PRINCETON PLASMA PHYSICS LABORATORY

ENG - MEMO

PROPOSED RESOLUTION OF THE G10 RING ISSUE - PEER REVIEW RECOMMENDATION

MAG_191126_SPG_1

Work Planning #:	
Effective Date:	**11/27/2019**
Prepared By:	**Stefan Gerhardt**

Approved By	Stefan Gerhardt, Preparer	11/27/2019 21:16:13 PM

National Spherical Torus eXperiment Upgrade

MAG-191126-SPG-01

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SUBJECT: Proposed Resolution of the G10 Ring issue - Peer Review Recommendation

0: Background and Intent of Memo

Considerable time has been spent by the Recovery Project team addressing concerns related to the G10 ring at the base of the NSTX-U OH coil. This memo attempts to describe the components (Section 1), describe the issues identified by the Recovery Project (Section 2), and make a recommendation on the path forward (Section 3).

This memo supports the peer review on 11/26/19, and therefore may or may not be consistent with the conclusions from the peer review or with the follow-on design activities.

The upper G-10 ring is not in scope for this memo.

Recommendations are provided in Section 3.3.

1: Geometry and Component Functions

1.1: Design Condition

The geometry of the region is shown in Figs. 1.1-1 through 1.1-2.

Fig. 1.1-1*: Image of the machine core*

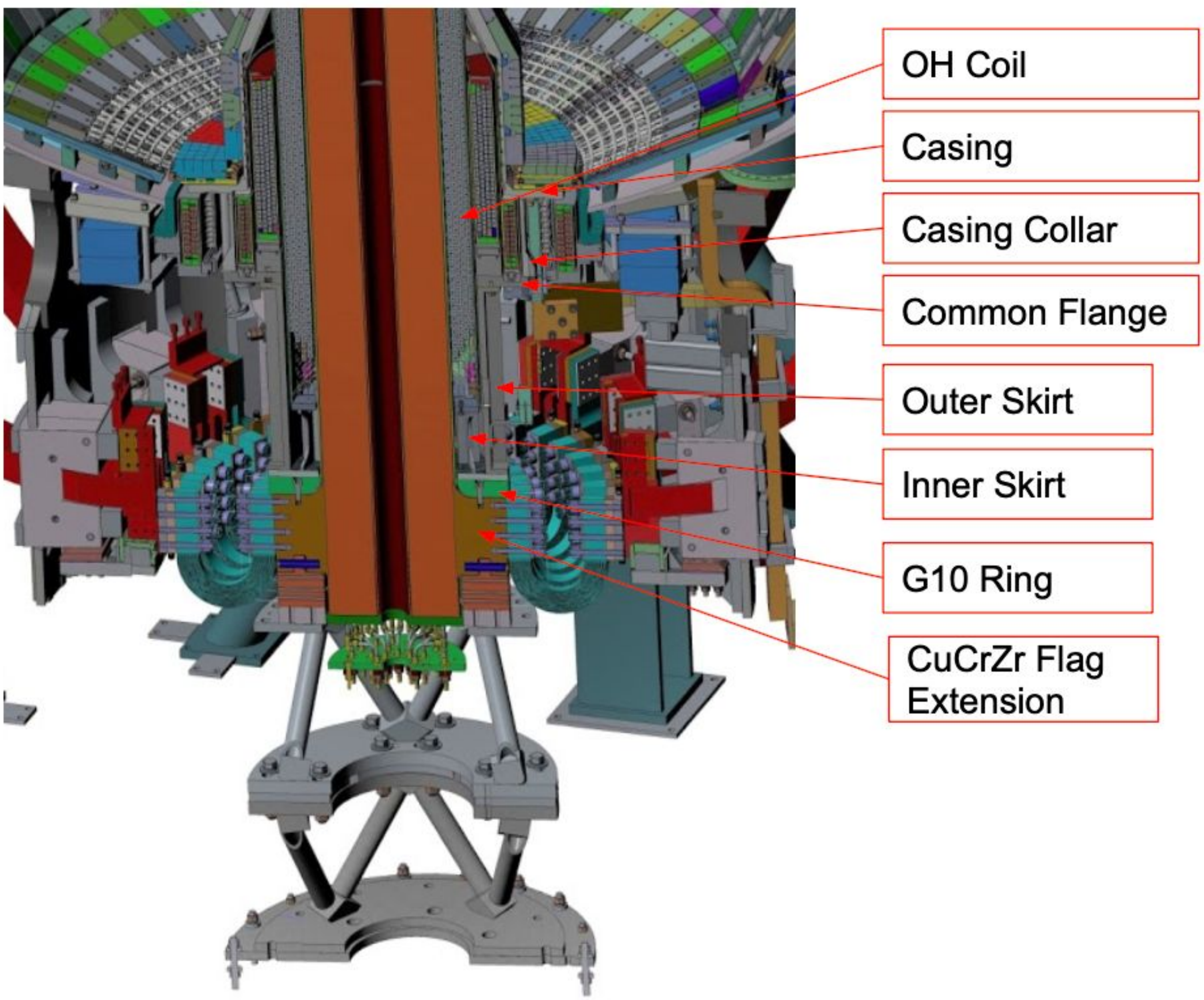
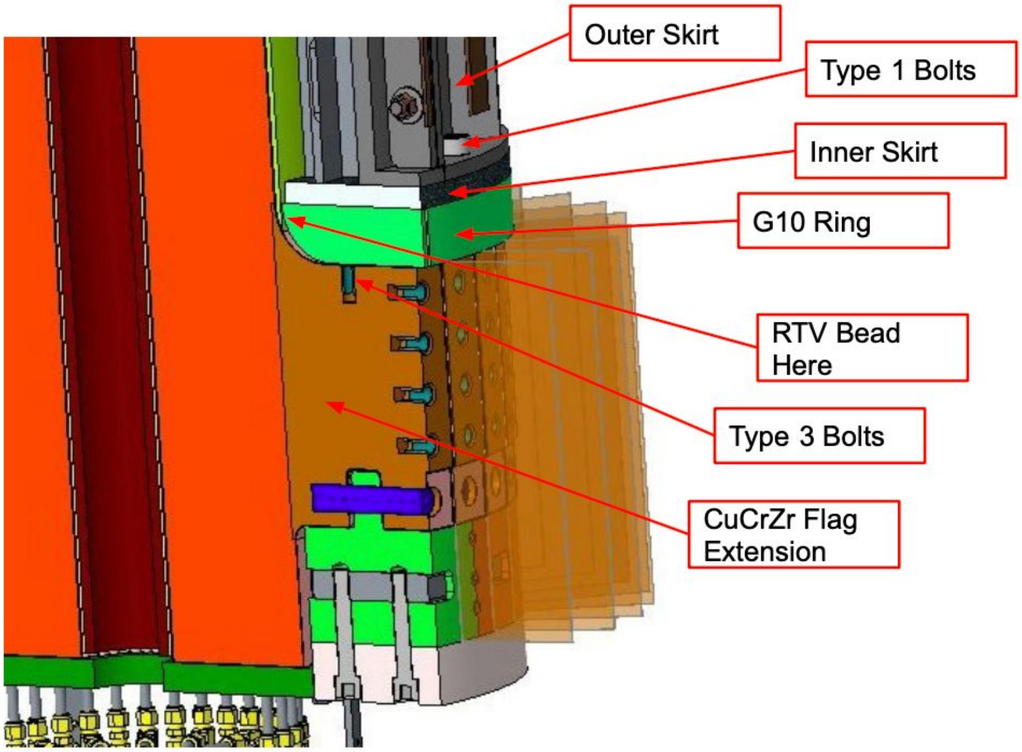


Fig. 1.1-2: *Image of the region in the vicinity of the G10 ring*



The further details of the inner-skirt and G10 ring are shown in Figs. 1.1-3 and 1.1-4. Note the naming convention on the bolts, as described in Table. 1.1-1.

Fig. 1.1-3: *Bolt types named in the G10 ring analysis, from E-DC1523*

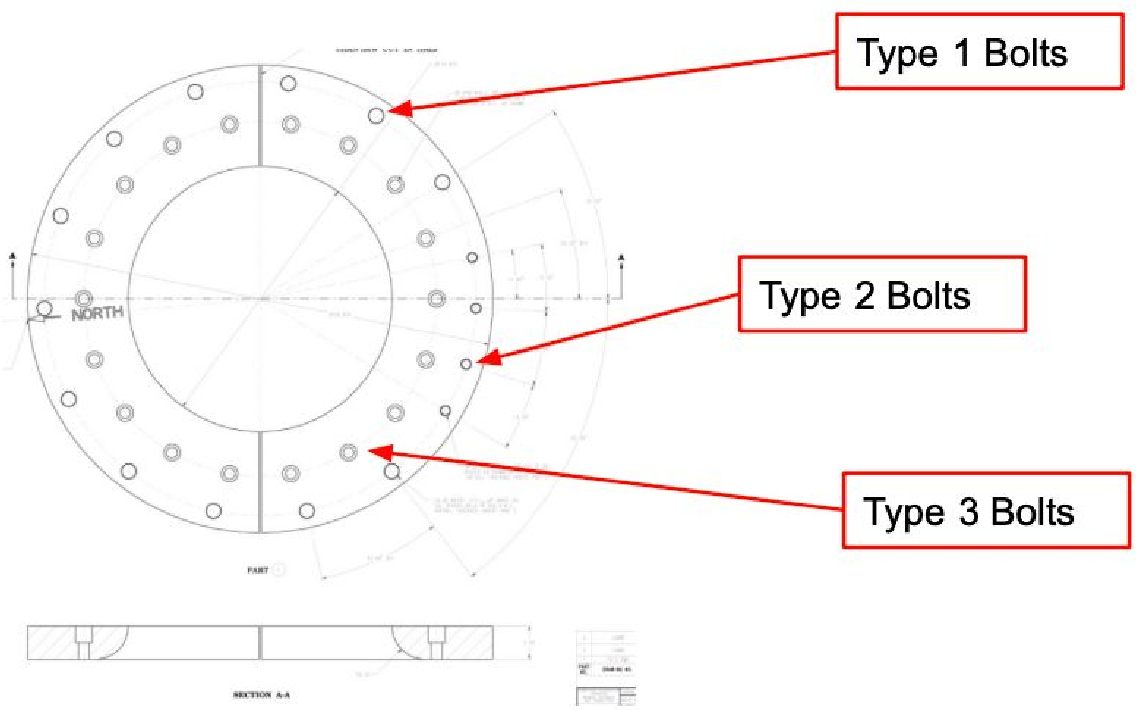


Fig. 1.1-4: *Geometry of the inner skirt, from E-DC1535*

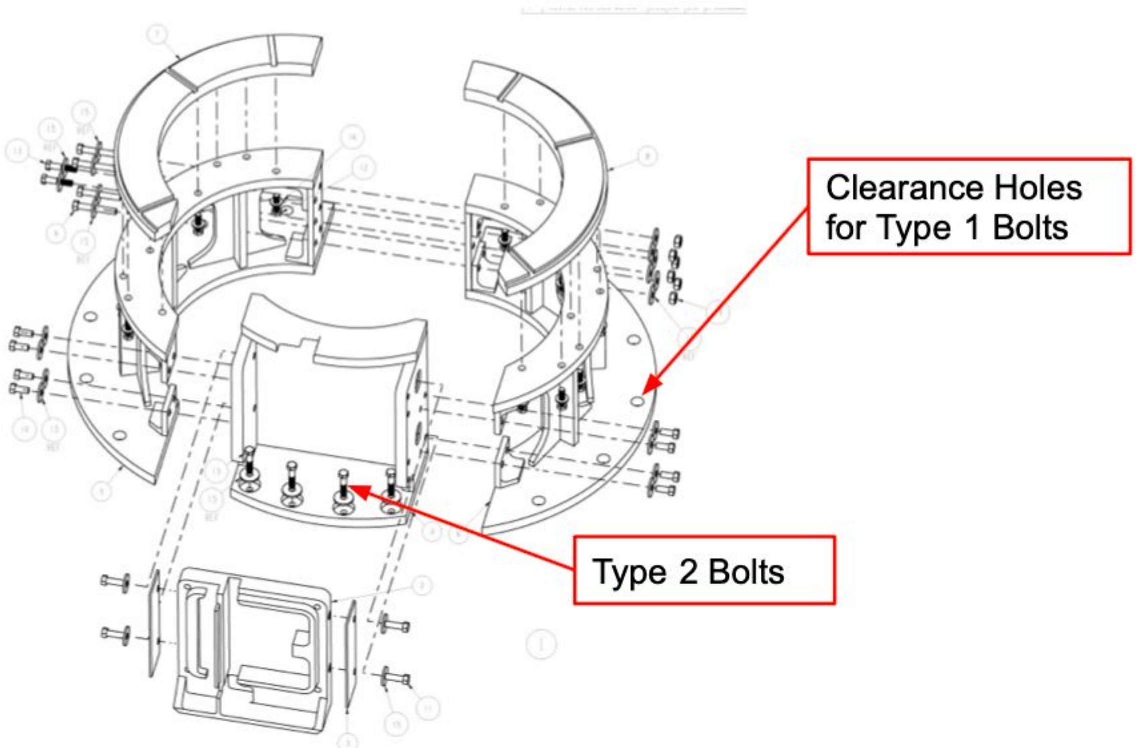


Table 1.1-1: *Naming conventions for the bolts*

	Bolt Type	Bold Description
1	Type 1 Bolt	Bolt which passes through flanges on the inner and outer skirt, threading into keensert in the G10 ring
2	Type 2 Bolt	Bolt which fixes the lead block housing to the G10 ring (via keensert)
3	Type 3 Bolt	Bold which sits in a counterbore in the G10 ring, and attaches to the TF conductor. These bolts are trapped by the inner skirt.

1.2: Functions, Interfaces, and Requirements

The fundamental functions of the G10 ring and skirts are as per Table 1.2-1.

__Table 1.2-1__: Function of components

	Component	Function
G1	G10 Ring	Provide reaction against the preload provided by the OH coil belleville stack.
G2	G10 Ring	Bear the weight of the full CS assembly[1] as transferred by the outer skirt
G3	G10 Ring	React static and transient vertical and lateral interface loads, transferred from the casing to the TF bundle via the outer skirt and G10 ring
OS1	Outer Skit	Bear the weight of the full CS assembly
OS2	Outer Skirt	Transfer static and transient vertical and lateral interface loads from the casing to the G10 ring
IS1	Inner Skirt	Provide reaction against the preload provided by the OH coil belleville stack (transfer to G10 ring).
IS2	Inner Skirt	Pending the options selected in Section 3, provide lateral restraint of the G10 ring (and therefore the casing) against the TF bundle, via the OH coil and the aquapour trapped between the OH and TF coil.

The functions are critical for registering the locations of coils and their leads relative to the externally supported bus work. These functions are also critical for maintaining alignment

Key physical interfaces are in Table 1.2-2.

__Table 1.2-2__: Key physical interfaces

	Component #1	Component #2	Loads
1	Outer Skirt	Inner Skirt	Vertical loads, sliding
2	Inner Skirt	G10 Ring	Vertical loads, sliding
3	G10 Ring	TF Bundle	Vertical loads, sliding

Key additional requirements that the assembly must meet are indicated in Table 1.2-3

[1] Note that the full weight of the CS, all CS tiles and tile assemblies, PF-1aU/L, PF-1bU/L and slings must be born by the G10 ring.

__Table 1.2-3__: Requirements to consider when evaluating solutions in Sections 2 and 3.

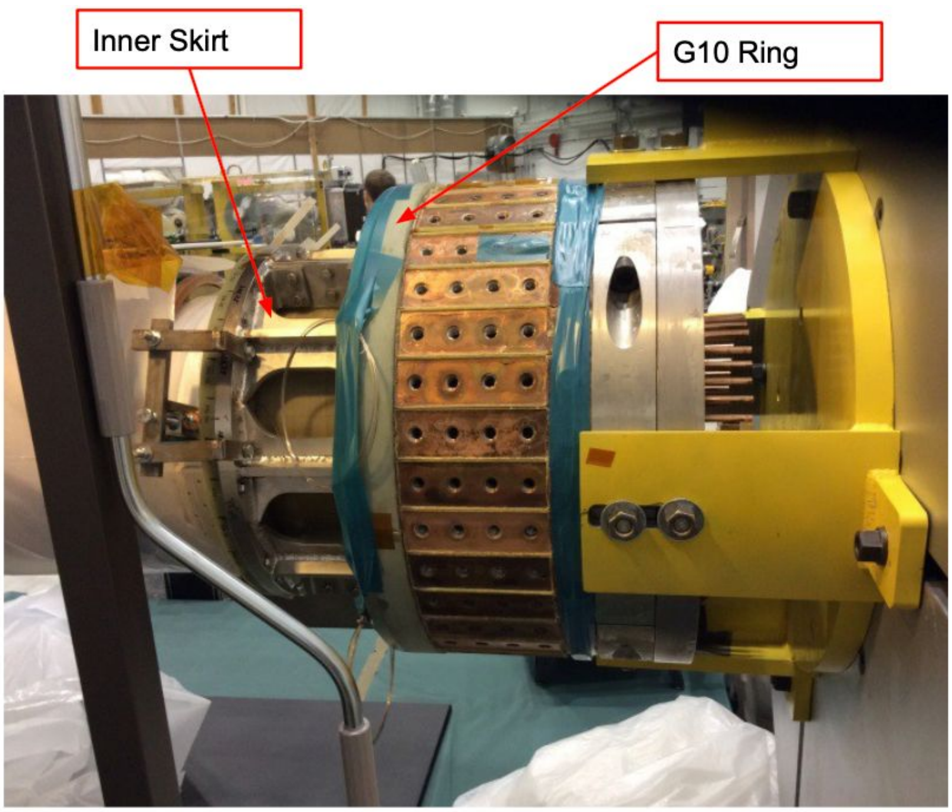
#	Requirement
1	The interface between the G10 ring and the TF bundle shall not put the ground insulation of the TF bundle into tension due to EM loads.[2]
2	The assembly shall be disassemblable.

Additionally, a “do no harm” philosophy must always be taken at all times; the cure must not be worse than the disease.

1.3: As-Built Conditions

This section provides some context on the fabrication and as-built condition to better understand the issues being addressed by the Recovery project.

Figure 1.3-1: *Configuration of the inner skirt and G10 ring during winding of the OH coil*



[2] As per the SDC, the insulation may not take primary tensile stress

The OH coil was wound (Fig. 1.3-1) with the G10 ring and inner skirt in place. The G10 ring has the green color expected of G10 in this image. The inner skirt was removed during the VPI and curing cycle, but the G10 ring was retained on the bundle (Fig. 1.3-2). The subsequent cure cycle exceeded the data-sheet maximum working temperature, and resulted in the G10 ring changing color (Fig. 1.3-3).

During the final assembly (post-VPI and cure), it was recognized that there was a gap, toroidally opposite the OH lead block, between the G10 ring and the top of the TF flags. This was due to toroidal nonuniformities in the thickness of the resin-rich area on top of the TF flags. Based on the thesis that G10 ring would always be under compression, a set of narrow G10 shims were tapped into place under the ring; they are held in place by a small amount of RTV. It is worth noting that the shims are located on the north side of the bundle, opposite the OH lead block.

Note also that an RTV bead was applied between the G10 ring and the TF bundle, as indicated in Fig. 1.1-2.

Figure 1.3-2: *Configuration of the OH bundle in the mold, during VPI. The bundle and mold are in turn installed in the oven in the CTC.*

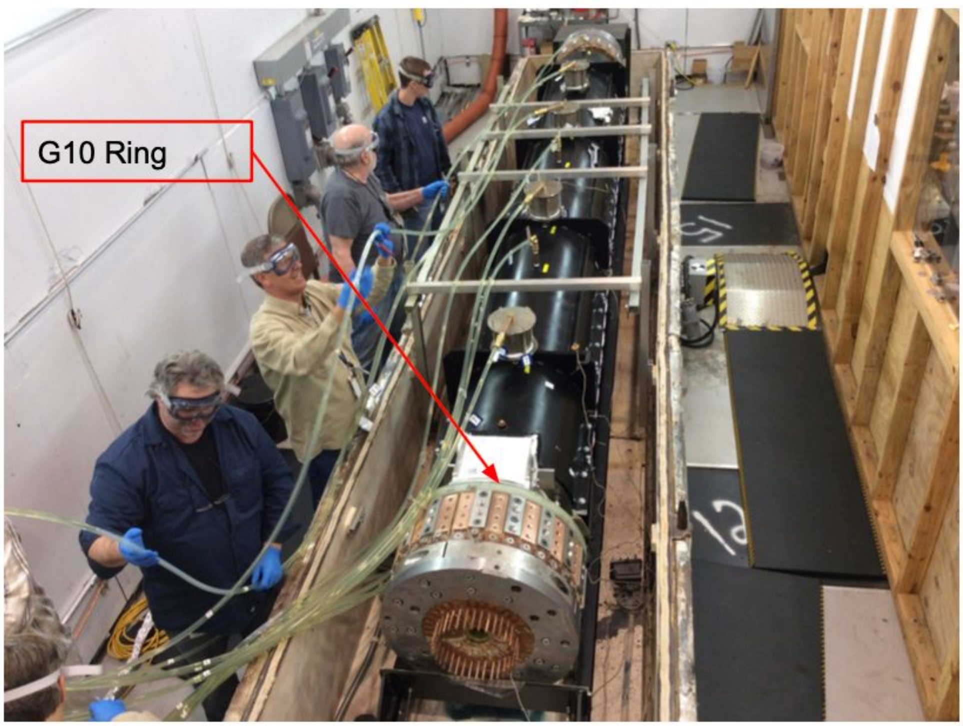


Figure 1.3-3: *Configuration of the OH bundle immediately following the cure cycle*

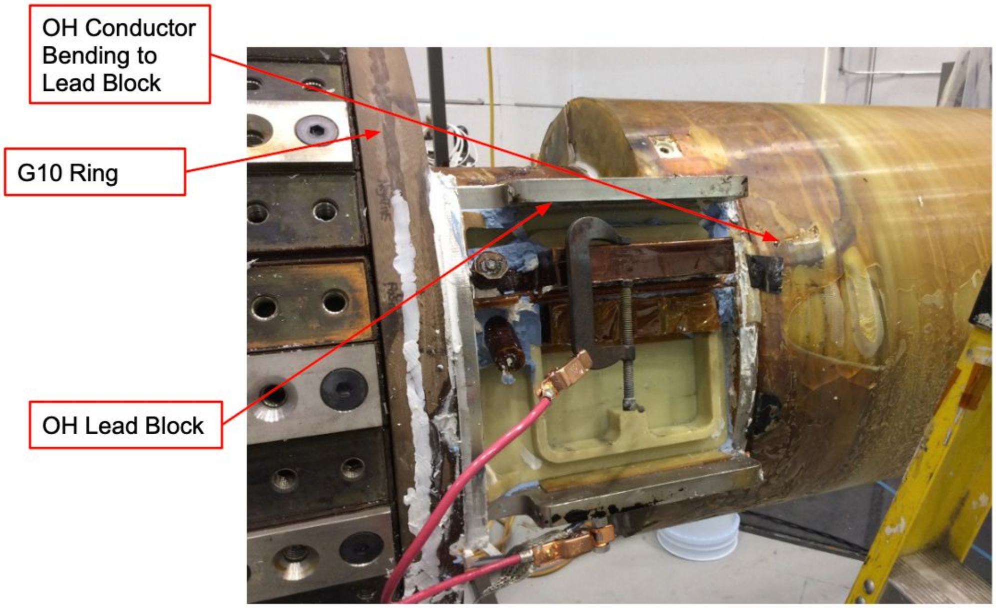


Figure 1.3-4: *Present configuration of the bundle with the outer skirt removed (1 of 3).*

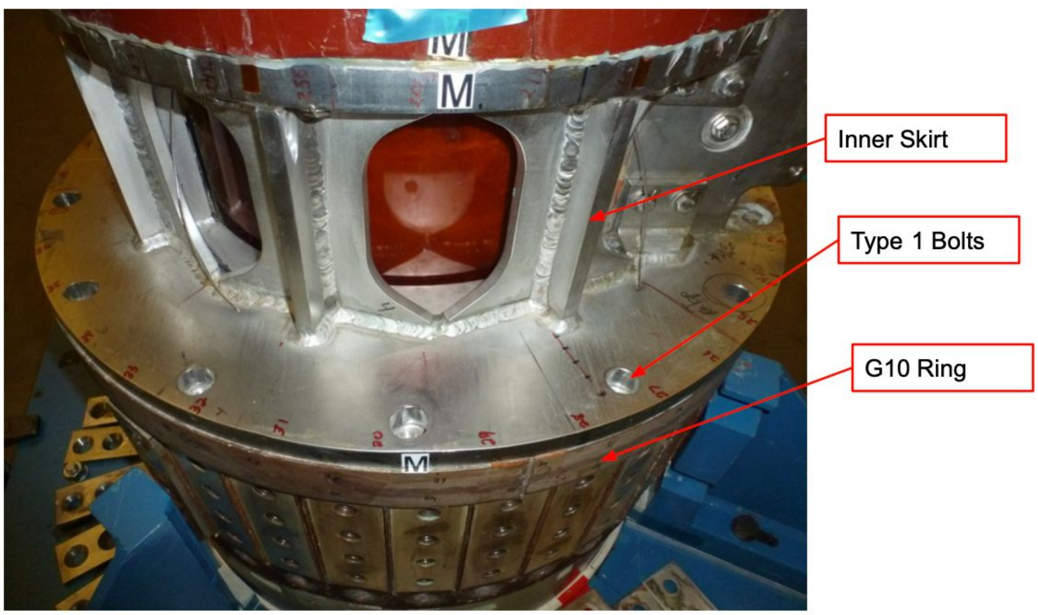


Figure 1.3-5: *Present configuration of the bundle with the outer skirt removed (2 of 3). Note that the shims noted here may in reality be multiple thin stacked shims.*

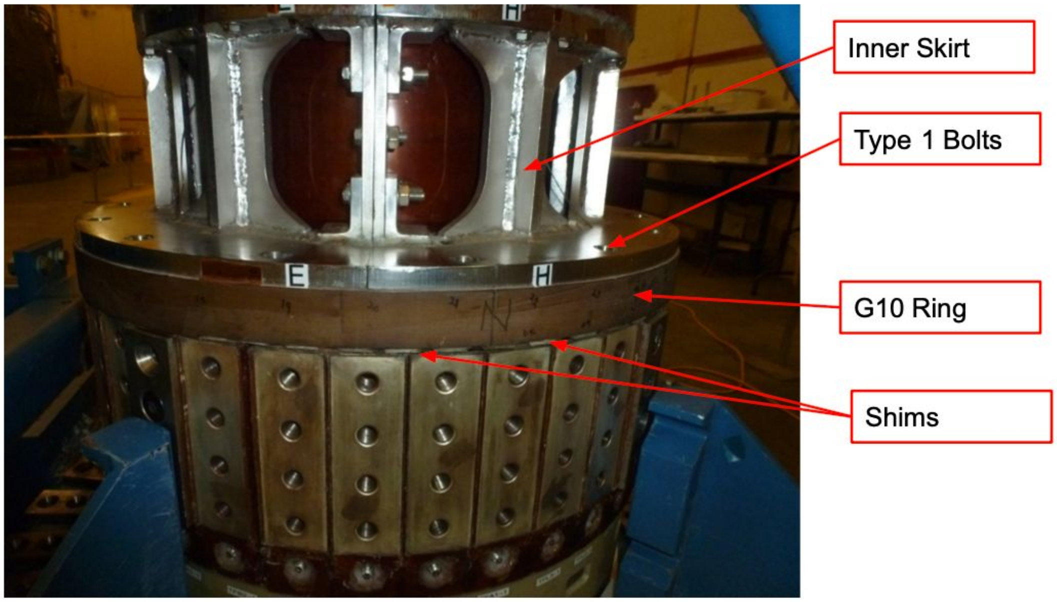
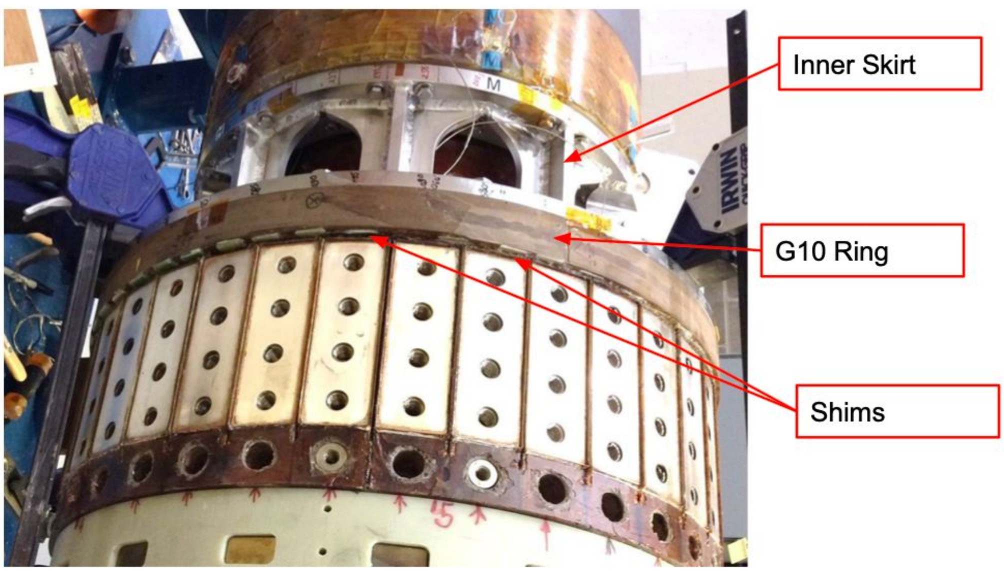


Figure 1.3-6: *Present configuration of the bundle with the outer skirt removed (3 of 3).*



2: Concerns to be Addressed

There are concerns related to this region are as stated in Table 2.0-1.

Table. 2.0-1: *Summary of the concerns being addressed by the Recovery Project*

	Issue	Consequence	Functions Impacted
C1	The G10 ring had been baked beyond its rated service temperature during the curing, potentially weakening it.	The tensile capability of the keensert compromised, resulting in them failing and the casing coming loose.	G3
C2	New vertical loads identified during Recovery may overstress the keenserts and G10	The tensile capability of the keensert exceeded, resulting in them failing and the casing coming loose.	G3
C3	Lack of positive restraint at the three interfaces listed in Table 1.2-2.	Casing may slide “sideways”, compromising alignments and stressing coil leads	G3, OS2
C4	Ability of the shims to work their way out under loads	Casing may become loose, compromising alignments and stressing coil leads	G1, G2, G3
C5	Non-uniform loading of the TF bars due to point contact on the localized shims	May apply vertical loads to the TF flags in a fashion inconsistent with assumptions of the inner-TF analysis from summer 2019	G1, G2, G3

These are addressed in the following sections.

2.1 Concerns C1 and C2: Vertical Load Handling at Bolts

Concerns C1 and C2 are related to the ability of the G10 ring to properly handle the vertical loads. They were addressed through a series of tests and simulations.

2.1.1: Keensert Testing Data

A series of tests were done by A. Falcon and M. Pauley on baked and unbaked samples of G10 with keenserts.

On 9/25/19, A. Falcon and M. Pauley static failure data for baked and unbaked G10. Table 2.1-1 shows the typical static failure for the double-keensert geometry, i.e. a block with keenserts on either end. Both baked and unbaked samples are provided; this geometry is shown in

***Figure 2.1.1-1**: Photo of a failed double-keensert test*.

The bolts are those found on the outer ring of the G10 plate, which mount the two skirts to the G10 ring. The results show that unbaked samples tended to fail at ~6000 lbs, while the baked samples failed at ~3500 lbs. Thus, baking reduced the static strength by a factor of 2. Note that these tests applied tension perpendicular to the plane of the laminates.

***Table 2.1.1-1**: Static failures of the double-keensert geometry*

Double Keensert Tensile

Specimen	Baked (X)	Peak Load (lbf)	Failure Location
1		6266.4	End of Keensert
2		6352.4	End of Keensert
3		5986.3	End of Keensert
4		6046.1	End of Keensert
	Average	**6162.8**	
	Standard Dev.	**174.6**	
Specimen	**Baked (X)**	**Peak Load (lbf)**	**Failure Location**
B1	X	3919.1	End of Keensert
B2	X	2956.6	End of Keensert
B3	X	3547.4	End of Keensert
B4	X	4915.8	End of Keensert
B5	X	3448.8	End of Keensert
	Average	**3757.5**	
	Standard Dev.	**732.9**	

The second set of tests were of dogbone samples, applying tension along the laminates. An example failed sample is shown in Fig. 2.1.1-2.

Figure 2.1.1-2: *Photo of a failed dogbone sample*

The results in Table 2.2.2-2 show that there is minimal degradation of strength along the laminates with bakeout of the sample. Note that this is more of an academic result, as the primary loading in the present case is not parallel to the laminated.

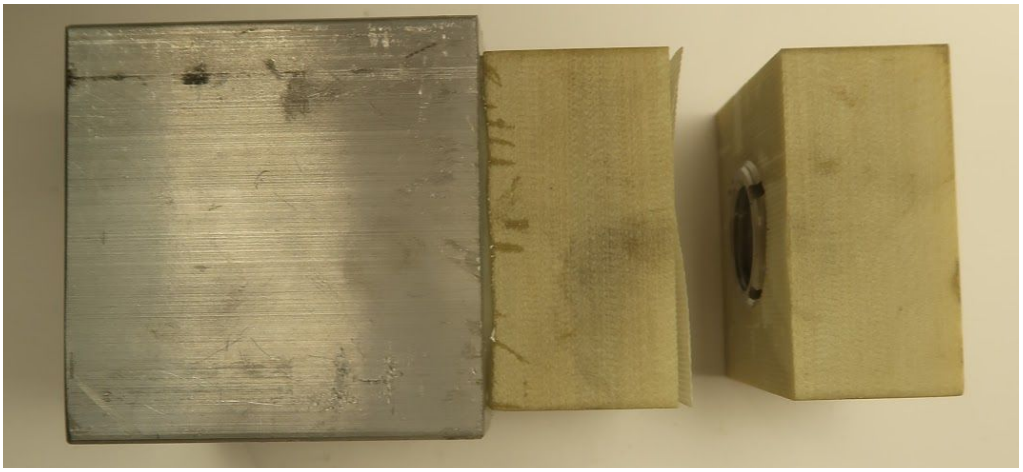
Table 2.1.1-2: *Static tests of dogbone samples*

Dogbone Tensile

Specimen	Orientation	Baked (X)	Peak Stress (ksi)
1	Parallel		53.7
2	Parallel		59.4
		Average	**56.6**
Specimen	**Orientation**	**Baked (X)**	**Peak Stress (ksi)**
8	Parallel	X	51.1
9	Parallel	X	54.6
		Average	**52.9**
Specimen	**Orientation**	**Baked (X)**	**Peak Stress (ksi)**
4	Perpendicular		57.7
10	Perpendicular		61.8
		Average	**59.8**
Specimen	**Orientation**	**Baked (X)**	**Peak Stress (ksi)**
5	Perpendicular	X	59.4
6	Perpendicular	X	59.6
		Average	**59.5**

Table 2.1.1-3 shows results using “small keensert samples”, which had only a single keensert (see Fig. 2.1.1-3).

Figure 2.1.1-3: *Photo of a failed dogbone sample*



These showed a similar near factor of 2 reduction in the failure strength with bakeout. These failed at the end of the keensert as well.

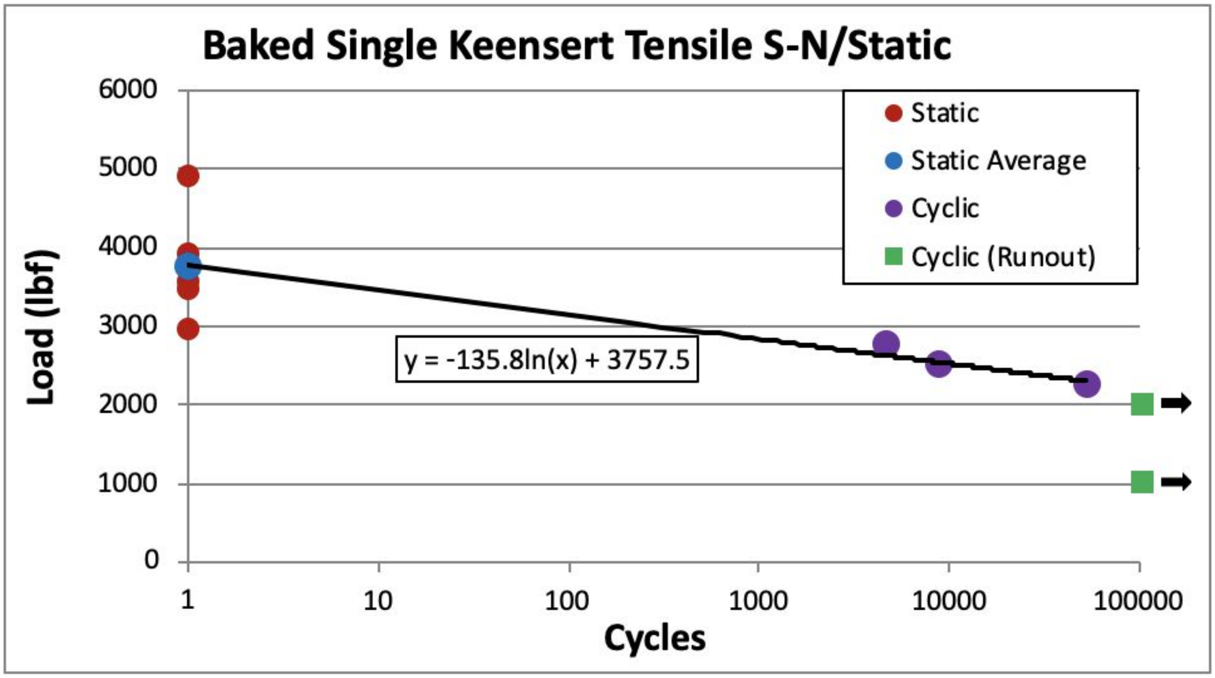
Table 2.1.1-3: *Static tests of small keensert samples*

Single Keensert Tensile

Specimen	Baked (X)	Peak Load (lbf)	Failure Location
1		5223.4	End of Keensert
Specimen	**Baked (X)**	**Peak Load (lbf)**	**Failure Location**
B1	X	3707.0	End of Keensert

On 10/2/19, the graph in Figure 2.1.1-1 was provided, for baked samples of the small keensert tests. *This figure shows that grossly speaking, a factor of 5 on life is achieved at 2000 lbs pull-out force.*

Figure 2.1.1-1: *Fatigue strength of baked keenserts*



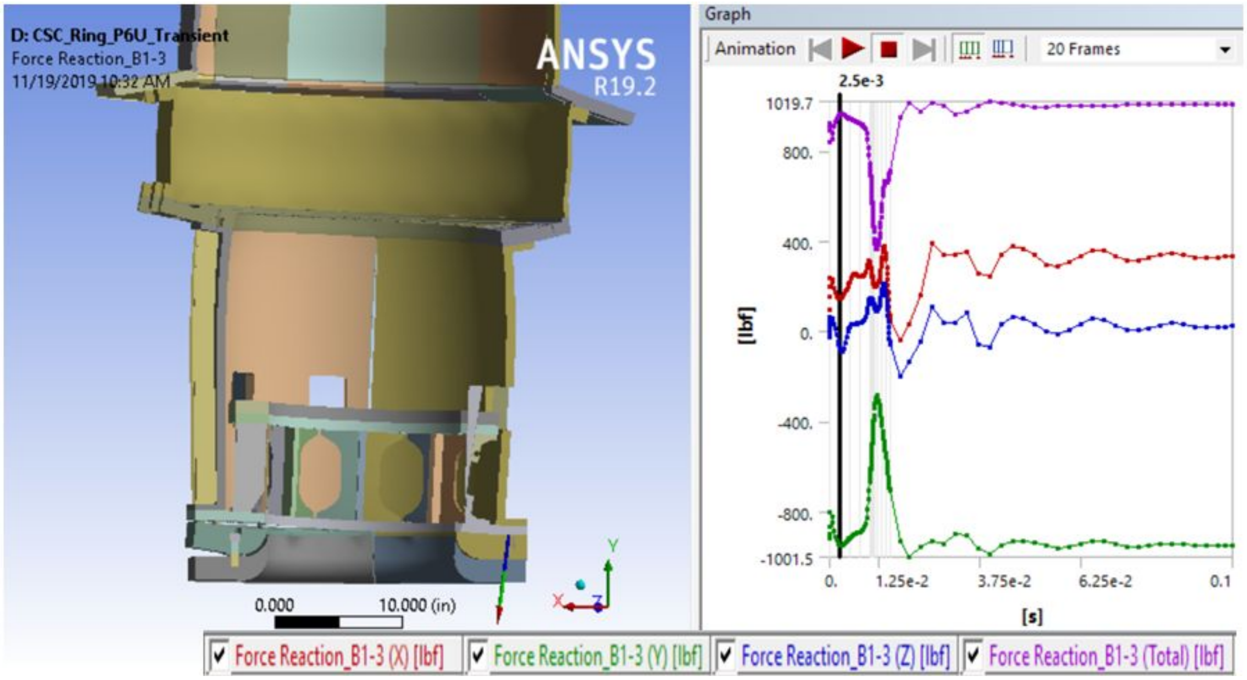
2.1.2: Simulations of Bolt Reaction Forces

Jiarong Fang did a large number of simulations of the pull-out force under various assumptions regarding bolt preload and friction at the interfaces of interest. These simulations were of the P6U disruption scenario[3], which is the most demanding scenario as pertains to the G10 ring and its interfaces.

A key dynamical feature of these simulations is the tendency for the casing to lift upwards under vertical load from the disruption. This results in a “dishing” like distortion in the skirt flanges and G10 ring, due to the radial offset between the Type 1 and Type 3 bolts.

[3] As per NSTX-U-RQMT-RD-003, the P6 Upper scenario has the plasma landing on the upper vertical target, driving halo currents which cause the casing to have a large side load.

***Fig 2.1.2-1**: Transient behavior of the skirts and G10 ring under the P6 Upper disruption. The interface between the skirts is bonded in this simulation.*



From the slides presented on 10/2/2019, the peak force on the bolts is given in Table 2.1.2-1.

***Table 2.1.2-1**: Peak reaction forces for the bolts on the G-10 ring*

	No Friction, No Grout, No Preloaded	**Friction and Grouted Type 1 Bolts, Preload= 1000 lbs Type 2&3 Preload=600 lbs**
Bolt 1 Peak Transient Reaction Force	550 lbs	1020
Bolt 2 Peak Transient Reaction Force	322 lbs	1052
Bolt 3 Peak Transient Reaction Force	393 lbs	1339

A few notes go along with this table:

- larger values of bolt preload tended to reduce the amount of dishing, but at the expense increased reaction forces on the keenserts.
- There is no OH coil or aquapour in this simulation. This will become relevant in Section 2.2.

- This table should not be taken as the documentation of record for the reaction forces, nor this memo as the document of record for the FEA; see calculation NSTXU_1-1-3-3_CALC_10.

2.1.3: Conclusions Regarding Concerns C1 and C2

Comparing the results in Table 2.1.2-1 to those in Fig. 2.1.1-1, it can be seen that the keensert reaction force is within the acceptable range provided that the bold preloads are kept modest.

2.2: Concern C3: Lateral Restraints

2.2.1: Explanation of Concern

As per Fig. 2.1.2-1, there is a tendency for the interfaces to separate. This, in concert with the large halo current induced side loads on the casing, results in a potential for horizontal sliding of the casing at each of the interfaces in Table 1.2-2. This could result in the following detrimental effects:

- Shifting of the inner-PF coils outside of the alignment tolerances specified in -RD-11
- Extra load on coil leads due to shifting
- Bellows stress

Initial models had only frictional interface between the skirt flanges and the G10 ring, and between the G10 ring and the TF bundle. More recent models included grout within the Type 1 bolt clearance holes, which register the skirt flanges relative to the G10 ring.

Figure 2.2.1-1*: Shifting of the G10 ring on the TF bundle (right); the blue shift of 1e-4” is predicted for this disruption.*

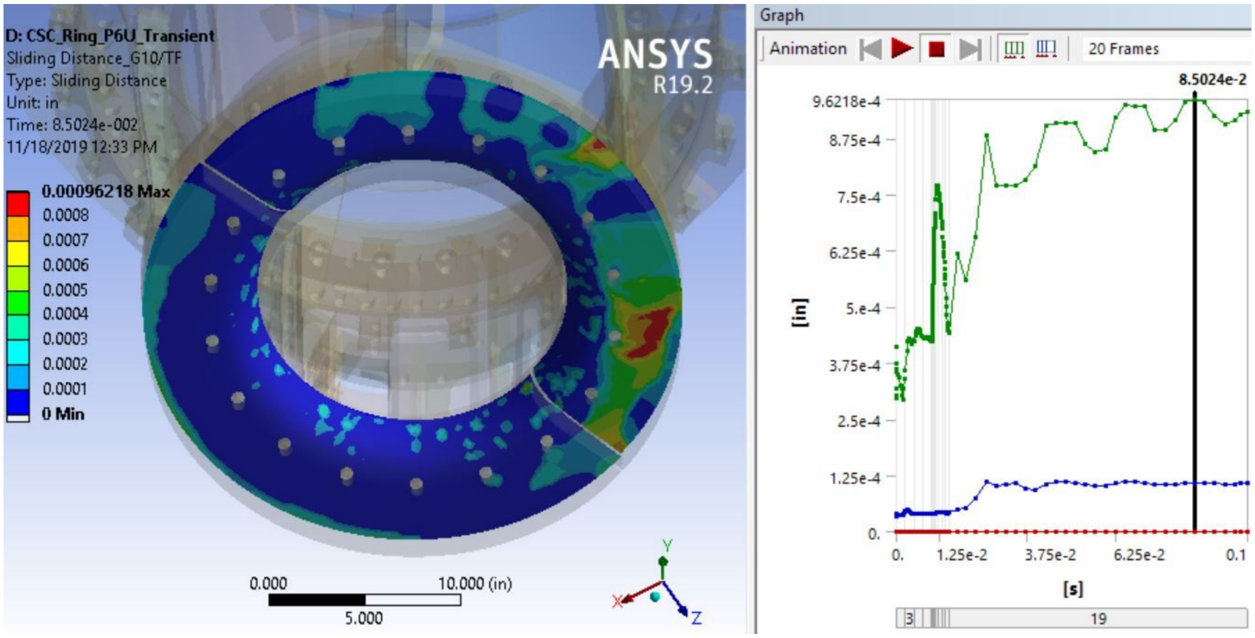
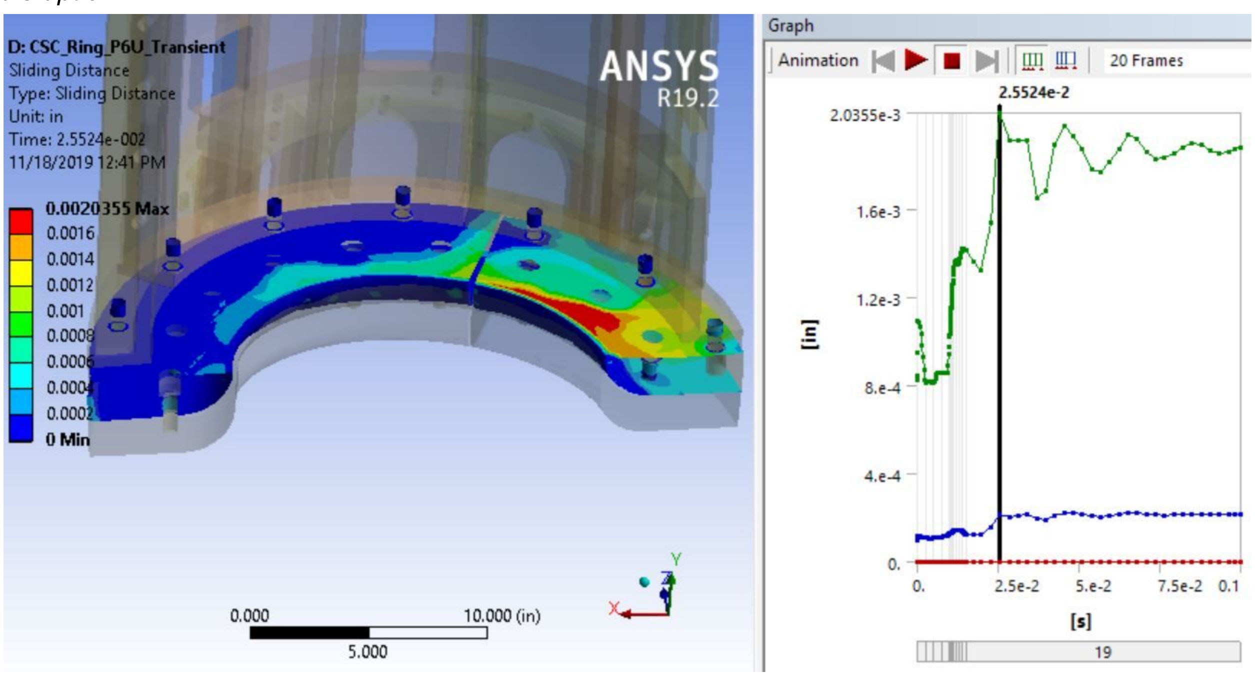


Figure 2.2.1-1*: Shifting of the inner skirt on the G10 ring (right); the blue shift of 2e-4” is predicted for this disruption.*



2.2.2: Mitigating Considerations and Potential Actions

Two mitigating considerations are in play with regard to this conclusion:

- The scenario of interest here is the P6 Upper disruption, which is conservatively postulated to occur 5% of the time as per NSTX-U-RQMT-RD-003; indeed, this scenario did not even exist in the Upgrade-Project requirements basis due to its infrequency. The full 2 MA, 1T case occurs in only 4000 total pulses as per the GRD. Hence, only 0.05*4000 = 200 total of these disruptions are expected to occur. If all displacements occur with the same toroidal phase, this results in a displacement of (0.0001+0.0002)"x200 = 0.06"=1.5 mm. This is approximately 1/2 the positional tolerances required in -RD-11.

- The present model neglects the aquapour embedded between the TF and OH coils. The aquapour serves to register the TF coil relative to the OH coil. NSTX-U is operated such that the temperature of the OH always exceeds that of the TF. In the worst case, a free radial gap of 0.4 mm, or 0.015", opens at the slip-plane interface between the TF and OH on any pulse; it then closes again.[4] Because the OH coil is interfaced to the G10 ring via the inner skirt, this aquapour can act to prevent the G10 ring from sliding relative to the TF. It should be noted that the interface of the inner-skirt to the OH coil is frictional, i.e. there are no direct bolts into the OH coil, but rather a frictional interface loaded by weight and the OH belleville stack.

Note that the aquapor is already credited with maintaining the position of the OH relative to the TF; there are no shims installed either during operations, or when storing in the horizontal position.

Potential actions to take to address the concern of lateral restraints at the skirt interfaces include:

- Do nothing beyond that done in 2014, and rely on frictional restraints at all interfaces
- Grout[5] the Type-1 bolts to register the skirt interfaces to provide positive restraints at the skirt interfaces.

Potential actions to address the concern of lateral restraints at the G10/TF interface include:

- Rely on the aquapour, in concert with friction, to provide restraint at the G10 to TF interface.
- With inner-skirt in place, attempt an in-situ fill with low-viscosity "grout" to fill in sufficiently around G-10 to TF interface, providing positive lateral constraint.

[4] The OH bunde is approximately 0.25 m in radius. The circumference is therefore 1.57075 m. When heated to 100 C, this circumference increases by 0.00267 m, to 1.57342 m. This implies a gap of 0.425 mm opens between the TF and OH coils (assuming the TF stays cool), presumably at the teflon slip-plane.

[5] Throughout this document, the phrase "grout" is used to signify any electrically non-conducting structural filler.

- Remove the inner-skirt, remove the Type-3 bolts, reinstall the Type-3 bolts in a grouted configuration to provide restraint at the TF interface, reinstall inner skirt.[6]
- Remove inner skirt, partially remove G10 rings, reinstall with more positive lateral restraint at interface between the TF and the G10 ring.

These will be discussed more in Section 3.

2.3: Concern C4: Shims Loosening

As shown in Fig 1.3-5 and 1.3-6, the G10 shims may begin to wander under repeated impulses of the type shown in Fig. 2.1.2-1. If these shims were to come out, the G10 ring would have an asymmetric interface to the TF bundle. This could result in excessive motion of the casing and OH, putting components such as coil leads at risk. It would also non-uniformly load the bundle.

Options to better trap the shims include, in order of increasing complexity:
- Do nothing and assume the RTV is sufficient to hold the shims.
- Installation of a band of wet layup around the shims, which prevents them from coming loose
- Injecting some grout/filler material into the gaps between the shims to lock them together
- Removal of the back G10 ring, allowing the shims to be replaced by a more uniform layer of wet layup.

These will be discussed more in Section 3.

2.4: Concern C5: Non-uniform loading of the TF Flags

The shims place a non-uniform vertical load on the TF bundle; the vertical load is transferred at only the locations of shims. This asymmetric loading on the flags may be problematic as it violates the assumptions of the inner-TF review from the summer of 2019. Indeed, it is difficult to be confident what the full bearing area for vertical load is at the G10/TF interface.

A few options for consideration include the following:
- Do nothing and accept the non-uniformity
- Install some grout between shims. In this case, the grout may be thicker since it is not expected to fill in all voids under the G10 ring, but rather simply improve the uniformity of the preload.
- Remove the inner skirt and back G10 ring, set up an improved interface (some wet-layup or grout), and then reinstall components.

These will be discussed more in Section 3.

[6] This option suggested by S. Raftopoulos on 11/13/19

3 Options and Recommendations

3.1: Options at the Skirt Interfaces

At the skirt interfaces, there are two options to consider, as shown in Table 3.1-1

Table 3.1-1: *Options at the skirt interfaces*

	0	**1**
	Assemble as in 2014	**Grout Type 1 Bolts (and Type 2 if possible)**
risks	None beyond concern C3	none
C1	Low preload allows for acceptable bolt forces	Low preload allows for acceptable bolt forces
C2		
C3	Lateral restraints at skirt interfaces provided by friction	Lateral restraints at skirt interfaces provided by friction ***and*** grouted connection
C4	N/A	N/A
C5	N/A	N/A

3.2: Options at the interface of the G10 ring to the bundle

At the interface of the G10 ring to the bundle, there are 4 options, as described in Table 3.2-1 and 3.2-2 (note that 2 and 3 were provided by S. Raftopoulos in his presentation of 10/3/19).

Table 3.2-1: *Options at the G10 ring to TF interface*

#	**Description**
0	• Do nothing; leave deployed exactly as at present
1[7]	• Spray mold release into voids between shims • Use a high viscosity grout, potentially thixotropic, to trap shims and provide a more uniform loading surface. ○ Do not credit it with filling *behind* the shims, or with providing any lateral restraint at the interface • Apply a thin fiber-glass & hysol layer to trap shims and grout

[7] Note that there may be similar concepts to this "thick grout" concept; the key point is to develop significantly more uniform vertical loading of the TF, but to not require the solution improve the radial registration.

2	● Apply mold release though the volume under the G10 ring ● Do a complete in-situ fill throughout the full volume trapped by the G10 ring, in an attempt to provide a full lateral restraint and completely uniform bearing area.
3	● Remove inner-skirt ● Remove the back ½ of G10 ring ● Grout beneath/behind fixed ½ of G10 ring to provide lateral restraint (after mold releasing) ● Reinstall the removeable ½ of the G10 ring on a bed of wet layup or similar (after mold releasing ● Reinstall the inner-skirt, potentially before the wet-layup sets
4[8]	● Remove the inner-skirt ● Remove all accessible Type 3 bolts ● Reinstall those Type 3 bolts with grout to take up the space ● Reinstall the inner-skirt ● Spray mold release into voids between shims ● Use a high viscosity grout, potentially thixotropic, to trap shims and provide a more uniform loading surface. ○ Do not credit it with filling *behind* the shims, or with providing any lateral restraint at the interface ● Apply a thin fiber-glass & hysol layer to trap shims and grout

Table 3.2-2*: Risks and benefits of the methods described in Table 3.2.1. The concerns are in Table 2.0-1. Note that columns here corresponds to rows in Table 3.2.1-1.*

	Option 0	Option 1	Option 2	Option 3	Option 4
Requires disassembly	No	No	No	Yes, inner skirt and back G10 ring	Yes, inner skirt
Bundle position for work	N/A	vertical	Horizontal best for filling	Horizontal (due to removal of skirt)	Horizontal, then vertical
Risks	Concerns C4 and C5 unaddressed	Minimal thick/thixotropic grout unlikely to spill out over electrical faces, or between G10 ring halves	Thin resin/grout spilling onto electrical faces of bundle or into flash-shield slots Filling best with horizontal bundle, but may build in small offset.	Unknowns during significant disassembly Need to align ½ of G10 ring once it is installed. Risk of resin/grout spilling onto electrical faces	Unknowns during disassembly and removal of inner skirt. Other risks as per Option 3.

[8] This option combines the thick-grout idea of option 1 with S. Raftopoulos' idea to grout the Type 3 bolts

C1 **C2**	Low preload allows for acceptable bolt forces	Low preload allows for acceptable bolt forces	Low preload allows for acceptable bolt forces	Low preload allows for acceptable bolt forces	Low preload allows for acceptable bolt forces
C3	Lateral restraints at G10/bundle interface provided via aquapour between TF and OH	Lateral restraints at G10/bundle interface provided via aquapour between TF and OH	Lateral restraints at G10/bundle interface provided via complete in-situ fill of region under G10 ring	Lateral restraints at G10/bundle interface provided via complete in-situ fill of region under G10 ring	Lateral restraint provided by combination of aquapour and grouted Type 3 bolts
C4	Shims may walk out	Shims trapped by grout and fiberglass/hysol band	Shims trapped by resin	Shims may be removed/replaced	Shims trapped by grout and fiberglass/hysol band
C5	Continued non-uniform vertical loading of the TF	Loading uniformity improved by thick grout between the shims	Uniform loading achieved by fully uniformly installed grout	Uniform loading achieved by grouting and wet layout	Loading uniformity improved by thick grout between the shims

3.3: Recommendation

Based on the concerns C1-C5 and the articulated risks, it is recommended to take the following actions:

At the skirt interfaces, implement Option 1 of Table 3.1-1: - *Grout the Type 1 bolts (and Type 2 bolts if possible)*

At the G10/bundle interface, implement Option 1 of Table 3.2-1 - *Inject thick grout between the G10 ring and TF bundle, in between the shims*

The subsequent requirements are as follows:

- The grout chosen should be thick enough that it fully bonds to both the top of the TF flags and the bottom of the G10 ring.
- The grout should not shrink or expand a meaningful amount during curing.
- The method of injecting this grout should facilitate containment of said grout under the G20 ring, without contamination of the TF faces or flash-shield slots.