) tubes with 10" OD, 0.125" wall thickness, and maximum length of 20 ft., with 12" Conflat Flanges (CF) on both ends (D1900443-v7)
- Tubes joined by either 6-way crosses (D1900485-v3), expansion joints (bellows) or directly as CF joints
- A spacing of 6-way crosses to support anticipated vacuum group operational needs for pumping and instrumentation. In the LVEA and FCES all non-bellows connections are 6-way crosses. In the FCE every 3 to 5 tube lengths (60 to 100 ft.) has a 6-way cross.
- A number of gate valves are deployed along the FCT length in order to isolate chambers and adjacent sections of the FCT (so that the vacuum state can be different) and to isolate sections of the FCT for leak hunting.

5.1 Anchor, Guide and Bellows Spacing (pitch)

5.1.1 EJMA Guidance

The guidelines from the Expansion Joint Manufacturers Association[6] recommend as good design practice (for expansion joint applications intended to absorb axial pipe expansion) to employ one expansion joint between two main anchors, where the expansion joint is close to one anchor, an alignment guide is close to the expansion joint and subsequent alignment guides are placed as indicated in Figure 2.

[6] Standards of the Expansion Joint Manufacturers Association, Inc., 6th edition, 1993.

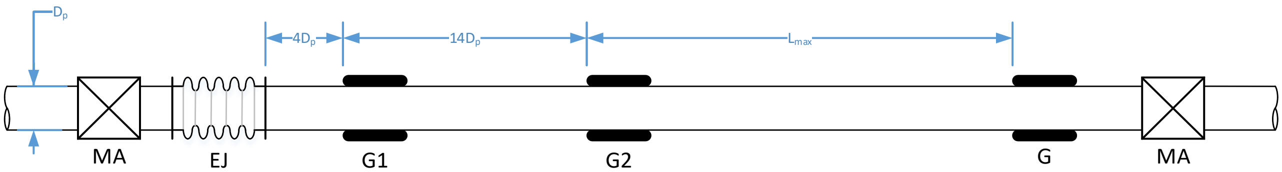


Figure 2 Typical Expansion Joint (EJ), Main Anchor (MA) and Guide (G) Arrangement

Derived from figures B1 and B30 of the Standards of the EJMA, 6th ed.

The maximum spacing between guided supports is based on one-half of the critical length of a pinned-pinned Euler column (equation B-9 of the Standards of the EJMA, 6th ed.):

$$L_{max} = \frac{\pi}{2}\sqrt{\frac{E_p I_p}{P_d A_e + f_i e_x}}$$

where

E_p = elastic modulus of the pipe material

I_p = moment of inertia of the pipe cross-section

P_d = design pressure difference (pressure inside pipe minus pressure outside pipe)

A_e = bellows effective area (corresponding to the mean convolution diameter)

f_i = bellows theoretical initial axial elastic spring rate per convolution

e_x = equivalent axial movement per bellows convolution (+ for compression, - for extension)

Note that for the case of a column (pipe) with a fixed restraint at one end and a pinned restraint at the other end, the coefficient is $\frac{\pi}{\sqrt{2}}$ instead of $\frac{\pi}{2}$, as is the case for the main beam tube (see section 5.1.2).

Internal pressure in the pipe/tube results in a positive pressure thrust term (P_d A_e) which tends to extend the bellows and compress the pipe/tube like a column between supports. Internal vacuum results in a negative pressure thrust term (P_d A_e) which tends to compress the bellows and extend the pipe/tube. Since the pressure thrust term generally dominates over the bellows spring force term (f_i e_x), even when the bellows is compressed from the thermal expansion of a bake-out condition, buckling of the pipe/tube is generally not a concern in a vacuum application. The FCT will operate under vacuum, and will be baked (to reduce outgassing) also while under vacuum.

During assembly/installation the FCT will be at ambient pressure but may experience diurnal temperature swings. The worst case vented scenario is installation at a cold ambient temperature extreme (winter), without pre-extension to compensate, and then venting the FCT at a hot ambient temperature extreme (summer). In this case the bellows spring force due to a ~50C FCT rise from the zero strain temperature places a compressive load on the FCT which is not offset by a vacuum thrust. However even if the tube is baked at 200C while vented, the maximum guide spacing is ~380 ft. due to the relatively low estimated spring rate of the bellows (~100 lbs/in for the bellows). Consequently (with reference to Figure 2) there is no need for the additional guided supports at a spacing of L_{max} for the FCT.

The purpose of the first and second guided supports (G1 and G2 in Figure 2) is to “insure proper application of movement of the Expansion Joint”[7]. Guides G1 and G2 together insure that the pipe/tube does not shift laterally (shear the bellows) or rotate (apply angular displacement to the bellows due to tube bending). For the FCT diameter, D_p = 10 inches O.D. (D1900443-~~v5~~v7), so the EJMA recommended spacing of the G1 and G2 supports is:

- G1 @ 4 D_p = 3.3 ft., and
- G2 @ 14 D_p = 11.7 ft.

5.1.2 Beam Tube example

The layout of the LIGO main Beam Tubes (BT) does not comply with the EJMA guidance regarding proximity of the bellows (expansion joint) to a main (fixed) support, nor the installation of a second guided support (G2) within 14 diameters of the first guided support. Instead the bellows is placed in the center of the tube between two fixed supports; The BT support arrangement is as indicated in Figure 3.

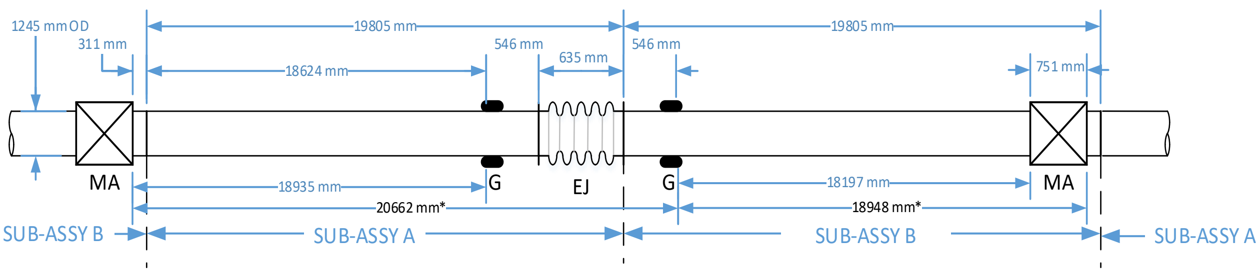


Figure 3 Typical Beam Tube Support and Bellows Spacing

*The LIGO Beam Tube (BT) layout of the 2 km modules (D950031) indicates the typical sequence of BT sub-assemblies (… B A B A …). The dimensions of the sub-assemblies (D950034) are indicated in this sketch, and are consistent with the spacing between fixed and guided supports given in D950033 (*with the exception that D950033 indicates a spacing of 20676 mm, not 20662 mm).*

In order to avoid shear loading on the bellows (due to the weight of the tube, plus any seismic load), the bellows have close guide supports on both sides. These two guided supports are integrated into a single support structure frame (D950044). In addition, while there isn’t a second guided support at a distance of 14 diameters from the first guided support, there is instead a fixed support at a distance of 15.2 diameters. This support arrangement provides less lateral and angular deflection at the bellows than would an arrangement in compliance with EJMA guidelines. This is only possible because our application is a vacuum system. Even under worst case assumptions (installation at a seasonally minimum temperature and 200C bake out at atmospheric pressure), there is no risk of BT buckling. (For a synopsis of the tube and bellows layout/configuration considerations reviewed as part of the BT design, see pgs. 46-56 of C1900321-v1)

5.1.3 Conflat joint consideration

Each of the pipe sections of the FCT assembly are joined with 12” O.D. conflat joints, either with 6-way crosses or single conflat joints. Conflat joints provide UHV sealing with knife edges that ‘bite’

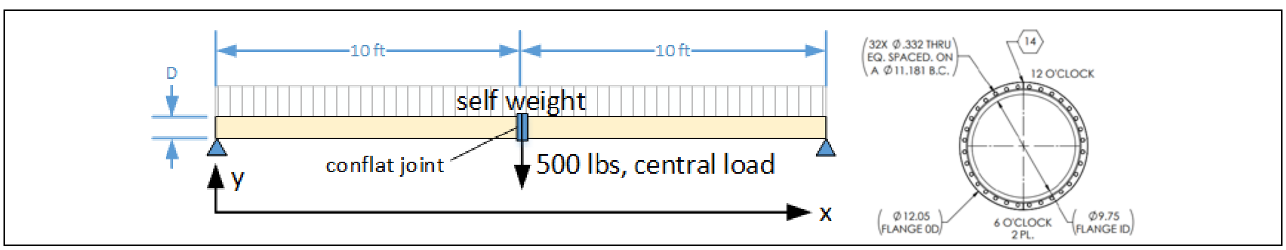
[7] Section B-2.4.2, “Pipe Guides and Guiding” of the Standards of the EJMA, 6th ed.

into copper gaskets. These joints are not intended to be structural. Any significant weight of pumps or instrumentation connected to the 6-way cross should be supported separately and isolated from the FCT conflat joints. This is typically accomplished with a support stand for the pump (see D1400385 for an example) or a flex hose. In the BT analysis a load of only 150 lbs was assumed for each of the 10” pump ports and gate valves along its length[8].

In the current versions of the A+ Vacuum Equipment top-assembly drawings (D1800238-v13 for LLO and D1800241-v10 for LHO) supports are shown notionally at the mid-span of the (typically) 20 foot long pipe sections. This arrangement allows unfettered access for piping and instrumentation at the 6-way crosses. However a simple beam analysis of a conflat joint (confirmed with a simple Ansys beam analysis; see ~~Figure X~~Figure 4) of this arrangement indicates that for a (perhaps) not unreasonable load[9] of 500 lbs at the conflat joint, the resulting loads on the conflat joint bolts (~~~30~~25% of yield for stainless steel bolts) may cause yielding (when coupled with the bolt pre-load of ~75% of yield stress) which would lead to vacuum leaks. Consequently the piping supports should be proximate to the conflat joints.

If one of the guided (pinned) supports near a conflat joint is within one-quarter span (5 feet), then the resulting loads on the conflat joint to counter the imposed moment are only ~8% of the bolt yield stress; This additional bolt load seems acceptable.

An alternative to placing the supports relatively close to the conflat joints might be to use high strength bolts (instead of stainless steel bolts), so that the conflat joint can take the structural loads without yielding the CF joint bolts. However compliance in the stainless steel conflat flange itself may lead to opening up leaks in the copper gasket. This unorthodox approach is not recommended since the support stands do not place significant constraints on the placement of, and access to, port hardware (pumps, RGAs, pressure gauges, etc.). If this design option were to be pursued more analysis (and possibly testing) would be needed to confirm that there is no risk of accidentally developing vacuum leaks.



[8] LIGO-C930063-x0, “CBI Beam Tube Module Design and Qualification Test: Preliminary Design Review Data Package (DRD #8)”, pg 47

[9] Suppose two full size adults decide to do chin-ups on the FCT near the conflat joint. Although not advisable this scenario would result in ~500 lbs of weight applied mid-way between the supports, near the conflat joint.

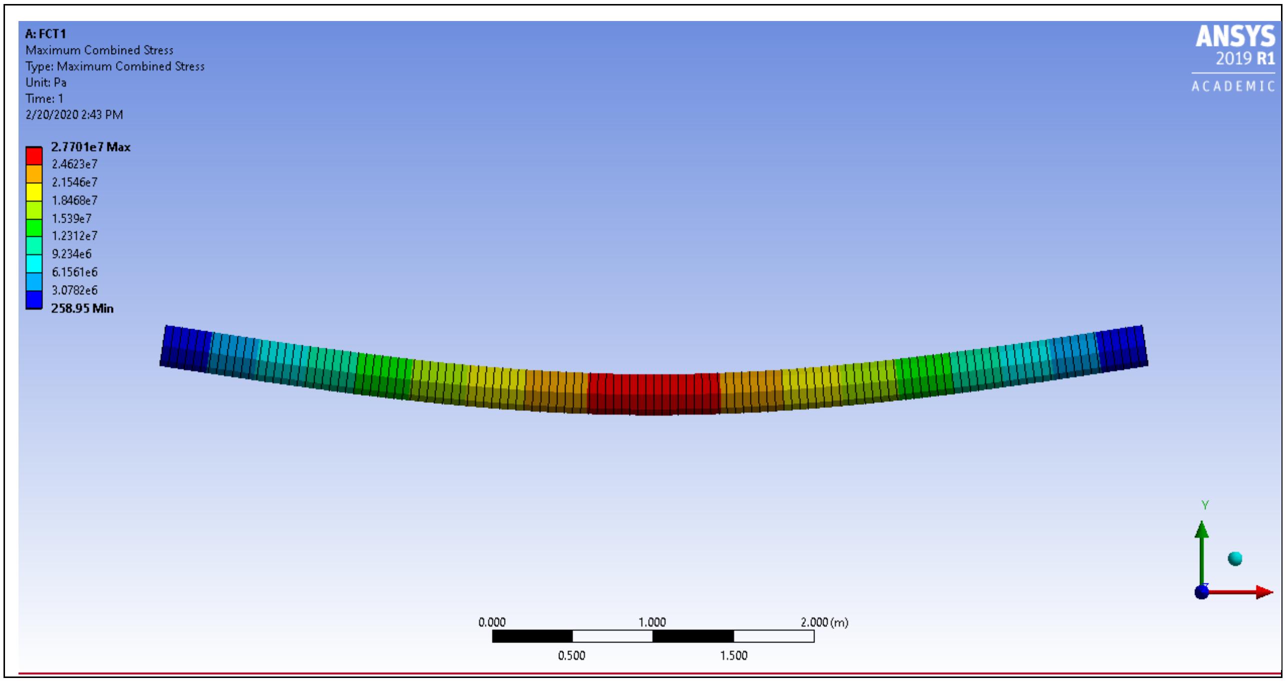
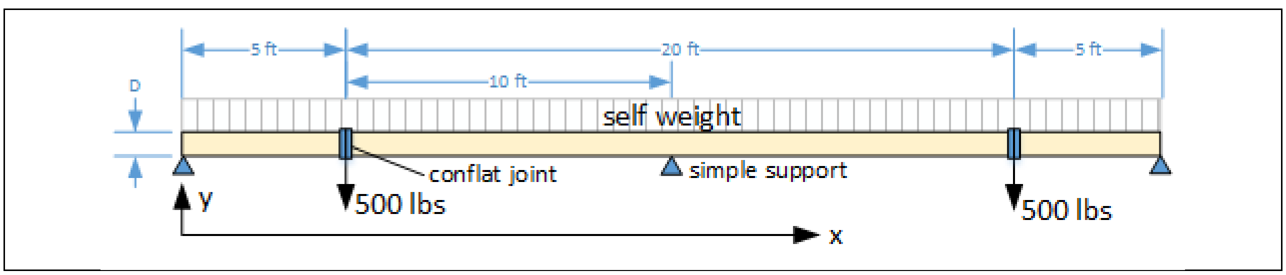


Figure 4 Simple Beam Analysis: Supports only at mid-span (10 ft) from conflat joints

ANSYS Beam Analysis of FCT simply supported mid-span with self-weight and a 500 lbf (2224 N) vertical load at center (on 12” Conflat joining 20 ft long pipe sections). Deflection is ~~2.3~~3.6 mm and pipe bending stress is ~~17.4~~27.7 MPa (~~~8~~13% of yield). The maximum CF bolt stresses is ~~62.9~~52.2 MPa, or ~~30~~25% of yield for 18-8 stainless steel bolts.



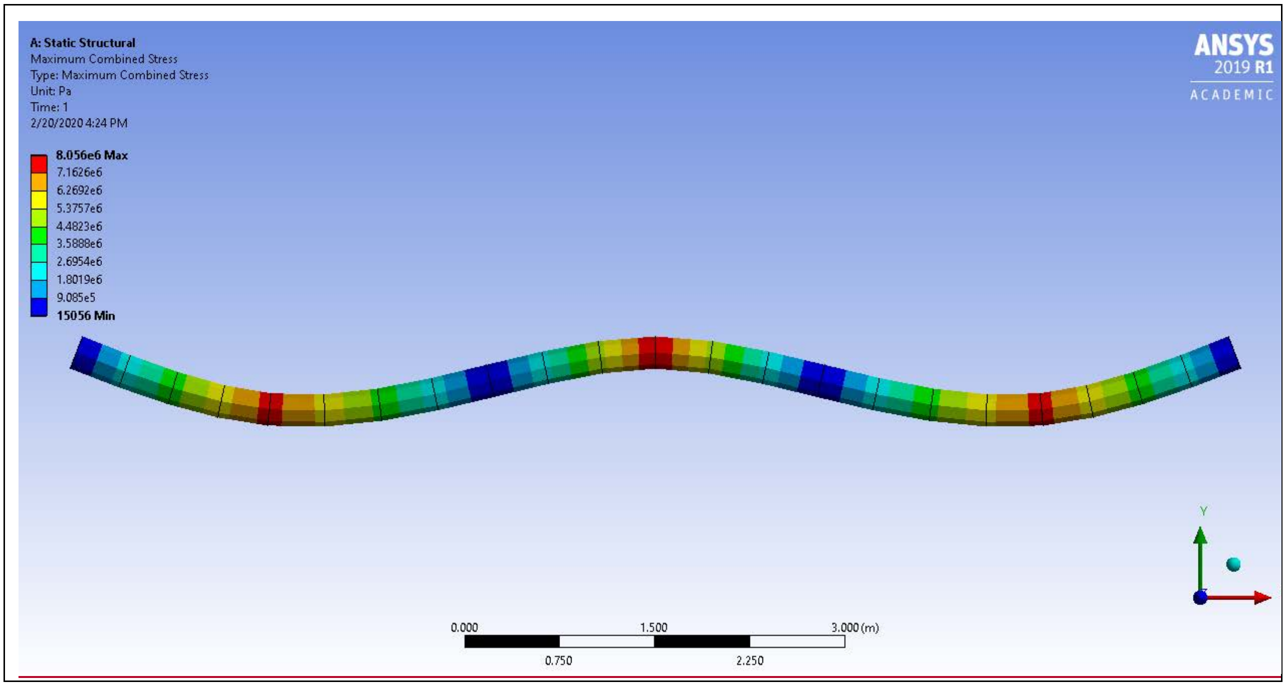


Figure 5 Simple Beam Analysis: Supports at mid-span (10 ft) and within one-quarter span (5 ft.) of conflat joints

ANSYS Beam Analysis of FCT simply supported at mid-span and within a quarter span from each conflat joint, with self-weight and a 500 lbf (2224 N) vertical load at each conflat. Maximum deflection is 0.~~3~~ 4 mm and maximum pipe bending stress is ~~5.8~~8.1 MPa. The maximum CF bolt stress is 62.9 MPa, or 8% of yield for 18-8 stainless steel bolts.

5.1.4 Gate Valve considerations

A number of gate valves are placed along the FCT. The gate valves serve to (a) isolate chambers from adjacent sections of the FCT so as to permit the vacuum state of the FCT or the chamber to be different and (b) isolate sections of the FCT for the purpose of leak hunting.

PDR Action item: What are the permitted vacuum states? Can all FCT sections be arbitrarily/independently at either vacuum or at atmospheric pressure? Which FCT sections will be routinely vented and removed for access? (e.g. just the first pipe section adjacent to each chamber?) Additional fixed and guided supports may be required!

5.1.5 Recommended Support and Bellows Spacing

Taking all of the above into consideration, the layout and spacing of the fixed and guided supports and the expansion joints (bellows) are as shown in Figure 6:

- One bellows between each fixed support (anchor).
- Fixed supports every two or three pipe spans (typically 20 ft)
- Bellows placed close to a fixed support, but with adequate clearance for access to the conflat flange and the support for installation, alignment and servicing.
- Gate valves are placed near fixed supports and bellows
- First guided support located within 3.3 feet of the bellows

- Second guided support within 11.7 feet of the first guided support and within 5 feet of the conflat joint
- A guided support mid-span in a pipe section which is not joined to either a bellows or another pipe section with a fixed support near its connection
- A guided support within 5 feet of a conflat joint if the other end is near a fixed support

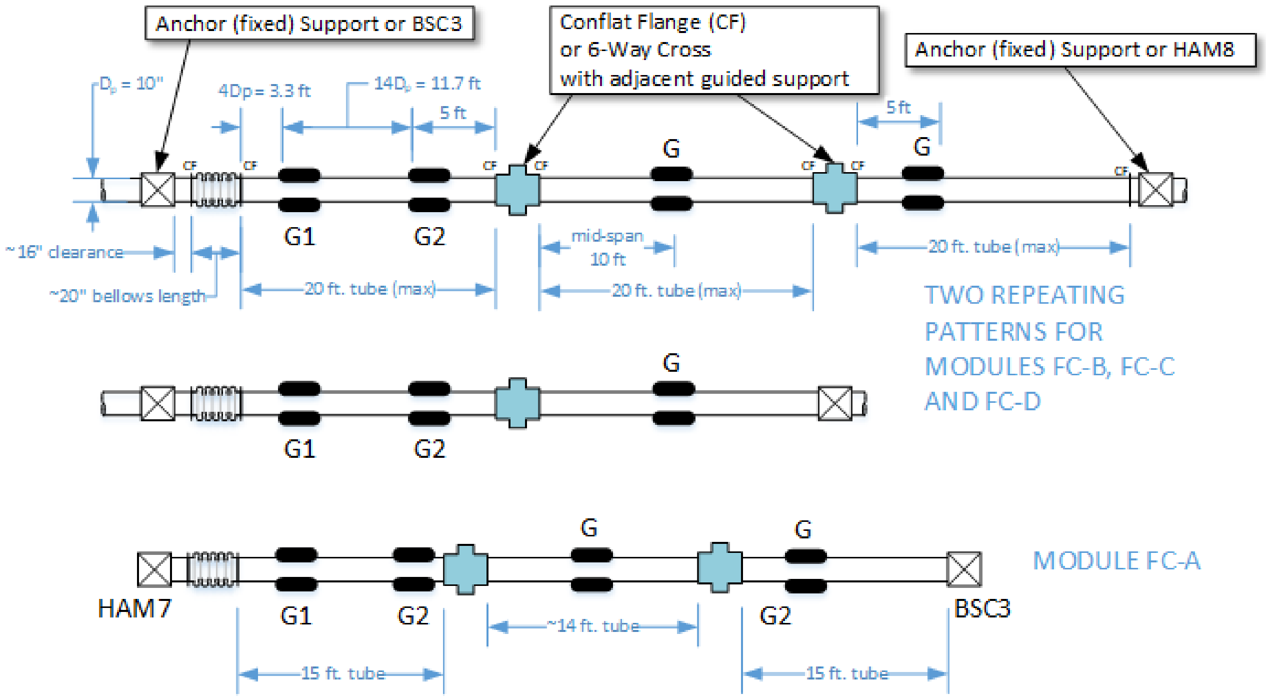


Figure 6 Basic Layout Patterns for Bellows, Tube Anchors and Tube Guides

6 Support loads

The FCT support loads will be calculated in the same way that the BT support loads were calculated. For a synopsis of the BT support loads, see T1900628 and the reference therein.

(For details of the calculation, see the excel workbook uploaded with this document in the LIGO Document Control Center (DCC).)

6.1 Thermal (bake out) Load

The axial load (RA) at the fixed support is based on the following parameters:

- maximum expansion joint spring rate, K = Kej * (1 + Eej) = TBD lbs/in
- thermal expansion, x = 2.588 in.
- longitudinal force, Pbc = K * x = TBD lbs (axial force on termination foundation)
- fixed support axial load, Rfz9 = 2 * Eej * Kej * x = TBD lbs

The BT expansion joint documentation indicates very significant variation in the spring rates. While the FCT bellows may not have the same spread in spring rates, we will assume they will until better information is available.

6.2 Vacuum Load

The vacuum load is (almost entirely) reacted by the fixed supports. The fixed support load should be simply equal to the tube interior area times the maximum atmospheric pressure.

PDR action: However, as noted above, each of the permitted vacuum states must be defined and the load paths and loads determined for each of these states.

6.3 Dead Weight Load

The dead weight loading on the supports was calculated by CB&I using a beam analysis code called RISA-2D[10] (mentioned on pg 6 of T940074). The results of this beam analysis were reported in CB&I's document "Final Design Review Data Package (CDRL 15, DRD 09, for the "BT design and qualification" contract). Document C960366-v1 uses the beam analysis from these original design calculations (cited on last page, CDRL#15, DRD#9, Item IV, section 5). For the FCT a beam finite element analysis is in preparation using Ansys.

PDR Action item: Complete the Ansys FCT FEA.

6.4 Seismic Loads

The seismic loads are based on the earthquake conditions for Hanford, WA and calculated using the methodology in the Uniform Building Code (UBC), likely the 1994 version. The UBC was replaced in 2000 by the new International Building Code (IBC) published by the International Code Council (ICC). According to wikipedia (I have not confirmed), It has been adopted for use as a base code standard by most jurisdictions in the United States. The latest version of the IBC is 2018.

The reaction loads on the BT supports are calculated with the results of the beam tube analysis. Then the distribution of seismic loads on each reaction point, of each support type, was calculated by simple static load balancing.

6.5 Settlement Loads

The maximum allowable differential settlement for the BT is derived on page 145 of C960366-x0 as 0.556 inches. Until/unless better information is available the same settlement will be assumed for the FCT.

The total vertical load on the fixed BT supports due to this settlement is derived from the shear diagram given in C960366-v1, sketch #2, pg 40. A similar approach will be used for the FCT once the Ansys FEA has been completed.

6.6 Horizontal Alignment

The lateral force required to correct a BT non-linearity of 0.160 inch is given as 341 lbf at each fixed support, in document C960366-0 on pg 149. The resulting vertical forces are derived from a simple statics balance. The lateral force required to make the same correction at the guided supports is scaled from the calculations in document L960370-01, and then distributed to the reaction points using statics balancing.

[10] Rapid Interactive Structural Analsyis – 2 Dimensional: https://risa.com/p_risa2d.html

A similar approach will be employed in the FCT support load analysis once the Ansys FEA has been completed.

6.7 Fixed Supports

PDR Action item: Provide a summary table of loads on the FCT fixed supports, and loads on the FCTE foundation slab at the attachment points.

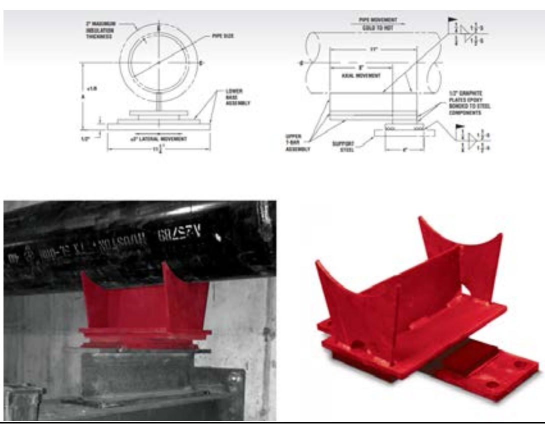
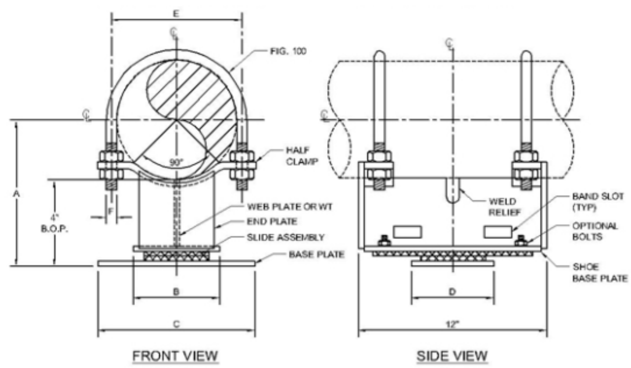
6.8 Guided Supports

PDR Action item: Provide a summary table of loads on the FCT guided supports, and loads on the FCTE foundation slab at the attachment points.

7 Guided support design

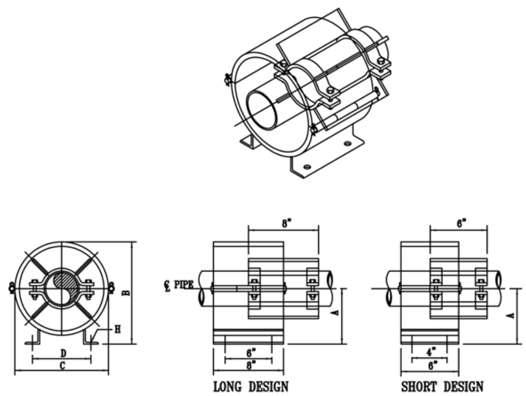
7.1 Sliding plate designs

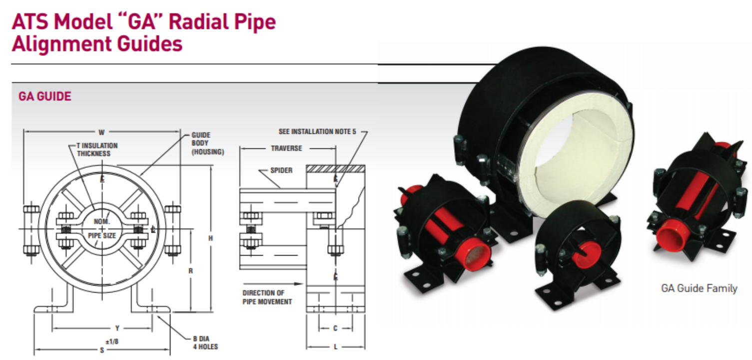
A simple cradle or V-block, or a U-bolt cradle support (such as depicted in Figure X) is not an adequate guided support to restrain against seismic loads. In addition the sliding plate assembly under these designs permits angular tolerances in the Conflat Flange perpendicularity to be converted to significant lateral displacement at the bellows due to the long length between fixed supports.

	
Low Friction Guide/Support (Advanced Thermal Systems, Inc.) http://www.advancedthermal.net/catalogs/ATSGuidesAndSupportsCatalog.pdf	U-bolt cradle support with slide plate https://pipingtech.com/products/pipe-shoes-pipe-guides/supports-with-no-field-welding/#spec-jump

7.2 Radial Pipe Alignment Guides

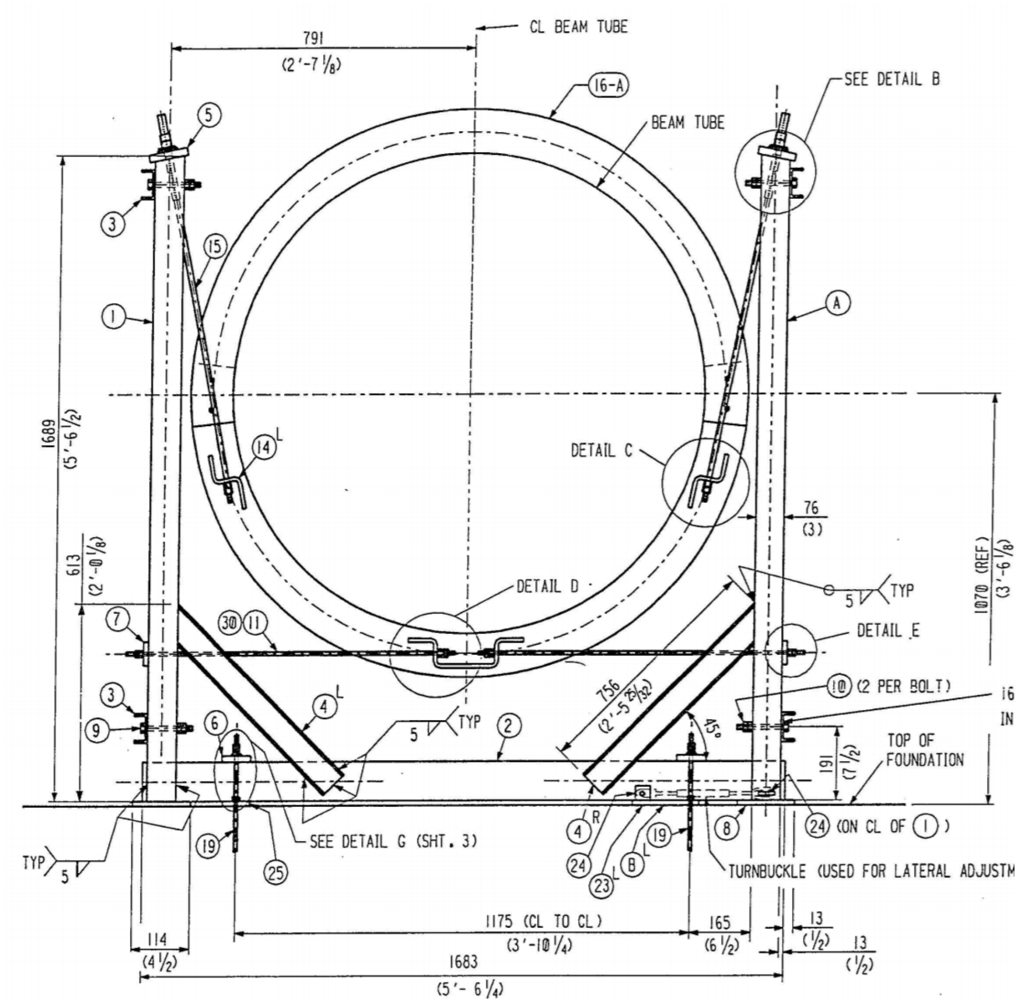
A cylinder pipe guide (spider guide), as depicted in Figure X, provides adequate restraints to vertical and lateral forces while allowing for axial movement. This type of guide may be acceptable if the stick-slip (sticktion) is acceptable.

<table>
<tr>
<td>

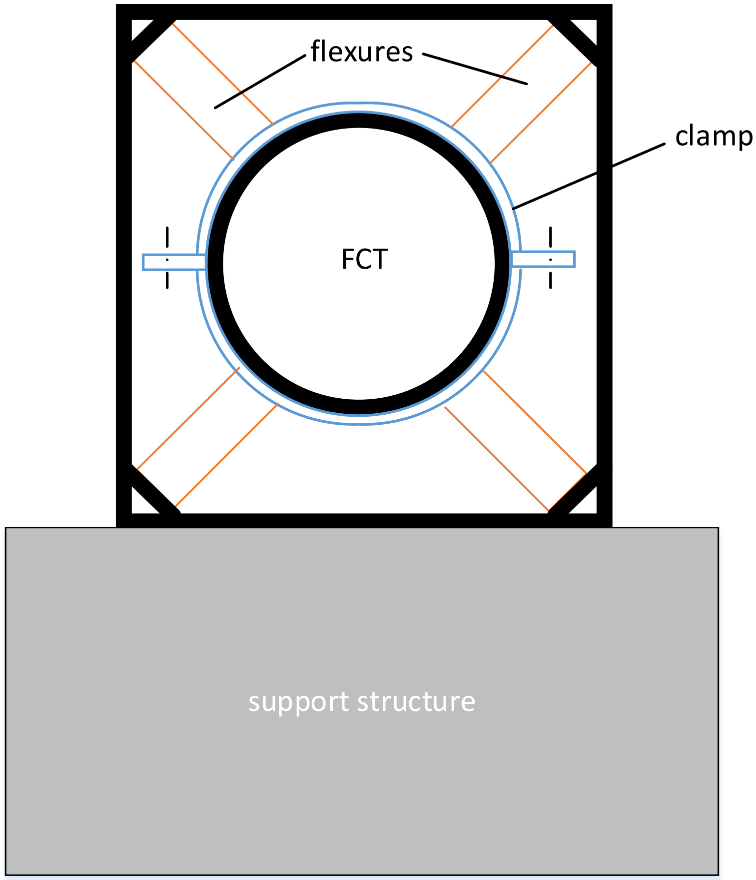
APPLICATION: Design for use on pipe lines containing expansion joints or other critical components where lateral pipe movement needs to be controlled. More than one spider guide should be used adjacent to avoid a fulcrum, imposing lateral deflection on critical components (expansion joints). The guide can be furnished with split sleeve or solid, and they can be modified to suit.</td>
<td>
</td>
</tr>
<tr>
<td>https://pipingtech.com/products/pipe-shoes-pipe-guides/supports-with-no-field-welding/#spec-jump</td>
<td>http://www.advancedthermal.net/catalogs/ATSGuidesAndSupportsCatalog.pdf</td>
</tr>
</table>

7.3 Flexure guide design

If stick-slip release is a concern, then either a suspended cable support (similar to the BT guided support) or flexure support could be designed/developed. Either of these approaches would likely require a completely custom design and fabrication.



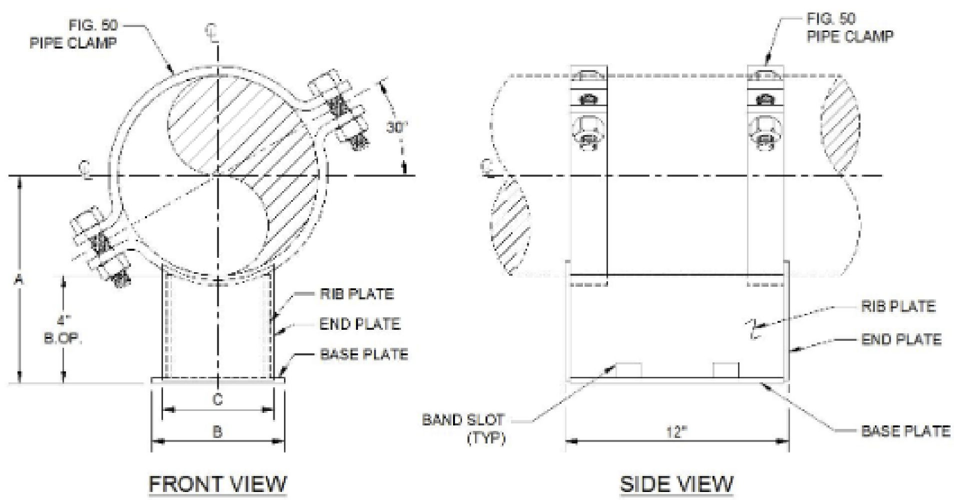
D950044, BT guided support example



8 Fixed support design

A pipe shoe clamp can be used to provide the basic interface between the fixed support structure and the FCT, as depicted in Figure X. A thermal block (e.g. a fiberglass epoxy plate) can be incorporated into the load path. Since the tube sections are featureless, with the exception of the conflat flanges, the fixed support must rely upon friction at the clamps to react against the axial forces. The axial force is dominated by the atmospheric/vacuum pressure difference which is ~1300 lbf (based on the mean diameter of the bellows). The static coefficient of friction for steel on steel (clean and dry) ranges from 0.5 to 0.8. Using the low end of the range, a clamping (normal to the surface) force of ~2600 lbf is needed, which will not be difficult to achieve.

FIG. 1400: PIPE SHOE CLAMP



Source: