National Spherical Torus eXperiment Upgrade

NSTX-U Recovery Project Shielding Plan

NSTX-U-RQMT-PLAN-017-02

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Record of Revisions

Date	Version	Brief Description of Changes
4/4/18	Rev 0	Initial Release
7/22/18	Rev. 1	Corrected a mis-labelled penetration on Fig. 6.1-2 (6495->6496)
		Added QA to the signatory list as per the documents and records plan.
		Added outline Section 1.2
		Added all photographs throughout the document
		Significant expansion of Section 2, including description of historical use of the room and many photos of the present configuration
		Added Section 3, which summarizes tests during the run
		Removed Note 5 from the table of D-T generator summary results, and modified 4.2.2 to make assessments of any additional shielding work that should be done to this door (to the NBPC building).
		Added Section 4.3, summarizing the philosophy for shielding design.
		Added Appendix 2, summarizing the philosophy for identifying problematic penetrations.
12/21/18	Rev. 2	Adjusted signatures as per changes in both types of roles and individuals filling roles
		Added a short description of Section 6 to Section 1.2
		Modified 4.2.10 to eliminate verbiage about engineering controls to prevent access to the MER or MER mezzanine during operations.
		Updated 4.2.4 to have the distinction between observation and equipment windows. Changed the verbiage in 4.2.1 through 4.2.4 to have the requirement to assess and improve as necessary the shielding in the equipment windows and large circular penetrations, many of which have 1’ thick plugs.
		Added requirement to shield all the vision and equipment windows at floor level on the north and northeast walls; previously some have been Phase II.
		Added requirement to augment shielding around the HHFW waveguides
		Moved 1591-1594, 1634-1636 into Phase I
		Moved the MPTS penetration (6136) in Phase II
		Substantial re-write of Section 2. Move all photographs to this section, so that the overview of the test cell would be more coherent and conclusive.
		Substantial reorganization of Section 4.2. Now has separate sections for each wall, with the individual penetrations sorted by which wall they are in.
		Removed assertion that dosimetry will not be in place during initial phase of operations after the Recovery outage.

References

[1] NSTX-U-RQMT-SRD-010: NSTX-U Test Cell System Requirements Document
[2] NSTX-U-SDD-DIAG-NEUT-R0: Fission Chamber Neutron Detectors System Design Description Document
[3] NSTX-U SAD Rev. 6 (this SAD supported NSTX-U operations as a high hazard facility under ESH-025 during the FY-2016 run campaign)
[4] S. P. Gerhardt, et al., Nuclear Fusion **52**, 083020 (2012)

1: Structure of the Shielding Plan

1.1: Overview

During the 2016 run campaign, measurements at locations around the NSTX-U Test Cell demonstrated the need to improve the Test Cell shielding. In particular, some doors and penetrations lacked sufficient shielding to reduce the neutron flux from the test cell to acceptable levels.[1]

As part of the NSTX-U Recovery Project Extent of Condition assessment, a number of chits were written regarding the need to improve the shielding. These chits are listed in Table 1-1. Remediation of these shielding deficiencies was identified as high-priority by the laboratory and the Extent of Condition committee.

Table 1-1: *DVVR[2] chits related to NTC shielding that are addressed by this plan.*

Chit #	Chit text
RMS1	Data from the Radiation Monitoring System will need to be reviewed, as it becomes available, to determine if penetration shielding needs to be improved.
RMS3	Shielding, especially local shielding of penetrations may be insufficient for future operations. Restart design and analysis of local shielding around penetrations. A survey of penetrations could identify a few bad actors.
RMS4	Consider using D-T generator to assess which penetrations or features of the NTC walls/ceiling/floor are causing the worst dose (after appropriate review of course...)
RMS5	Please consider moving the card reader on the south door to the door to the south high bay.
RMS6	Continue process to identify and shield penetrations that are most problematic.
RMS10	Identify penetrations such as water, laser guides, fiber optic bundles, RF Feeds and shield the entry and exit sides of the penetration with additional shielding.
RMS11	Consider adding a labyrinth to the south high bay door to mitigate southeast gallery radiation issues.
RMS12	Consider ways to improve the shielding at the North door. Poly sheets, other concrete, or close the battleship door?

The shielding plan described here is based on a three phase approach. The first two phases include testing with the D-T neutron generator to identify the most problematic penetrations, followed in each instance by implementation of the engineering steps required to remediate those penetrations. This two-phase process is needed because the contributions of small or marginally shielded penetrations to

[1] Note: a staged approach to improving the test cell shielding had been envisioned before the 2016 run. It was envisioned that this would commence following the FY2016 campaign, with the measurements described in Section 3 motivated partly by those plans. The Recovery activity accelerated those plans.

[2] DVVR = Design Verification and Validation Review, a type of topical review that formed the basis for the Extent of Condition process.

the total neutron flux from the Test Cell can be difficult to identify in the presence of large or poorly shielded penetrations.

The final step of the plan is to assess the performance of shielding during plasma operation. This is described in Phase III below. The shielding shall be deemed to be adequate if, during plasma operations:

- The NSTX-U dose component at the site boundary is sufficiently small to accommodate a total dose of 10 mrem/yr.
- Access to regions indicated as requiring unrestricted access[3] in Table 2.3-1 of Ref [1] meets this requirement.

Note that a staged NSTX-U operations plan, with a gradual increase in plasma performance over a 2-3 year operations phase, provides time to do any residual remediation that may be identified as part of Phase II.

1.2: Outline

The outline of this Plan is as follows.

Section 2: Underlying Motivations and History - This section briefly describes the underlying motivations for the shielding upgrades, as well as some history relevant to understanding the present plans

Section 3: Phase 0 - Measurements During the FY-16 Run Campaign - This section summarizes measurements of radiation and dose in various relevant locations during the run campaign.

Section 4: Phase 1 Shielding Development - This Section summarizes the Phase I D-T Neutron Generator tests, the resulting decisions regarding penetrations to shield, and the methodology for determining shielding methods.

Section 5: Phase 2 Shielding Overview - This section describes the likely activities during the Phase 2 shielding activity.

Section 6: Phase 3 Testing When Operations Resumes - This Section briefly describes the testing that will be done when operations resume, as part of the lab's 10 CFR 835 RPP.

2: Underlying Motivations, Background, and History

The requirements for the NSTX-U test cell are provided in Ref. [1]. High level shielding requirements are given in Section 2.3 of that document, including site boundary requirements (<10 mrem/year from all sources) and desire for access to D-site locations in the vicinity of the test cell w/o dosimetry (<50 microrem/hr).

[3] Unrestricted access allowed for regions having a radiation field <50 μrem/hr.

The contents of this plan will be more meaningful if the history of the NSTX-U Test Cell (NTC) is understood. The test cell was originally constructed as a hot cell in support of the Tokamak Fusion Test Reactor (TFTR). It functioned as a test facility for TFTR neutral beams, and had a fully functional neutral beam system located in a sarcophagus structure within the room. In later years, it served as a facility for contaminated laundry and housed a neutral beam clean room and decontamination facility during TFTR D-T operations. Given these roles, it was designed with capabilities for gamma-shielding and was sealed for tritium containment. However, it was not intended as a true fusion device test cell, and therefore had numerous penetrations that allow neutrons to escape.

The NSTX device was built in that room between 1997 and 1999, see Fig. 2.1. This facility had the core NSTX device (in foreground of the figure), and utilized the neutral beam injector that had previously been installed in that room. That injector can be seen behind the American flag in Fig. 2.1; three individual ion sources are mounted to the far side of the beamline (and cannot be seen in this view). The three large orange cylinders are known as High Voltage Enclosures (HVEs), and contain neutral beam power supply components in an SF_6 atmosphere. The High Harmonic Fast Wave (HHFW) waveguides can be seen running along the east wall, then coming to the NSTX device itself.

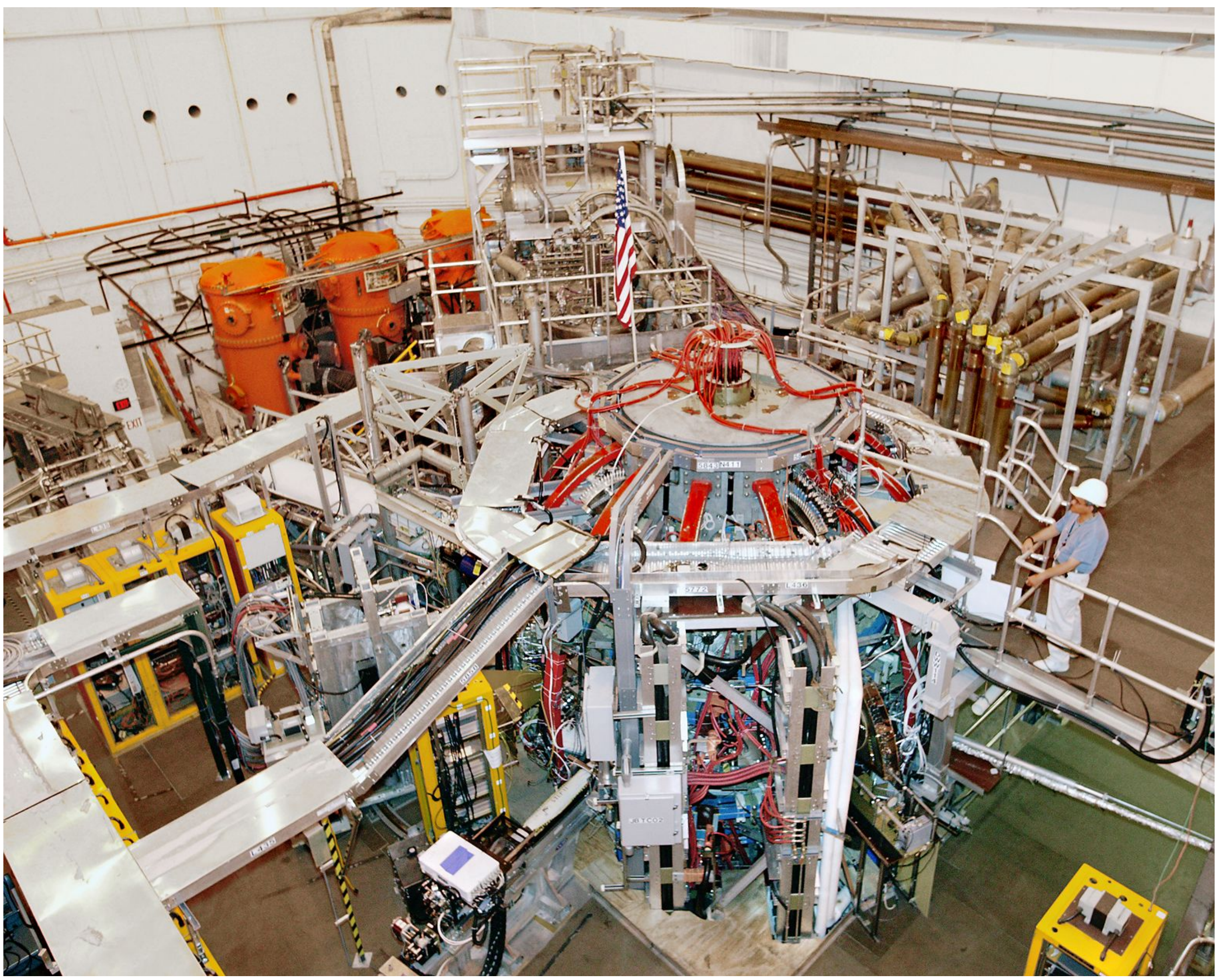


Figure 2-1: *View of the legacy NSTX device from inside the test cell, looking to the north east. This was the configuration of the test cell from 1999 through 2010.*

NSTX operated from 1999-2010, after which an upgrade was made to the facility; see Figure 2.2 for an image of the core NSTX-U device. The primary upgrade to the core of the device was a new magnet assembly. A second neutral beam injector was also installed, as indicated in Figures 2.3 and 2.4. Together, these upgrades allow significant upgrades to the device performance, including a substantial increase in the production of 2.45 MeV neutrons produced by D-D fusion reactions. The projected increase is described in Section 3.3.

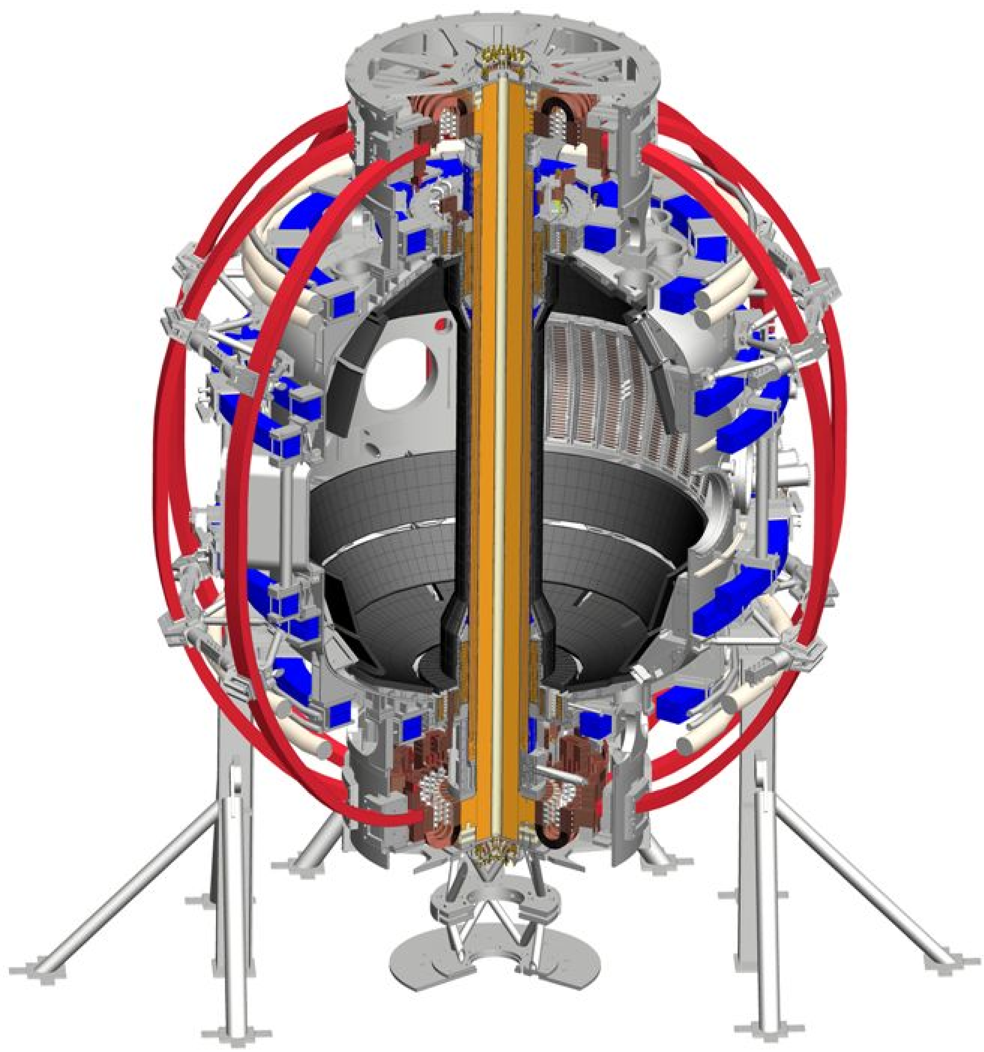


Figure 2-2: *View of the upgraded NSTX-U core device.*

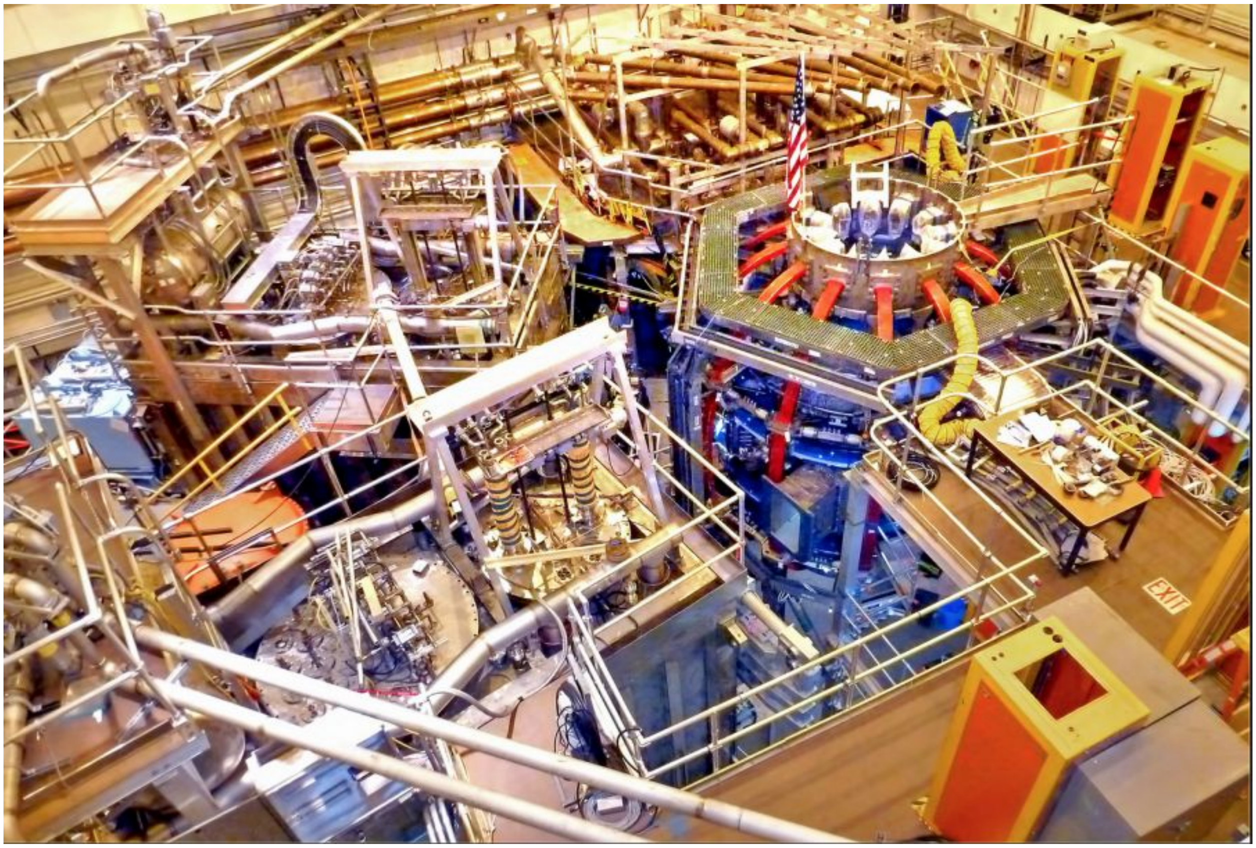


Figure 2-3*: View of NSTX-U from inside the test cell, looking to the south-east. The second neutral beam is in foreground left, while the legacy neutral beam is in the background on the left. The south high bay is visible in the upper right corner of the image. The three ion sources of legacy beamline are visible in the blue boxes on the rear of the beamline.*

The failure of a magnet caused the FY2016 run campaign, the first with the upgraded device, to end prematurely. Due to the premature end of the campaign, NSTX-U performance did not exceed the performance achieved in NSTX before the upgrades. A number of additional device deficiencies were identified during the Extent of Condition review that followed the magnet failure. The project to remedy these design deficiencies is known as the “NSTX-U Recovery Project”. The Recovery Project includes a component of shielding enhancement, as described in subsequent sections.

It is worth noting the other areas around the NSTX-U test cell. The test cell itself has the primary area containing NSTX-U, and a smaller area known as the South High Bay. These two areas are separate by a shield wall, with a large gap between the top of the shield wall and the ceiling allowing the crane to move items between the two areas; see Figures 2-5 through 2.7. The south, north and west walls of the test cell are 4’ thick standard concrete; the northeast and east walls are 3’ thick standard concrete.

Access to the test cell is via two doors: a door in the north wall and a door in the south high bay. The personnel door in the south high bay is shown in Figure 2-7. The south high bay also has two large mobile doors, one on the west wall providing access to the TFTR test cell, and one on the south wall providing access to the Neutral Beam Power Conversion Building. The TFTR test cell shield door is shown in Fig. 2.6, while the inside and outside of the NBPC shield door are shown Fig. 2-7 and 2-8.

The area underneath the test cell is the mechanical equipment room (MER). The MER has a mezzanine, which is primarily located underneath the south high bay.

The north and east sides of the test cell are bordered by hallways known as the north and east galleries (see Figure 3.2.1-1). The south side of the test cell shares a wall with the neutral beam power conversion building. The west wall of the test cell is shared with the TFTR test cell. The east gallery has a mezzanine containing components for the MPTS (multi point Thomson scattering) and MSE (motional Stark effect) diagnostics.

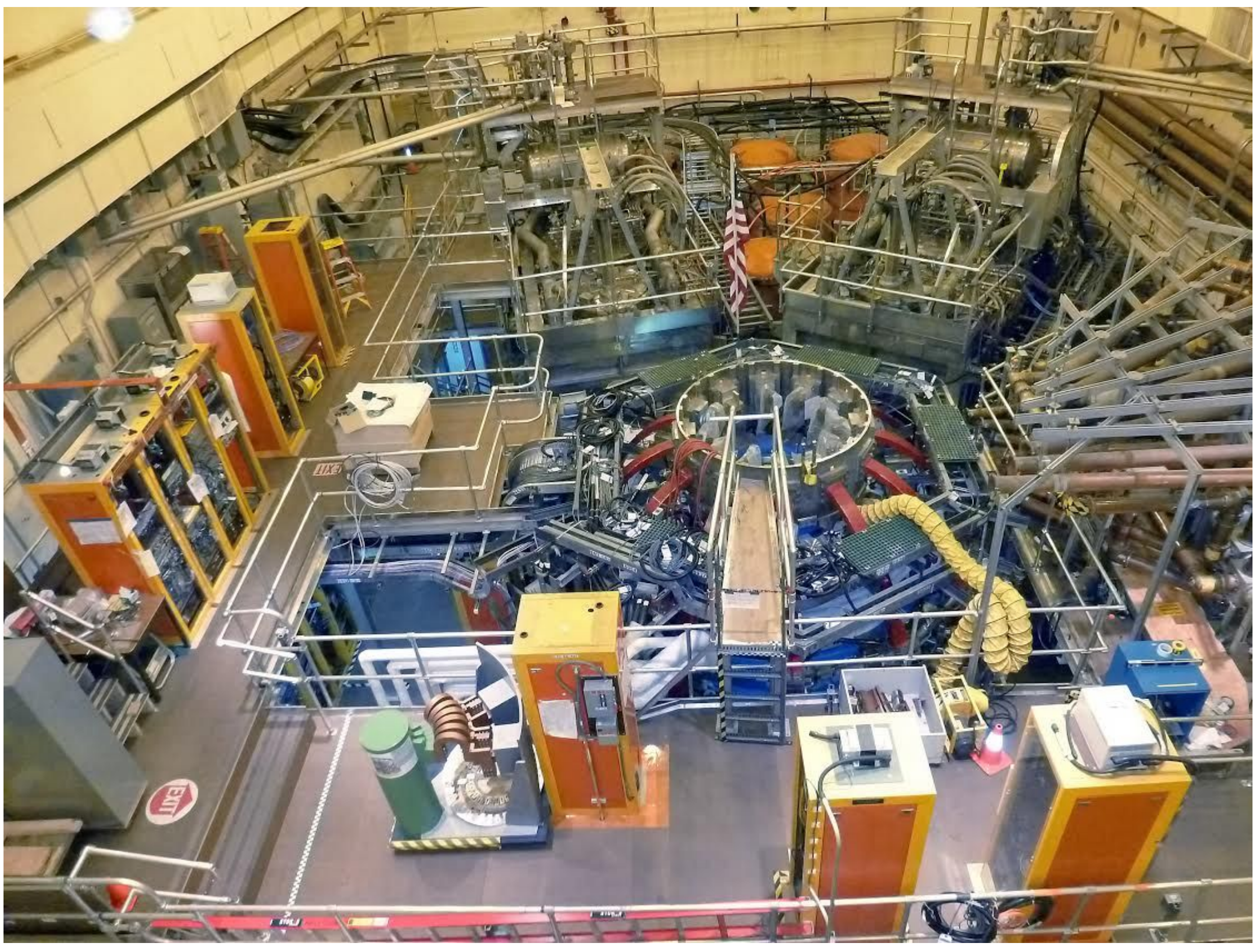


Figure 2-4*: View of NSTX-U from inside the test cell, looking to the north. The legacy neutral beam is the system in the background on the right, while the new neutral beam is in the background on the left.*

***Figure 2-5**: Views over the south shield wall from within the south high bay, viewing towards the north-east corner (right) and north-west corner (left).*

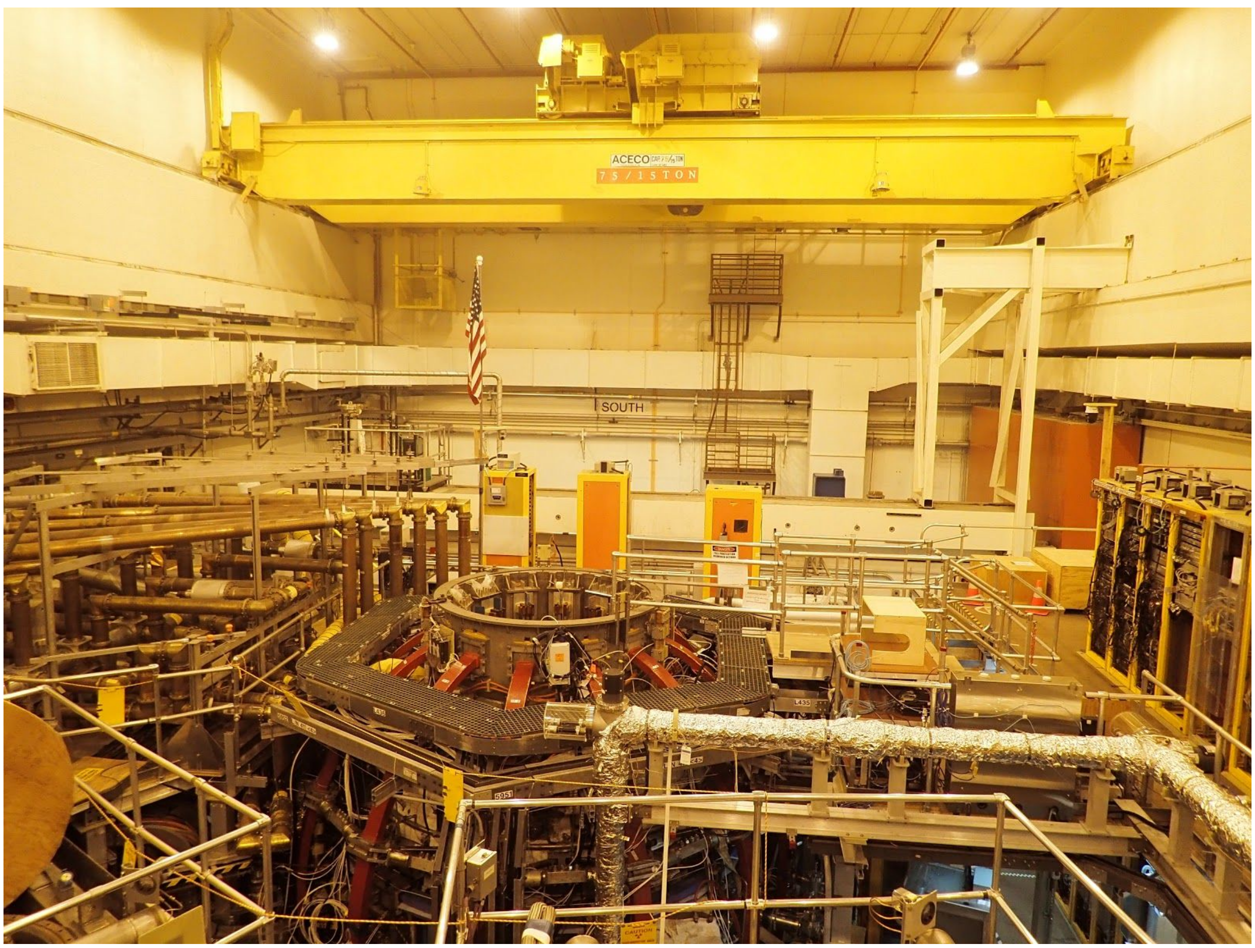


***Figure 2-6**: View to the south from NB #2, viewing the NSTX-U device and into the south high bay over the south shield wall. The large mobile door on the right in the south high bay provides access to the TFTR test cell.*

***Figure 2-7**: Photographs of NSTX-U South High Bay, looking toward the door to the east gallery. The neutral beam power conversion building mobile shield door is on the right of the figure. The NSTX-U device is on the left on the other side of the shield wall. The personnel door beneath the exit sign is a primary source of neutron leakage from the test cell.*

***Figure 2-8**: Photograph of the neutral beam power conversion mobile shield door, from the power conversion building. The south high bay is on the other side of the door.*

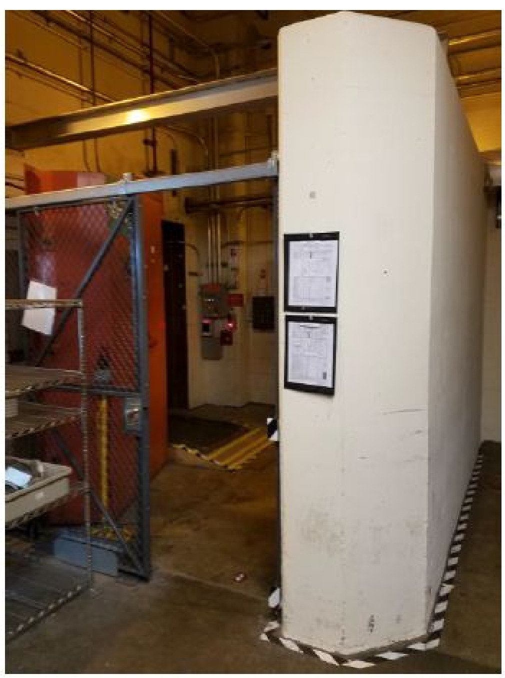


***Figure 2-9**: Photograph of NSTX-U North Door area with shield wall (right) built during the Upgrade Project.*

Some work on the shielding capabilities of the NTC were done as part of the Upgrade Project described above. There had previously been a small labyrinth at the north door inside the test cell; this labyrinth had to be removed in order to provide space for the installation of the 2nd neutral beam. Therefore, an additional concrete wall was constructed outside the north door (see Fig. 2-9). The shielding properties of this wall are discussed in Section 3.4.1.1.

There are a number of window in the test cell. The windows are of two varieties; vision windows have a 10" pane of leaded glass with a recessed cavity on both sides of the glass; see Fig. 2-10. Equipment windows are of the same size as the vision windows, and were originally intended for some style of manipulator arms within the hot cell, but now have a concrete plug. Some of these plugs are 12" in thickness, while others are 22" thick.

Figure 2-10*: Photograph of a typical vision window in the NTC wall. A piece of 10" thick leaded glass sits at the midpoint of the window.*

In addition to the windows, numerous circular penetrations, typically 10"-12" in diameter, exist in the north, east, and northeast walls. These are plugged in some cases with a concrete plug, or are used for cable, cryogen, fiber optic, and fluid feedthroughs into the test cell.

A set of six 9" diameter waveguides are used to bring 30 MHz RF power to NSTX-U. These waveguides pass through a set of six penetrations in the northeast corner of the test cell, as shown in the upper right of Fig. 2-4. The northeast wall is angled with respect to the north and east walls, such that the waveguides pass through in an oblique fashion relative to the wall. This is shown in Fig. 2-11 and Fig. 2-12.

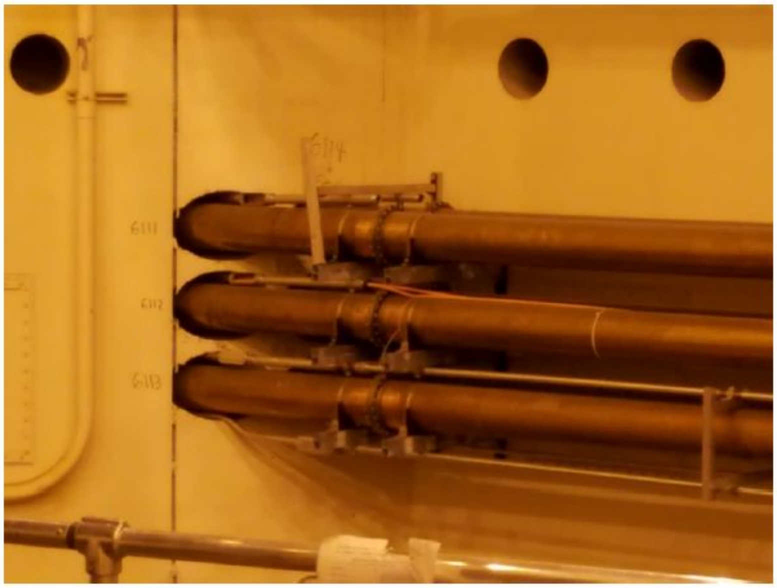


Figure 2-11: *Photograph of the HHFW transmission lines as they pass through the test cell in the northeast corner. View is from inside the test cell. Penetrations 1616-1618 are visible as circles, and the steel cover on window 6502 is visible on the lower left of the figure.*

Figure 2-12: *Photograph of the HHFW transmission lines from the gallery, as they pass from the test cell. The waveguides pass through the northeast wall of the test cell*

A final wall penetration of note is dedicated to the multi-pulse Thomson scattering diagnostic. This east wall penetration (6136) is enclosed in a polyethene dog house; the laser flight tube in Fig. 2-13 is mounted to the south high bay shield wall.

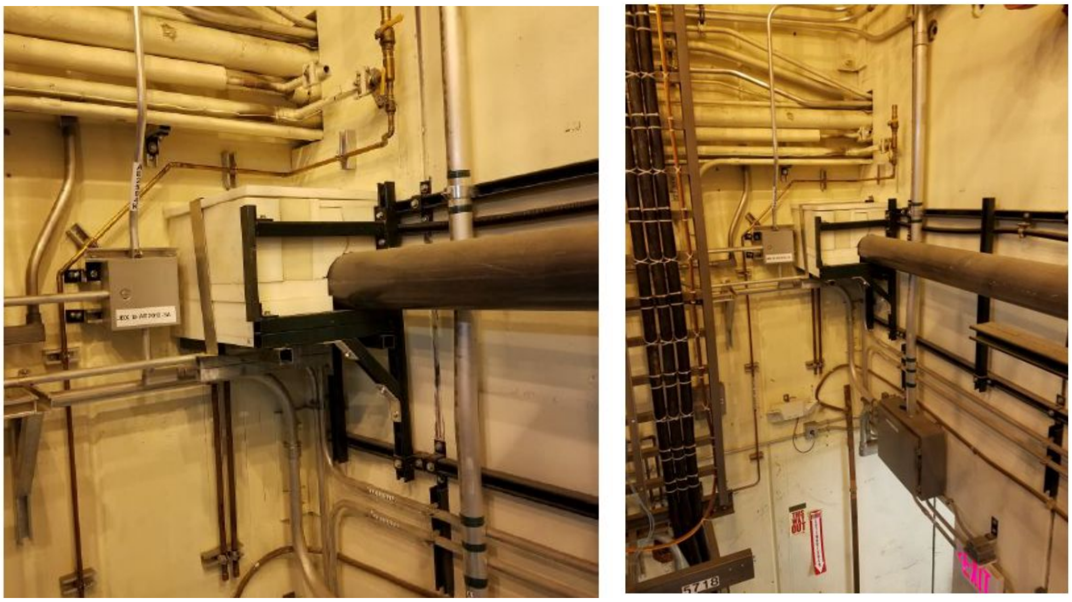


Figure 2-13: *View of penetration 6136 from the inside of the test cell, showing the laser flight tube passing along the south shield wall.*

Figure 2-14: *Photograph of the neutral beam water pipes as they pass through the penetration in the test cell floor. The left image is of penetration 515, while the right image is of penetration 506.*

In addition to those in the walls, there are a large number of penetrations in the NSTX-U test cell floor. Most of these penetrations are filled with concrete plugs. However, a small number of them allow services to pass from the Mechanical Equipment Room (MER) to the test cell. Two examples are shown in Fig. 2-14. These penetrations are packed with firestop, but do not have any dedicated neutronics shielding.

3: Phase 0 - Measurements During the FY-16 Run Campaign and Extrapolation to the Future

3.1: Measurement Motivations

The measurements described in this section were motivated by a number of goals. At a fundamental level, these measurements surveyed D-site radiological conditions during operations to ensure compliance with 10 CFR 835 posting requirements. Specific goals include:

- Test effectiveness of external north door shield wall, constructed during the Upgrade Project outage before the FY-15 plasma KPP operations and FY-16 run campaign.
- Survey radiological conditions during operations in the north and east gallery hallways and the MSE/MPTS mezzanine to determine if posting and dosimetry are required for general occupancy.
- Survey north and east site boundaries (boundary trailers) to monitor dose and maintain compliance with regulatory dose limits.
- Survey other areas around NSTX-U test cell for radiological exposure hazards (MER, north stairwell to tritium areas, NB shop area, NSTX-U high bay and Neutral Beam Power Conversion Building)
- Perform extensive grid measurements (with passive dosimetry) of the North and East gallery walls looking for areas where shielding is weak or non-existent.

3.2: Measurement Methods

Two groups of radiation detection instruments were used in this study. The first group are various systems deployed by the Health Physics group used to assess dose and exposure to employees and the public (Section 3.2.1). The second group are shot-synchronized fission chamber neutron detectors, primarily used for physics analysis (Section 3.2.2).

3.2.1: Detectors Operated by the Health Physics Group

The distribution of detector types in the vicinity of the NSTX-U test cell is shown in Figure 3.1-1. Three types of instruments are shown in the legend, as follows:

- The neutron integrating detectors were Helium-3 Proportional Counters deployed in the south high bay, the east and north galleries, inside the test cell at the north door, and in the stairwell to the tritium area.
- The Gamma/Neutron Dose Rate Detectors were Helium-3 proportional counter and pressurized ion chambers, connected to Ludlum Model 375 control units.
- The outer walls of the NSTX-U north and east gallery were lined with a 3x3x10 foot grid of albedo neutron dosimeters (Lithium Fluoride) and OSL (optically stimulated luminescence) dosimeters. These dosimeters integrated over the NSTX-U run. Note that these dosimeters require knowledge of the neutron spectrum to produce an actual dose.

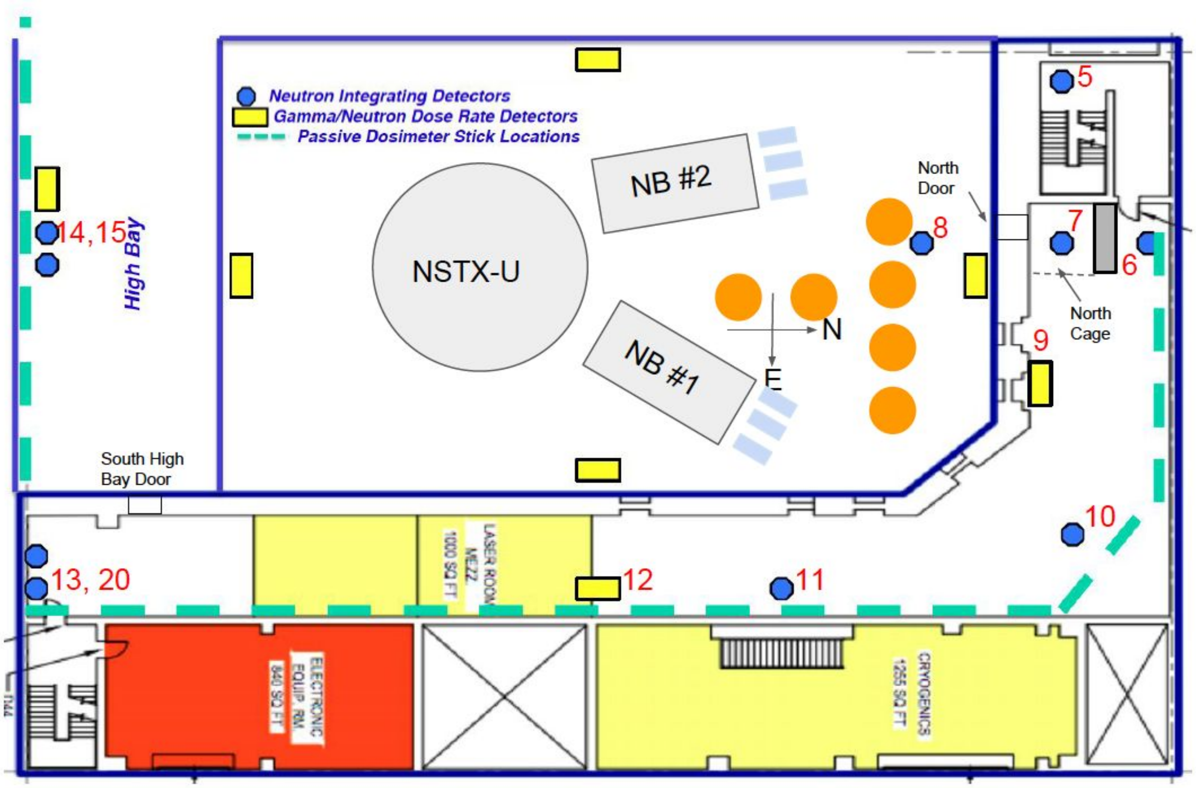


Figure 3.2.1-1*: Radiation detector locations during the FY-16 run campaign. The NSTX-U device, neutral beam, and high voltage enclosures are shown schematically for reference.*

Table 3.2.1-1*: Radiation detectors with information provided by Health Physics for this report.*

Index	Name	Comment
1	Boundary Trailer #2-Detector #1	Boundary Trailer on the northeast site boundary.
2	Boundary Trailer #2-Detector #1	Boundary Trailer on the northeast site boundary.
3	Boundary Trailer #3-Detector #2	Boundary Trailer on the southeast site boundary.
4	Boundary Trailer #3-Detector #1	Boundary Trailer on the southeast site boundary.
5	North Stairwell	See Figure 3.2.1-1
6	Outside North Shield Wall	See Figure 3.2.1-1
7	Inside North Cage	See Figure 3.2.1-1
8	Inside North Door	See Figure 3.2.1-1

9	Gallery North Wall	See Figure 3.2.1-1
10	Gallery North East Corner DATS	See Figure 3.2.1-1
11	Gallery East DATS	See Figure 3.2.1-1
12	Gallery East Wall	See Figure 3.2.1-1
13	Gallery South East Corner	See Figure 3.2.1-1
14	NSTX-U South High Bay	See Figure 3.2.1-1
15	NSTX-U South High Bay Backup	See Figure 3.2.1-1
16	Neutral Beam Shop	In the neutral beam shop, directly south of the NSTX-U south high bay
17	Mechanical Equipment Room (MER) Mezzanine	The MER mezzanine is located directly beneath the south high bay and extends north to be directly under the south side of the test cell
18	Neutral Beam Control Room	The neutral beam control room is located at 138' elevation, directly above the neutral beam power conversion building
19	Top of North Stairwell	At the top of the north stairwell.
20	Gallery South East Corner Backup	---
21	MER Mezzanine Back Up	---

3.2.2: Calibrated Neutron Detectors Operated by the Physics Group

The primary neutron diagnostics for physics research on NSTX-U are a set of three fission chambers and the associated signal measurement electronics [2]. Four fission chambers with different sensitivities are required for reliable measurements over the full range of neutron rates expected for NSTX-U. This is due to the fact that a given fission chamber has a limited dynamic range. The fission chambers are surrounded by polyethylene neutron moderators. The output of the signal detection electronics is digitized at 1 kHz by standard CAMAC digitizers and the data are acquired after each shot and archived in the MDS Plus tree. The time resolution of the measurement is 2-5 ms, determined by signal averaging and smoothing time constants of the signal processing electronics. Signal processing software is triggered to run automatically after the data are acquired and calibrated neutron rates are written to the database of physics data. The overall neutron rate range that can be measured by the four fission chambers is zero to 1.08 X 10^{16} neutrons/s. This is sufficient to cover the highest neutron yields expected for NSTX-U. Processing software is run after each shot to calculate the total number of neutrons produced by the shot and a running total of neutrons produced is logged.

Calibration of the fission chambers is done by placing a Cf-252 source of known activity inside the NSTX-U vacuum vessel during an outage and acquiring fission chamber signals with the source at a variety of locations that simulate the core neutron-producing region of the plasma.

3.3: Projection to Future Neutron Emission

As part of the projections in Section 3.4.1, it is necessary to assess the future neutron prediction of NSTX-U. Two representative numbers are provided for this assessment.

For the site boundary, the annual neutron production determines the NSTX-U contribution to the site boundary. A representative limit for the total annual neutron generation is 4×10^{18} N, as documented in the NSTX-U SAD R6 [3].

For the dose local to areas outside the NTC, the "maximum typical" dose per shot or per day are more relevant. Here, "maximum typical" refers to parameters that are near the upper bound of performance, but do not make extreme assumptions on plasma confinement or device performance; any neutrons generated by neutral beam conditioning are not included in this estimate. In order to estimate this performance level, Figure 3.3-1 and 3.3-2 are extracted from Ref. [4]. The figures show the typical neutron emission as a function of plasma current, for six and five projected scenarios respectively. Each polygon represents a single scenario, with two assumptions on the plasma thermal confinement level, and two assumptions on the shape of the plasma profiles. See Ref. 4 for additional details. Note that the small black dots are measured neutron emission rates from historical NSTX operations, illustrating that the neutron emission rate on NSTX-U will increase by an order of magnitude when full parameters are achieved.

In Figure 3.3-1, the scenarios chosen are designed to achieve the highest plasma current for the given heating power and toroidal field level consistent with a fully evolved minimum safety factor >1.

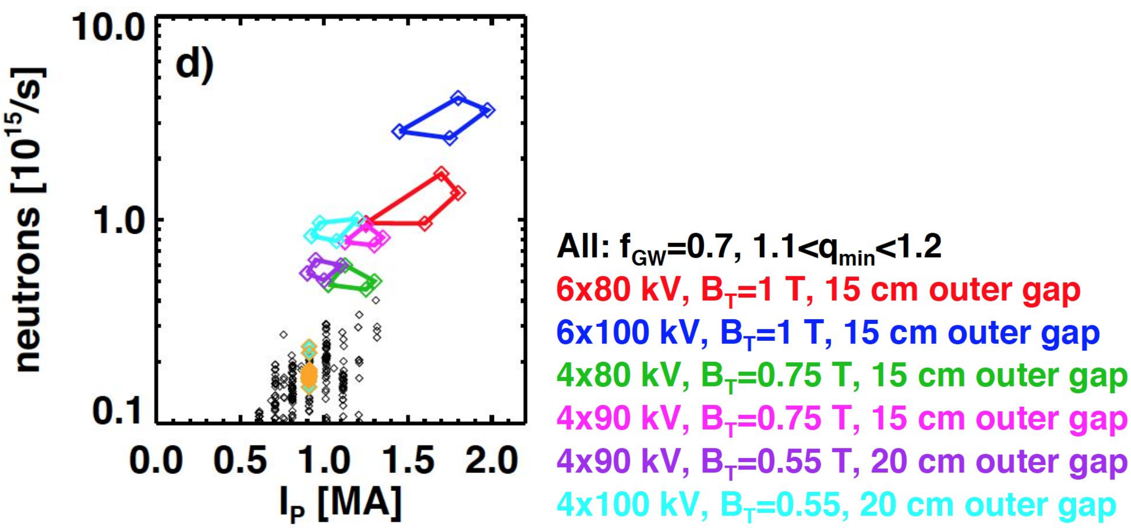


Figure 3.3-1: *Example neutron production as a function of plasma current (I_P), as computed by TRANSP for various scenarios. This image is extracted from Fig. 34 of Ref. [4]. See text for additional discussion.*

Similar calculations are shown in Fig. 3.3-2, for various other scenarios optimized to very low collisionality or very long pulse. See Ref. 4 for additional details.

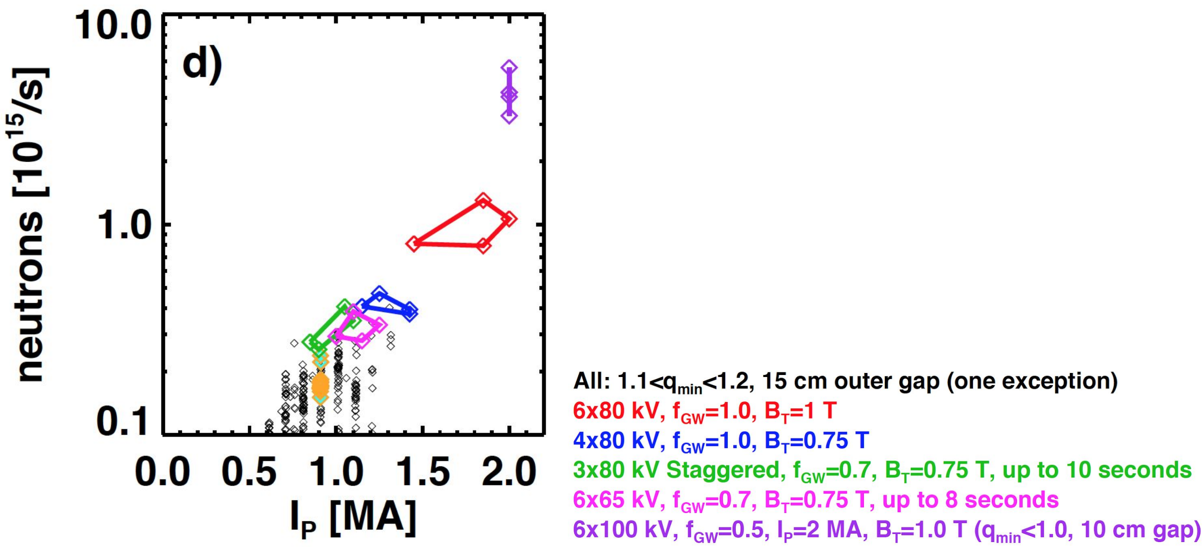


Figure 3.3-2*:Example neutron production as a function of plasma current (I_P), as computed by TRANSP for various scenarios. This image is extracted from Fig. 36 of Ref. [4]. See text for additional discussion.*

The calculations are summarized in Table 3.3-1, where the neutron emission from various scenarios is computed. The assumptions on the number of discharges per day are shown in Table 3.3-2.

Table 3.3-1*: Neutron production rates and levels for various projected NSTX-U future scenarios*

Figure	Color in Figure	Neutron Emission	Duration[4]	Neutrons/Discharge	Neutrons/day
		[N/s]	[s]	[N]	[N]
3.2-1	Blue	$3x10^{15}$	1.5	4.50E+15	1.22E+17
3.2-1	Red	$1.5x10^{15}$	5	7.50E+15	2.03E+17
3.2-2	Purple	$5x10^{15}$	1.5	7.50E+15	2.03E+17
3.2-2	Red	$1x10^{15}$	5	5.00E+15	1.35E+17
3.2-2	Blue	$4x10^{14}$	5	2.00E+15	5.40E+16

Table 3.3-2*: Parameters used in determining the number of discharges per day.*

Hrs/Day	9
Shots/Hr	3
Shots/Day	27

[4] The maximum discharge duration is determined by the neutral beam voltage, due to thermal limits on the ion dumps.

From this table, it appears that the largest emission from a single discharge would be approximately $7.5x10^{15}$, with the maximum emission in a single day equal to $2x10^{17}$. Note that the achievement of 27 discharges in a day would require both a significant upgrade to the power cabling for the toroidal field coil[5], and the development of robust and reliable plasma scenarios with high performance at high current; both of these are likely to occur only after a few years of sustained operations, if at all. Hence, it is conservative to use these numbers in projecting future dose. Note that NSTX-U made up to $0.8x10^{15}$ neutrons in a single day during the 2016 run campaign; the projected best day has 250 times larger neutron generation than this level.

Note that the energy of these neutrons produced by D-D fusion reactions is 2.45 MeV. This energy is determined by nuclear physics and is not dependent on any features or parameters of NSTX-U operations.

3.4: Results and Extrapolations of Dose

This section describes the results of measurements at specific locations during the 2016 campaign (Section 3.4.1), and then uses those results to extrapolate the dose to future operations *under the assumption that nothing is done to remediate the situation* (Section 3.4.2). Note again that the neutron generation during the 2016 campaign was much less than the ultimate performance capability of the device.

3.4.1: Dose Rate and Integrating Detector Results

3.4.1.1: Dose Rates vs. Date

This section describes the dose rate as a function of day, for various of the detectors indicated in Figs. 3.2.1-1. and Table 3.2.1-1.

The first result, shown in Fig. 3.4.1.1-1 shows the dose at the north end of the test cell at three locations, for the duration of the run. The green points are for location #8, within the test cell, and show rather large single day doses of up to 60 mrem in a single day.

The other traces are from locations outside the test cell, at locations on the left and right of the shield wall in Fig. 2-9. Note that the cage door in that image is closed during operations, such that no individual could stand in location #7. This dose is significantly attenuated by the time it reaches location #6, outside the north shield wall. However, daily doses on order ot 100 μrem were observed at this location. Extrapolation of those doses for future operations will be made in the next section.

[5] The present toroidal field cabling is sufficient to support a 40 minute shot cycle at full field.

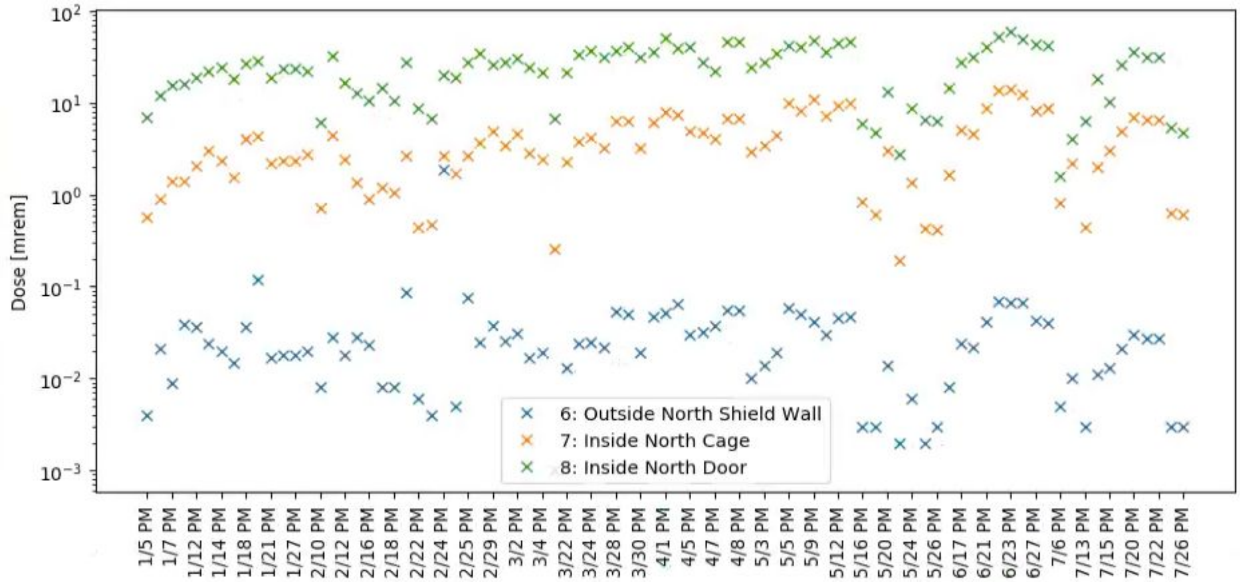


Figure 3.4.1.1-1*: Integrated dose measurements as a function of date in the vicinity of the NSTX-U North door*

Figure 3.4.1.1-2 shows the evolution of the daily dose for locations in and near the south high bay. Neutrons emitted by the NSTX-U plasma can enter the south high bay over the shield wall on the left side of Fig. 2-7, then exit the door in the center of the image, leading to dose in the gallery.

As per Figure 3.4.1.1-2, the daily dose at location 14, within the high bay, can be large, approaching 30 mrem within the high bay. The daily doses outside the high bay, in the south and south east portions of the gallery, are reduced. However, they can still approach 1 mrem for a day.

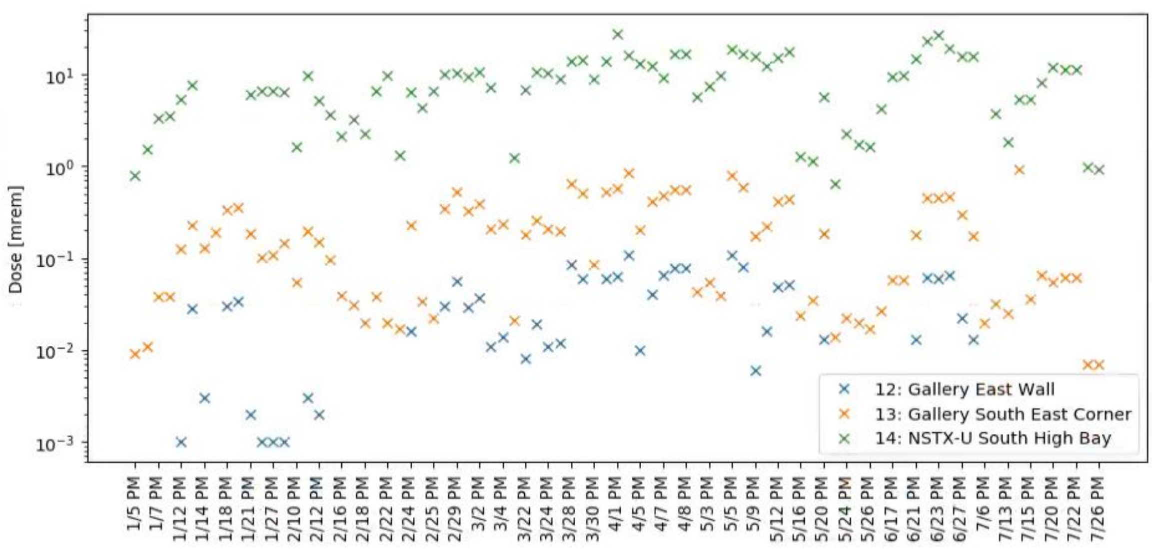


Figure 3.4.1.1-2*: Integrated dose measurements as a function of date in the vicinity of the NSTX-U South High Bay.*

3.4.1.2: Extrapolations of Dose

By combining the daily integrated dose at the various locations with the daily neutron production, it is possible to extrapolate the present dose to what may be the dose at full machine parameters, *if no shielding changes are made*. Examples of this calculation are shown in Figures 3.4.1.2-1 through 3.4.1.2-4. In each case, the measured dose per day, inferred from the health physics detectors, is plotted against the neutrons per day, as measured by the physics fission chambers. A linear fit to the data is provided. This fit is used to extrapolate the maximum dose for a full campaign at this location, based on a total neutron emission of 4×10^{18} N. The fit is also used to extrapolate to the largest daily dose possible at that location, based on a maximum daily neutron generation of 2×10^{17} N.

There is a significant complication to the analysis in these plots. Neutrons can be produced by two types of operational scenarios in NSTX-U. The first is neutral beam heating of plasmas during a plasma pulse, as discussed in Section 3.3. The neutrons generated in this case are measured by the fission chamber detectors. However, neutrons are also generated by neutral beam conditioning. In this mode of operations, the neutral beams are injected into copper calorimeters. The deuterium atoms of the neutral beams undergo fusion reactions with deuterium embedded in the calorimeter surface, creating neutrons of the same energy as those created during plasma operations. However, the fission chamber detectors do not detect these neutrons, as these conditioning pulses are not synchronized to the standard data acquisition clock cycle. Therefore, there can be dose detected by the HP detectors, which is due to neutrons not recorded by the fission chambers.

Other factors can complicate this effect. The conditioning shots, while producing a small dose, occur every 2.5 minutes during operations, whereas plasma shots are separated by 15-20 minutes. Furthermore, anywhere between 1 and 6 ion sources may be conditioned at any one time. These two modes of operations, and the associated detectors behavior, are shown in Table 3.4.1.2-1.

***Table 3.4.1.2-1**: Summary of distinctions between the various detectors used in extrapolating dose. Note that the physics fission chambers do not measure neutrons from beam conditioning.*

		Physics Fission Chambers	**HP Integrating Detectors**
		Located in the test cell near NSTX-U, digitize only during the plasma pulse, absolutely calibrated in N/s emitted from plasma	Located inside and outside test cell, continuous or integrated monitoring
Neutral Beam Conditioning	2.45 MeV neutrons, primarily from beam-target fusion with embedded D in the calorimeters		X
Plasma Operations	2.45 MeV Neutrons, primarily from D-D fusion between injected fast ions	X	X

	and the background plasma		

For these reasons, the dose extrapolations are done using the lower bound of the set of points. Note that future plasma operations will have many more neutrons (see Section 3.3), so that the conditioning neutrons will be a much smaller contribution to the total.

Figure 3.4.1.2-1 shows the dose in the north stairwell plotted against the neutron generation; note that this location is on the same side of the test cell as the neutral beams. There is considerable scatter in the data, due to the fact that neutron measurements in the conditioning discharges are not made with the fission chambers (as described above).

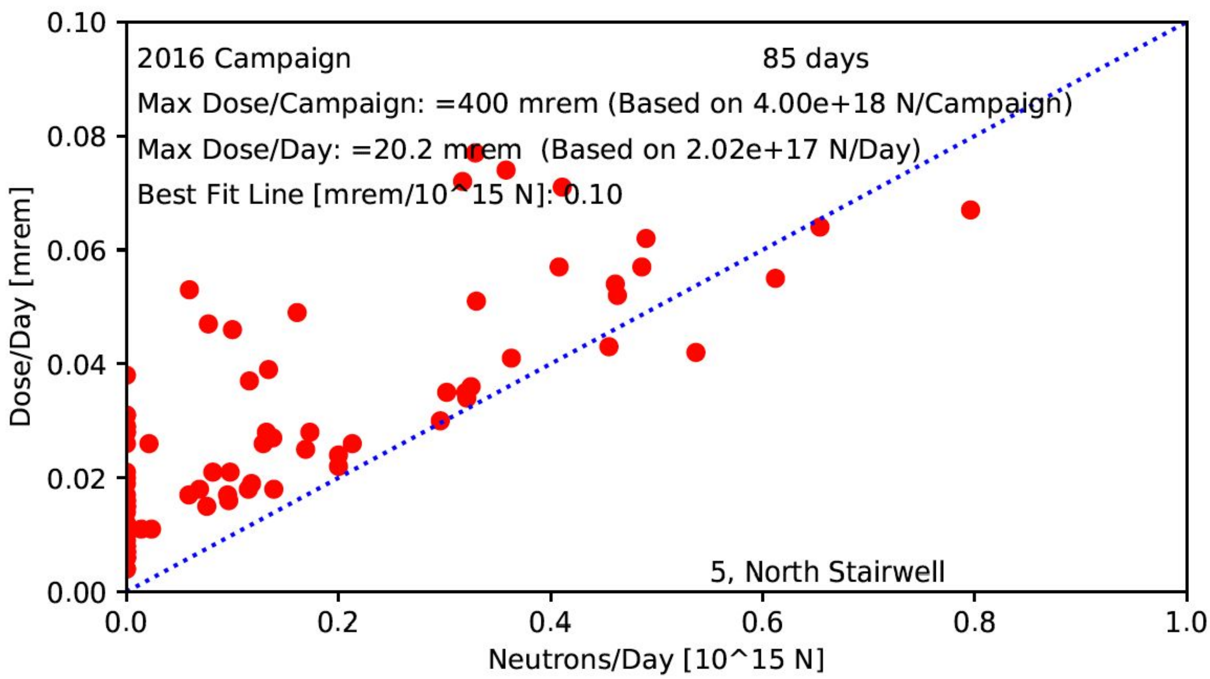


Figure 3.4.1.2-1*: Daily dose measured in the north stairwell, as a function of the total measured neutrons for that day.*

In contrast, Figures 3.4.1.2-2 and 3.4.1.2-3 show locations that are better shielded from the neutral beams and any neutrons generated at the calorimeters and ion dumps. At these locations, the daily dose correlates quite well with the daily neutron generation.

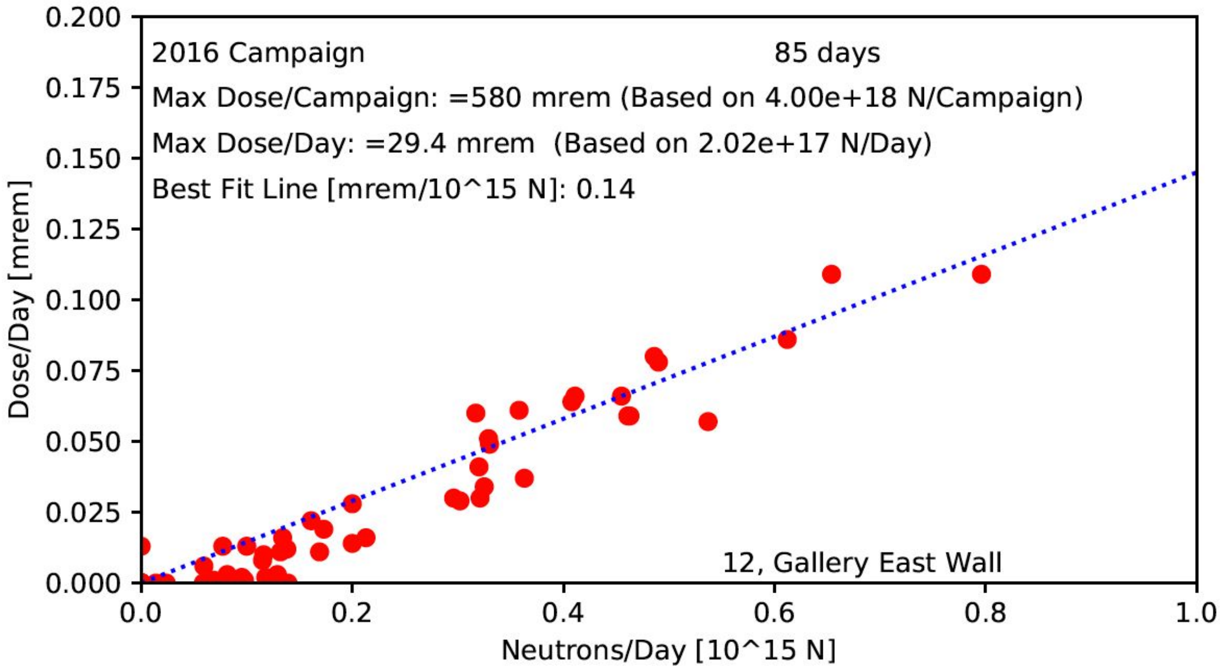


Figure 3.4.1.2-2*: Daily dose measured at the gallery east wall, as a function of the total measured neutrons for that day.*

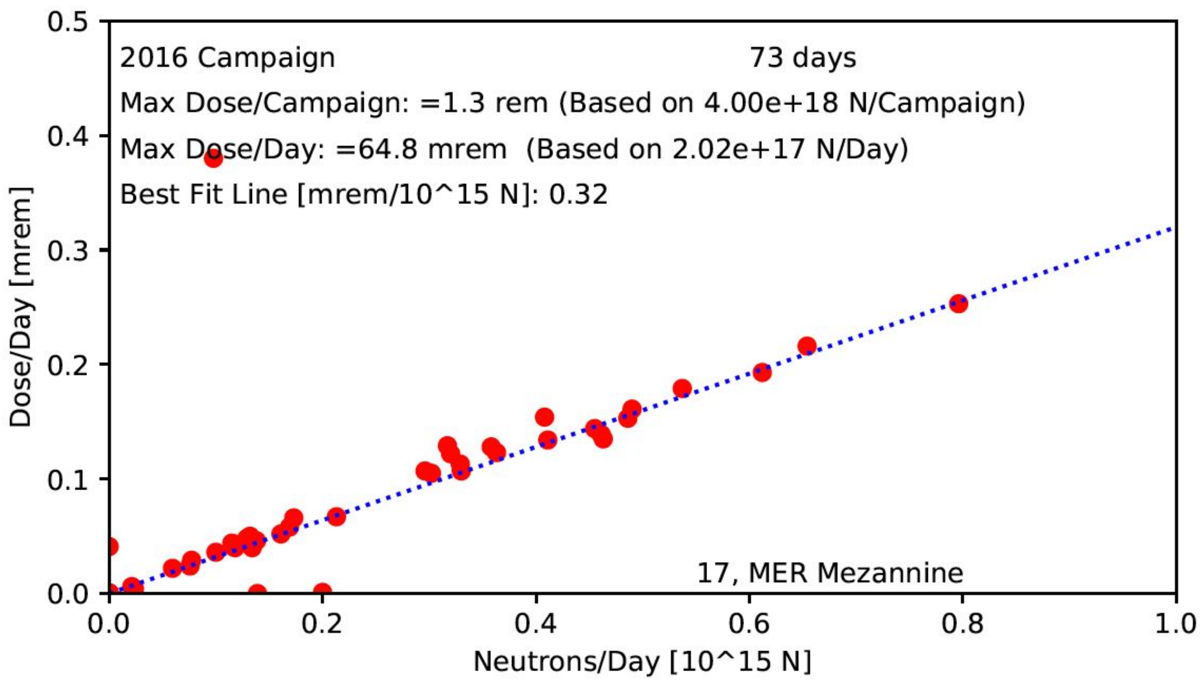


Figure 3.4.1.2-3*: Daily dose measured in the mechanical equipment room mezzanine, as a function of the total measured neutrons for that day.*

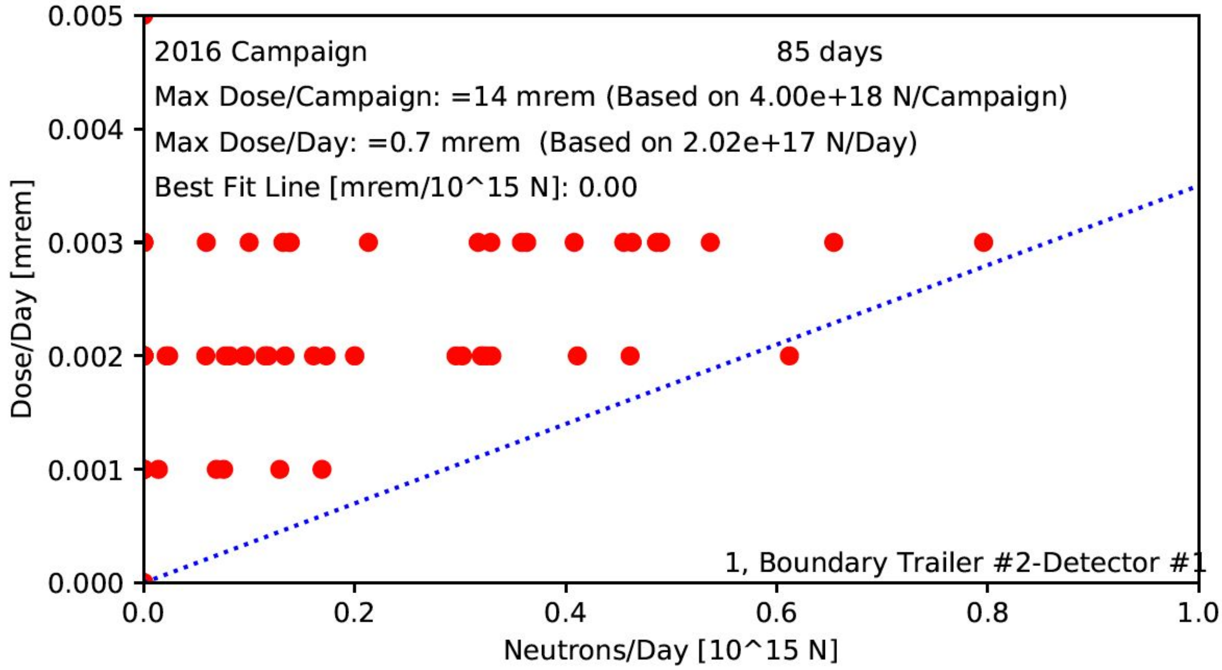


Figure 3.4.1.2-4: *Daily dose measured at boundary trailer #2, detector #1, as a function of the total measured neutrons for that day.*

Of particular note in the four example extrapolation figures is Figure 3.4.1.2-4, where the data from one of the boundary trailers is shown. While the data is sparse and the extrapolation clearly has significant error bars, it is clear that there is a risk of exceeding the annual site boundary limit of 10 mrem with the shielding present in the FY-16 run if the annual limit in the previous SAD is achieved ($4x10^{18}$ N). Note that the first year run of NSTX-U produced only ~$1x10^{16}$ N, or a factor of 400 less than the $4x10^{18}$ N limit noted above.

The full set of extrapolations is shown in Table 3.4.1.2-2. Locations on the site boundary have the projected future campaign dose displayed in the first four rows, since it is the annual dose that is relevant. All four detectors indicate that the site boundary limit of 10 mrem/year may be exceeded in a future campaign if upgrades to the shielding are not made.

Locations within the building have the projected maximum daily dose displayed in the following rows, as this would be the dose accrued by a worker if they stayed at that location for a full day. Note that there are no limits for the day or campaign provided for the locations in the south high bay and inside the test cell, as it is fully anticipated that individuals will not be allowed in these locations during operations. Also, there are fewer rows in Table 3.4.1.2-2 than in Table 3.2.1-1, because some measurement locations have insufficient data collected to make the extrapolation appropriately.

Table 3.4.1.2-2: *Extrapolation of the measurements taken in FY-16 to the maximum future campaign and daily dose.*

		Max Future Dose/Day	Max Future Campaign Dose	Limit for a Day[6]	Limit for a Campaign[7]
		mrem/day	mrem	mrem	mrem
1	Boundary Trailer #2-Detector #1	-	14	-	10
2	Boundary Trailer #2-Detector #1	-	12	-	10
3	Boundary Trailer #3-Detector #2	-	12	-	10
4	Boundary Trailer #3-Detector #1	-	20	-	10
5	North Stairwell	20	-	0.4	-
6	Outside North Shield Wall	20	-	0.4	-
7	Inside North Cage	2025	-	-	-
8	Inside North Door	12150	-	-	-
9	Gallery North Wall	30	-	0.4	-
10	Gallery North East Corner DATS	20	-	0.4	-
11	Gallery East DATS	10	-	0.4	-
12	Gallery East Wall	29	-	0.4	-
13	Gallery South East Corner	213	-	0.4	-
14	NSTX-U South High Bay	4455	-	-	-
15	NSTX-U South High Bay Backup	6075	-	-	-
17	Mechanical Equipment Room (MER) Mezzanine	65	-	0.4	-
19	Top of North Stairs	7	-	0.4	-
20	Gallery South East Corner Backup	162	-	0.4	-
21	MER Mezzanine Back Up	81	-	0.4	-

Many locations throughout the building show levels for a day significantly beyond the limit that requires posting and dosimetry. This is most clear for the locations near the south end of the east gallery, but also holds for other locations in the gallery, as well as the MER mezzanine. Neutrons can escape the test cell to the gallery through numerous doors and penetrations in the test cell wall. Neutrons can enter the MER mezzanine through multiple penetrations in the test cell floor. These penetrations are discussed in greater detail in Section 4, as will shielding steps to dramatically reduce the dose.

3.4.2: Passive Dosimeter Results

As indicated schematically in Fig. 3.1-1, dosimeters mounted on sticks were placed along the walls of the north and east gallery, as well as along the wall of the south high-bay. These dosimeters were then read out at the end of the run, providing a measure of the integrated radiation level at various locations along the gallery walls. These complemented the electronic measurements described in Section 3.4.1, by providing high spatial resolution measurements.

[6] 0.4 mrem comes from extrapolating the 0.05 mrem/hr requirement for posting/dosimetry to an 8 hour day

[7] It is assumed here that NSTX-U runs annual campaigns. Note that the 10 mrem/year design objective includes all sources of radiation at PPPL, and therefore the NSTX-U contribution must be somewhat less than 10 mrem/year.

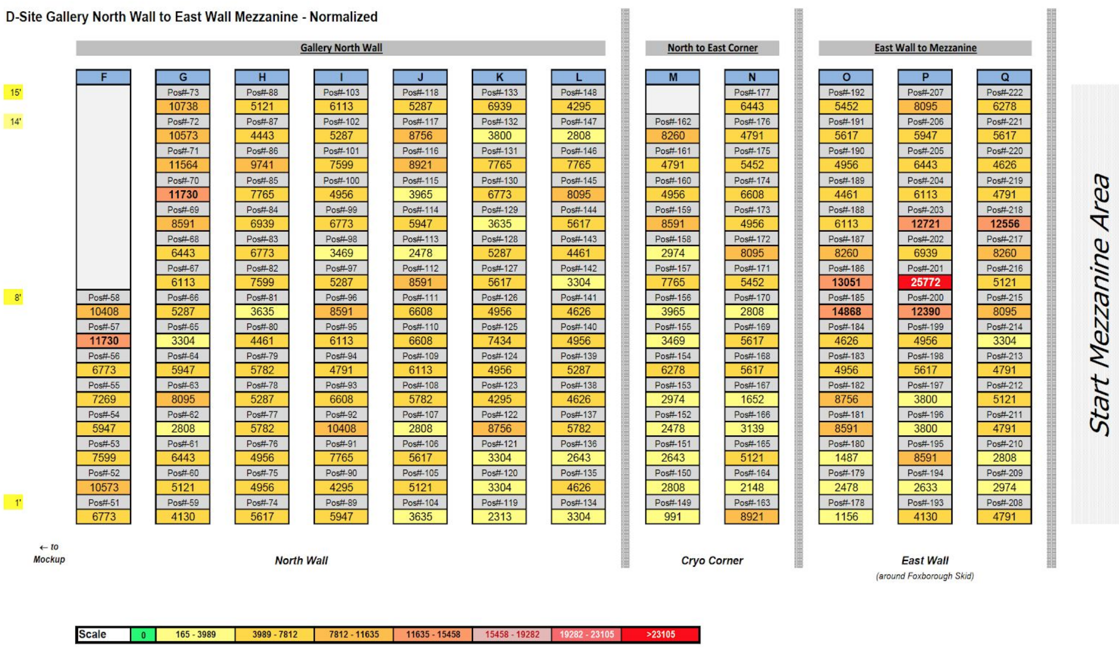


Figure 3.4.2-1: *Passive dosimetry results for locations along the north and northeast wall.*

As noted in Section 3.2.1, these dosimeters cannot be calibrated for dose unless the spectrum of neutron energies is known. However, the numbers in the figures are meaningingful, in that the output of the TLDs in the various regions can be compared. In particular, the values in these figures have been normalized to the total neutron emission from the device in FY2016, so that these measurements can be directly compared to future runs. Therefore, in Figures 3.4.2-1 through 3.4.2-3, the numbers themselves can be compared, but note that the color scale is reset for each plot.

Figure 3.4.2-1 shows the integrated signal level along the north wall, the north east corner, and the north side of the east wall. A specific hotspot is observed along the east wall. This may be due to HHFW penetrations (6111-6116) in the north-east corner of the test cell, or the large windows in the north and east walls (6502-6505). These penetrations and windows will be discussed in more detail in Section 4.

Figure 3.4.2-2 shows the normalized signal level along the remaining section of the east wall. The most significant feature is the significant increase in integrated signal on the south side of the east wall, directly across from the the door into the south high bay. This strongly incriminates that door as a major source of neutrons in the gallery

D-Site Gallery East Wall (Under Mezzanine to South Corner) and Laser Lab - Normalized

Laser Lab

	RL		SL	TL	UL	VL	WL	XL	YL	ZL	AAL	ABL	ACL	SE	SW
7.5'	Pos#-327	7.5'	Pos#-334	Pos#-341	Pos#-348	Pos#-355	Pos#-362	Pos#-369	Pos#-376	Pos#-383	Pos#-390	Pos#-397	Pos#-404	Pos#-408	Pos#-412
	1278		1789	0	767	1533	5111	5622	3322	0	1278	4600	8688	767	6388
	Pos#-326		Pos#-333	Pos#-340	Pos#-347	Pos#-354	Pos#-361	Pos#-368	Pos#-375	Pos#-382	Pos#-389	Pos#-396	Pos#-403	Pos#-407	Pos#-411
	1789		2044	2811	256	1533	3577	4089	4600	767	3322	3833	11755	4089	6644
	Pos#-325		Pos#-332	Pos#-339	Pos#-346	Pos#-353	Pos#-360	Pos#-367	Pos#-374	Pos#-381	Pos#-388	Pos#-395	Pos#-402	Pos#-406	Pos#-410
	4600		2811	3066	3066	2300	5366	2555	1278	5366	1278	6388	5111	7922	1278
	Pos#-324	4.5'	Pos#-331	Pos#-338	Pos#-345	Pos#-352	Pos#-359	Pos#-366	Pos#-373	Pos#-380	Pos#-387	Pos#-394	Pos#-401	Pos#-405	Pos#-409
	2300		1278	3577	4855	2811	2555	0	5877	1789	3322	9455	6899	5111	4089
	Pos#-323	3.5'	Pos#-330	Pos#-337	Pos#-344	Pos#-351	Pos#-358	Pos#-365	Pos#-372	Pos#-379	Pos#-386	Pos#-393	Pos#-400	South Wall	
	6899		1533	4600	4089	256	5877	511	6388	2300	5622	4089	10988		
	Pos#-322		Pos#-329	Pos#-336	Pos#-343	Pos#-350	Pos#-357	Pos#-364	Pos#-371	Pos#-378	Pos#-385	Pos#-392	Pos#-399		
	2300		3322	5111	2811	2300	5622	2300	2811	1789	3066	10733	9966		
1.5'	Pos#-321	1.5'	Pos#-328	Pos#-335	Pos#-342	Pos#-349	Pos#-356	Pos#-363	Pos#-370	Pos#-377	Pos#-384	Pos#-391	Pos#-398		
	4089		6644	2300	1789	1278	0	0	4344	1789	4344	6644	5877		
				MSE - LIF					MPTS - Poly			MPTS - Laser Room			

Gallery East Wall

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
7'	Pos#-229	Pos#-236	Pos#-243	Pos#-250	Pos#-257	Pos#-264	Pos#-271	Pos#-278	Pos#-285	Pos#-292	Pos#-299	Pos#-306	Pos#-313	Pos#-320
	3139	3635	3304	3304	3469	2478	4295	6939	4130	10408	19164	22303	11730	11895
	Pos#-228	Pos#-235	Pos#-242	Pos#-249	Pos#-256	Pos#-263	Pos#-270	Pos#-277	Pos#-284	Pos#-291	Pos#-298	Pos#-305	Pos#-312	Pos#-319
	1156	3965	4791	2478	4461	4461	6443	6443	5947	6443	22963	26928	9417	16355
	Pos#-227	Pos#-234	Pos#-241	Pos#-248	Pos#-255	Pos#-262	Pos#-269	Pos#-276	Pos#-283	Pos#-290	Pos#-297	Pos#-304	Pos#-311	Pos#-318
	3304	2478	4130	4626	2974	7104	5121	3139	7930	8095	21311	23129	15364	15529
	Pos#-226	Pos#-233	Pos#-240	Pos#-247	Pos#-254	Pos#-261	Pos#-268	Pos#-275	Pos#-282	Pos#-289	Pos#-296	Pos#-303	Pos#-310	Pos#-317
	3965	3800	4791	5287	2313	3469	1156	3139	3965	10573	20320	20816	9747	10408
	Pos#-225	Pos#-232	Pos#-239	Pos#-246	Pos#-253	Pos#-260	Pos#-267	Pos#-274	Pos#-281	Pos#-288	Pos#-295	Pos#-302	Pos#-309	Pos#-316
	2313	3965	1322	3139	6773	3139	7599	5452	3965	6608	23294	25607	6608	17821
	Pos#-224	Pos#-231	Pos#-238	Pos#-245	Pos#-252	Pos#-259	Pos#-266	Pos#-273	Pos#-280	Pos#-287	Pos#-294	Pos#-301	Pos#-308	Pos#-315
	4956	3965	2643	3139	4626	165	2974	4461	3965	13216	22303	22963	10078	14703
1'	Pos#-223	Pos#-230	Pos#-237	Pos#-244	Pos#-251	Pos#-258	Pos#-265	Pos#-272	Pos#-279	Pos#-286	Pos#-293	Pos#-300	Pos#-307	Pos#-314
	4461	4130	3139	3139	2643	3965	4461	3800	4626	9417	18503	19825	10243	10243
					Eye Wash			Door				Darm Door		

South Wall

to Neutral Beams →

Scale	0	165 - 3989	3989 - 7812	7812 - 11635	11635 - 15458	15458 - 19282	19282 - 23105	>23105

Figure 3.4.2-2*: Passive dosimetry results for locations along the east wall.*

Figure 3.4.2-3 shows the integrated signal along the west portion of the south wall in the south high bay; these measurements extend along the south wall from the west wall to the neutral beam power conversion door. These signals are the highest observed anywhere, as may be expected given that neutrons from the NSTX-U device and the neutral beam calorimeters reach that location after only a small number of bounces. Note that the large mobile door to the neutral beam power conversion building is immediately to the left of the dosimeters in this image, and therefore that door is exposed to significant neutron flux.

D-Site South High Bay - Normalized for Neutron

South High Bay Wall

	mrem	E	D	C	B	A
10'		Pos#-50	Pos#-40	Pos#-30	Pos#-20	Pos#-10
	Neutron	1513930	1528800	1504850	1327090	1183850
		Pos#-49	Pos#-39	Pos#-29	Pos#-19	Pos#-9
	Neutron	1511950	1525830	1409030	1236060	1076640
		Pos#-48	Pos#-38	Pos#-28	Pos#-18	Pos#-8
	Neutron	1498240	1506830	1359800	1210120	1120910
		Pos#-47	Pos#-37	Pos#-27	Pos#-17	Pos#-7
	Neutron	1468500	1445700	1373670	1215740	1023110
		Pos#-46	Pos#-36	Pos#-26	Pos#-16	Pos#-6
	Neutron	1280000	1488000	1330560	1113310	871288
		Pos#-45	Pos#-35	Pos#-25	Pos#-15	Pos#-5
	Neutron	1367400	1348730	1285120	1054500	870957
		Pos#-44	Pos#-34	Pos#-24	Pos#-14	Pos#-4
	Neutron	1295700	1319490	1291400	1060120	883843
		Pos#-43	Pos#-33	Pos#-23	Pos#-13	Pos#-3
	Neutron	1253900	1381440	1408040	1017330	829987
		Pos#-42	Pos#-32	Pos#-22	Pos#-12	Pos#-2
	Neutron	1223340	1365580	1308910	762914	760270
1'		Pos#-41	Pos#-31	Pos#-21	Pos#-11	Pos#-1
	Neutron	1190790	1226310	1086220	689067	834612

West Wall

Scale	0	689067 - 899001	899001 - 1108934	1108934 - 1318868	>1318868

Figure 3.4.2-3*: Passive dosimetry results for locations along south wall of the south high-bay.*

3.5: Conclusions and Relationship to the Phase I Shielding Tasks

The results in Section 3.4 show that there are remedial steps required to bring the test cell shielding up to expectations. In particular, the following findings are relevant:

- The north shield wall, constructed during the Upgrade Project and shown in Fig. 2-9, does a good job of shielding neutrons at locations directly behind the wall, as evidenced by the reduction in dose in Figure 3.4.1.1-1. However, due to a lack of ceiling or labyrinth structure, the dose in the north sections of the gallery still extrapolates to values well beyond the 50 µrem/hr posting/dosimetry requirement.
- There is significant dose within the south high bay, and the neutrons escaping the south high bay through the access door result in elevated signal levels in the east gallery.
- Doses in the MER mezzanine extraplate to well beyond the 50 µrem/hr posting/dosimetry requirement.
- The site boundary limit of 10 mrem/year may be in jeopardy during NSTX-U operations if there are not improvements to the shielding.

However, with the exception of the personnel access door in the south high bay, the results from the FY-16 run are not conclusive as to which penetrations in the NTC wall are allowing neutrons to escape the test cell and enter these areas of interest. Hence, D-T neutron generator tests were done to challenge specific aspects of the shielding. These are described in Section 4, as part of the Phase I Shielding Assessment and Remediation process.

4: Phase I Shielding Development

This Section describes the Phase I shielding plans. These involve:

Section 4.1: Phase I Shield Wall Test Results - This Section summarizes the results of the D-T neutron generator tests in May 2017.

Section 4.2: Phase I Shielding Assessment Recommendations - This Section uses the results of Section 4.1 to generate recommendations on penetrations to remediate.

Section 4.3: Methods for Shielding Design - This Section summarizes the intended design methodology for shielding.

4.1 Phase I Shielding D-T Generator Test Results

A survey of the test cell penetrations with a D-T neutron generator was performed in May 2017. This test was performed using procedure D-NSTX-IP-3931. The D-T neutron generator was placed at the 7 locations in the test cell listed in Table 4.1-1 and shown in Fig. 4.1-1. Note that these 7 locations were spread broadly throughout the NSTX-U test cell. These diverse locations were selected in order to effectively challenge all penetrations: the different locations prevent the shielding effect of any single object (the vessel, neutral beams) from obscuring a potentially problematic penetration.

Readings were taken at various areas outside the test cell using calibrated ^{3}He proportional counter detectors. The data were recorded in surveys SS-2017-05-24-0020, SS-2017-05-26-0005, and SS-2017-05-24-0019.

The summarized data from these surveys are listed in Table 4.1-2. Penetration numbers can be found in drawing E-FA1030 sheets 1 and 2 and in Appendix 1 of this document.

Readings less than or equal to 100 microRem/hr during the D-T neutron generator test are not considered to be sufficiently significant to address in the first round of shielding, and are therefore not shown. Areas in red in Table 4.1.-2 will be addressed in Section 4.2. In general, areas in green in Table 4.1-2 are not considered to be significant and will be assessed in Phase II. Areas in green that are greater than 100 microRem/hr have additional considerations that are listed in the notes to Table 4.1-2 and are sometimes further addressed in Section 4.2.

Table 4.1-1*: D-T neutron generator locations during May 2017 testing*

Location No.	Description
1	109' near RF Bay F&G Pointing South East
2	100' SE Corner Pointing North East Corner
3	Top NB#2 Pointing North East Corner
4	Top NB#1 Cryo stand Pointing North West Corner
5	100' NE Corner Pointing South West
6	119' SW Corner Pointing North East Corner
7	S High Bay Scissor Lift Elevated to 10’ Pointing East

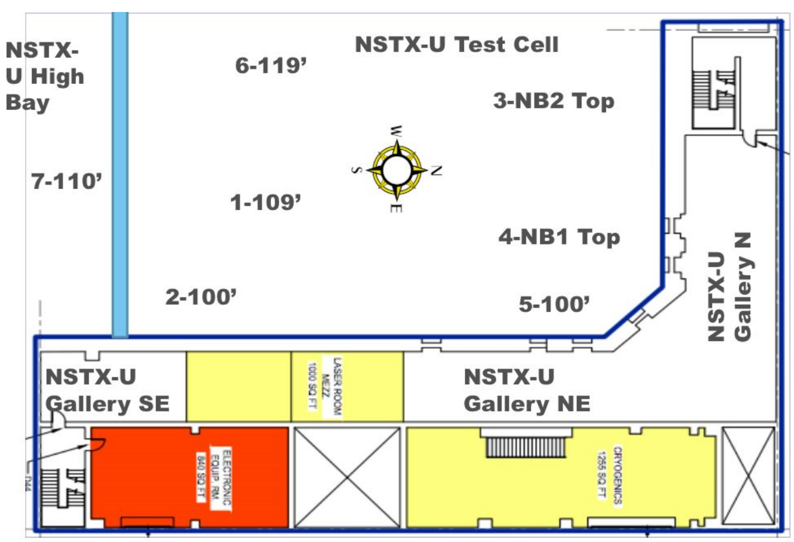


Figure 4.1-1*: Schematic of the locations where the D-T neutron generator was placed during the May 2017 tests*

***Table 4.1-2**: Significant test results from the May 2017 D-T neutron generator shielding assessment.*

	Location	Highest Reading Observed (μRem/hr)
1	NSTX Test Cell North Door and Vestibule	2,500
2	North Wall Center, Height 16 Feet, Lateral Distance 10 Feet Across From upper wall large windows 6500 and 6501 (NOTE 1)	100
3	RF Feed Thru #6111 - 6116 / Window 6502, Penetration 1616 and 1617	500
4	Penetration 1636 Northeast Wall	100
5	Penetration 1594 North Wall	100
6	Penetration 1591 North Wall	100
7	Large Window behind Panel B-GIS-2A North Wall #6495 (NOTE 2)	300
8	Inside gas cylinder cage North Wall (NOTE 3)	200
9	North East Wall at 8' between large window 6497 and cable tray penetrations 1622 and 1623	700
10	Window 6497 Center Contact	400
11	Cable tray penetration 1623	400
12	Large Window 6503 Lateral Distance 10 Feet, Height 12 Feet	300
13	General Area 12 Foot High Penetrations 1622, 1623, 1624, 1625	200
14	Penetration 6360 East Wall	100
15	Penetration 6310 East Wall	400
16	Door 44-110A South East High Bay Door (I-31)	25,000
17	Laser Water Chiller storage tank and pump (NOTE 4)	1,000
18	NB Power Conversion Bldg Door D44-116 8 locations	100 - 900
19	South / East MER Mezzanine	700
20	Penetration 6136 Laser Mezzanine	600

NOTE 1: This reading is at the 100 microRem/hr threshold; however, it is considered to be significant because the measurements were taken at a distance of at least 10 feet from the target windows. The dose rate at the window may be significantly higher. Note that some dose at this window may be due to the scatter out of the North door or the HHFW feedthroughs.

NOTE 2: This note removed in Rev. 2 of this plan.

NOTE 3: Same as NOTE 2.

NOTE 4: This note removed in Rev. 2 of this plan.

Note that data found with the D-T neutron generator is not representative of the equivalent dose that will be seen during NSTX-U operation. The dose quantities will be conservative due to the high energy level of the neutrons produced with the D-T generator (14 MeV), and in any case are used for the sole purpose of identifying problematic penetrations.

Also note that it was not possible to challenge all penetrations with this method. When a penetration of a specific type in a specific area was found to be problematic, it was generally inferred that other similar penetrations would be problematic. This is explained with greater detail in Section 4.2.

4.2 Phase I Shielding Assessment Recommendations

This section describes the recommendations for Phase I improved door and penetration shielding, based on the D-T neutron generator studies. The sections are organized in rough order of priority.

4.2.1 NTC East Wall and South High Bay

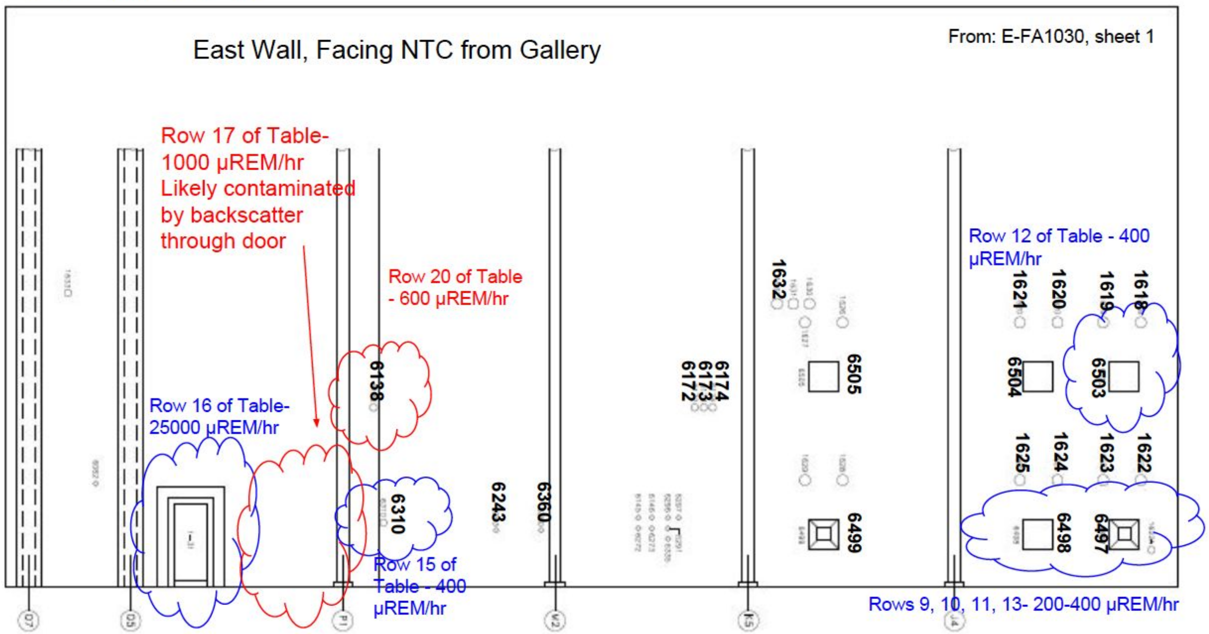
South East Door - Row 16 of Table 4.1.2

The personnel entrance to the High Bay area is identified in red in row 16 of Table 4.1-2, and is shown in Fig. 2-7. The probable impact of this door is also clear from Figure 3.4.2-2, where the passive dosimeters show a clear increase opposite the door. The shielding of this door should be improved by the installation of additional dedicated shielding labyrinth. Note that because of the extremely poor (nonexistent) shielding provided by this door it is likely that some readings taken in the general vicinity of this door were compromised. In particular, the readings in Rows 15, 17 and 20 of Table 4.1-2 were likely compromised by this large leakage, as indicated in Fig. 4.2.1-1.

Action: Construct shielded enclosure/labyrinth to prevent neutrons from leaving via this door. Document plan with calculations and design reviews.

Figure 4.2.1-1*: Illustration of D-T generator test dose rates on the outside of the east wall. The Table referred to here is Table 4.1-2.*

D-T Generator Tests



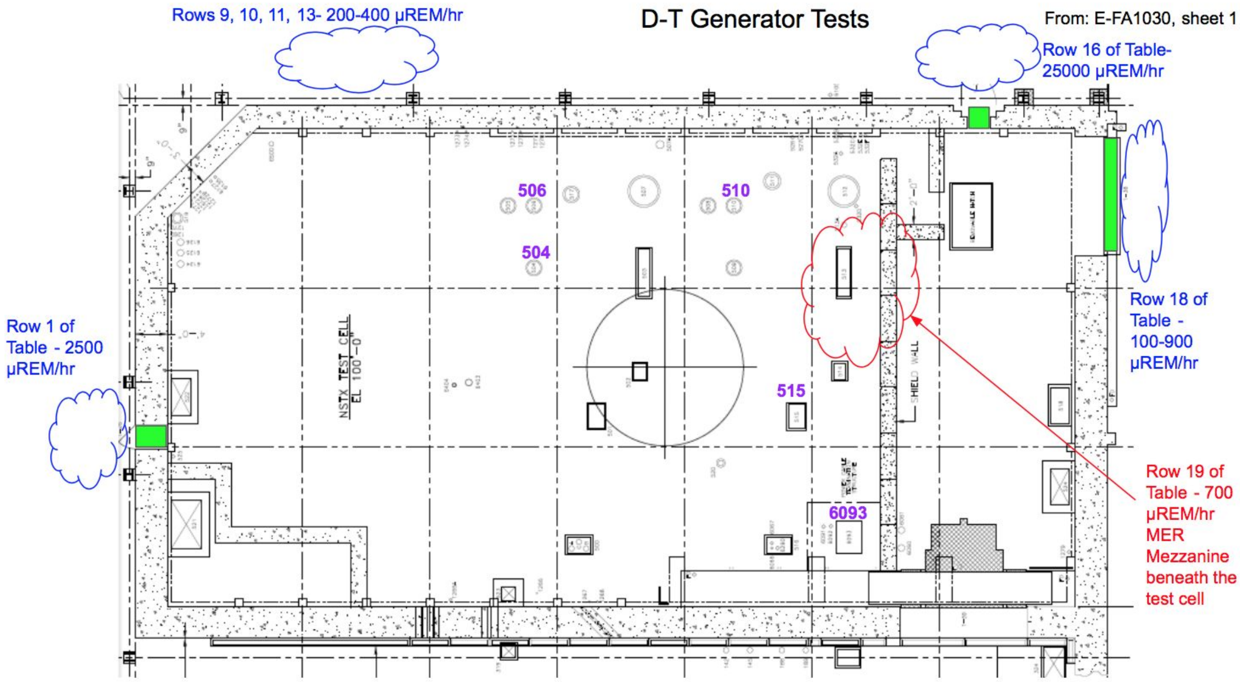
<u>*South High Bay Tritium Seal Door to Neutral Beam Power Conversion Building - Row 18 of Table 4.1.2*</u>

This door is identified in green in row 18 of Table 4.1-2, and is illustrated in Fig. 2-7, 2-8, and 4.2.1-2.

This door is fabricated with a ⅜" steel plate on the test cell side, with a 1' standard concrete fill. D-T generator tests identify it as a potential source of neutrons entering the neutral beam power conversion building. However, it should be noted that the D-T generator tests which indicated potential leakage were done with the D-T generator directly in front of the door; in the actual NSTX-U application, the shield wall prevents any line-of-sight interaction of neutrons from NSTX-U with this door.

Action: Develop methods to ensure that the door is closed during operations (scope for the PSS job). Make an assessment of any additional shielding that should be applied to this door and apply shielding as appropriate. Document plan with calculations and design reviews.

__Figure 4.2.1-2__: Illustration of D-T generator test dose rates on the outside of the east wall. The Table referred to here is Table 4.1-2.



<u>*Near vision window 6497 on the east wall, 100' level - Rows 9 -12 of Table 4.1-2*</u>

This observation window 6497 is identified in red in rows 9 & 10 of Table 4.1-2. This was the only accessible vision window along the east wall for which a direct reading could be obtained.

The surrounding windows 6498, 6499, 6505 were not directly tested. However, given their large size, and in many cases direct line of sight to the machine, these additional windows should be assessed for the need for additional shielding. This conclusion is further motivated by the readings in row 12 of Table 4.1-2, where strong readings were observed at a distance from equipment window 6503.

Action: Install shielding on vision windows 6497 and 6499; assess and potentially augment shielding on equipment windows 6498, 6503, 6504, and 6505. Document plan with calculations and design reviews.

<u>*Penetration 6310 on the east wall, 100' level - Row 15 of Table 4.1-2*</u>

This penetration is identified in green in row 15 of Table 4.1-2.

This penetration was removed from the Phase I shielding list following further consideration. After reviewing the measurement data this penetration, positive radiation readings were seen on one of the tests and no detectable radiation on any of the other tests. The test that had a positive result had the D-T neutron generator in the direct line of sight of this penetration.

Hence, it is recommended to remove this penetration from the list and wait for Phase II or D-D plasma operation (Phase III) to make a recommendation for this penetration.

Action: Defer further assessment of this penetration to Phase II.

Penetrations 1622, 1623, 1624, 1625 on the east wall, 100' level - Row 13 of Table 4.1-2

Four cable penetrations on the north end of the east wall (1622, 1623, 1624, 1625) are red in rows 9, 11 & 13 of Table 4.1-2.

Additional penetrations adjacent to the ones noted here were omitted from the test. Based on similarity of size and geometry, the following penetrations should should also be addressed: 1618-1621, 1625, 1626-1632, 1587-1590, 1617, and 1616. During the radiation survey these penetrations were difficult to identify and see but their proximity to the measurement points may have had an influence on the overall reading.

Note that penetrations 1587-1590 as well as 1617 and 1618 are easily visible in Figure 2-1.

Action: Assess and as necessary install shielding on penetrations 1622-1625 (east wall), 1618-1621 (east wall), 1626-1632 (east wall), 1587-1590 (north wall), 1616-1617 (northeast wall) as part of Phase I. Document plan with calculations and design reviews.

Penetration 6136 on the east wall, 109' level - Row 20 of Table 4.1-2

The 10" Penetration in the mezzanine laser room (Penetration 6136) is identified in red in row 20 of Table 3.1-2, and is shown in Fig. 2-13. Of all the penetrations measured in the mezzanine areas this was the only one that showed a positive result.

This result is mitigated, however, by two observations: this is a relative small penetration, and the signal in this region may be corrupted by the large leakage thought the south high bay door. For these reasons, it is decided to shift this penetration to Phase II

Action: Defer to Phase II

4.2.2 NTC North Wall

North NSTX-U test cell door and vestibule - Row 1 of Table 4.1-2

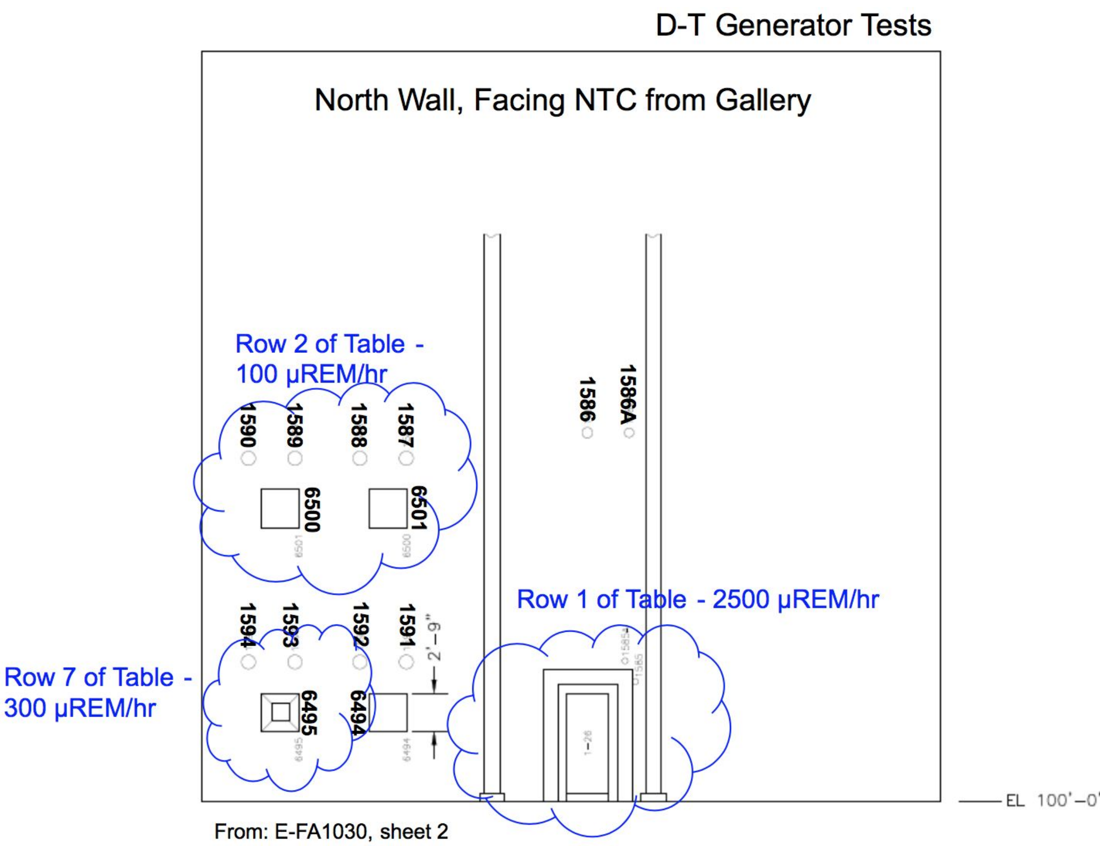
This area is identified as red in row 1 of Table 4.1-2, and is shown in Figure 2-9. The dose rates in this area were large during the D-T generator test, and represent a substantial source of neutron leakage.

Initial efforts to shield this area utilized the additional concrete wall in the north gallery, as in Fig. 2-9. However, Phase I tests indicated that this step was insufficient, and that additional steps must be taken. Those additional steps could involve the installation of additional concrete shielding.

However, after further investigation, it has been determined that closing the existing shield/seal door, potentially with modest supplemental shielding, is acceptable, following appropriate modifications to procedures and related electrical installations.

Action: Develop procedures, and make necessary modifications, to close the large shield/seal door ("battleship door") during plasma operation. Implement any necessary supplemental shielding. Document plan with calculations and design reviews.

Figure 4.2.1-3*: Illustration of D-T generator test dose rates on the outside of the north wall. The Table referred to here is Table 4.1-2.*



Window 6495 - Row 7 of Table 4.1-2

The vision window 6495 is red in row 7 of Table 4.1-2.

Action: Assess and, as necessary, install shielding in equipment window 6494. Augment shielding in vision window 6495. Additionally, augment shielding in penetrations 1591-1594. Document plan with calculations and design reviews.

Vicinity of windows 6500 and 6501 on the NTC northeast wall - Row 2 of Table 2.4-1

The two equipment windows on the east end of the north wall (6500 & 6501) are red in row 2 of Table 4.1-2. Note that these two recessed windows can be seen in the right of Fig. 2-12.

Action: Assess and, as necessary, install shielding in windows 6500 & 6501. Additionally, augment shielding in penetrations 1587-1590. Document plan with calculations and design reviews.

4.2.3 NTC North-East

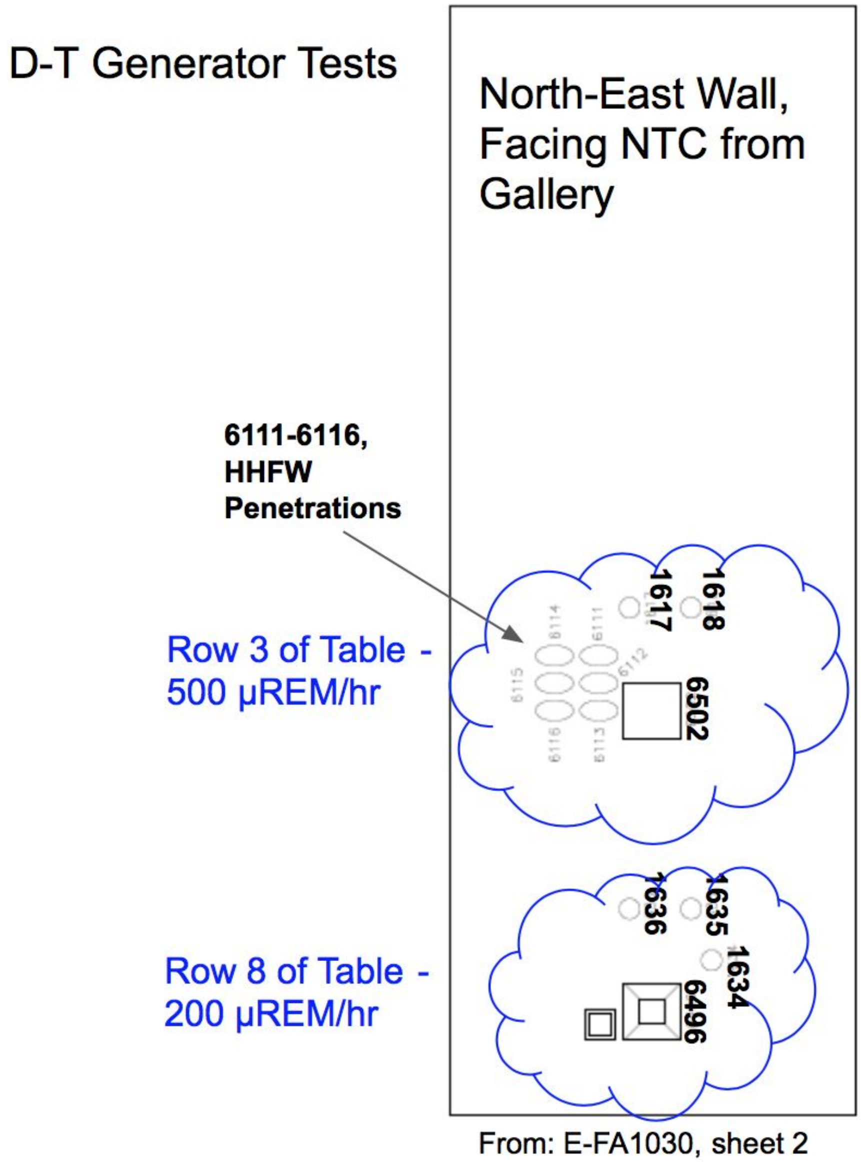
4.2.8: Area around the RF waveguide penetrations, northeast wall - Row 3 of Table 2.4-1

The RF waveguide penetrations at the 119’ level on the northeast wall are identified in red in Row 3 of Table 4.1-2. See photograph of this area in Figure 4.2.8-1.

However, it is not possible to determine if the actual waveguide penetrations or equipment window 6502 is the source of detected neutrons during the D-T neutron generator tests. The radiation survey could only determine that the general area around the waveguides is a problem, with increasing signals as the detector approached window 6502.

Action: Assess and as necessary install shielding in equipment window 6502 and penetrations 1616 and 1617. Take action to improve the shielding around the RF waveguides.

Figure 4.2.3-1: *Illustration of D-T generator test dose rates on the outside of the north wall. The Table referred to here is Table 4.1-2.*



<u>*Within the gas cylinder cage in the northeast gallery - Row 8 of Table 4.1-2*</u>

Dose was measured in the vicinity of the gas cylinder rack that resides near window 6494, in the northeast corner of the gallery. While this window is well shielded from NSTX-U by the presence of neutral beam boxes, it appears appropriate to augment the shielding in this vision window and nearby circular penetrations.

Action: Improve the shielding in window 6496. Assess and improve shielding in penetrations 1634-1636.

4.2.4 NTC Floor

NTC bakeout piping floor penetration (Penetration 515) - Row 19 of Table 4.1-2.

Penetrations for bakeout piping in the Test Cell floor to the South/East MER Mezzanine are identified in red in row 19 of Table 4.1-2, and are shown in Figure 2-14. However, it is not practical to shield these penetrations for two reasons:

- The large pipes cannot be shielded on their interior, resulting in an irreducible minimum penetration size.
- Any shielding material would need to be compatible with the high temperature of the helium piping or the hole in the Test Cell floor would need to be large enough to accomodate the insulation, which would further compromise the neutron shielding.

However, the MER is an underground room with concrete walls and is therefore an ideal location to capture neutrons.

For these reasons, the recommended path is to post and restrict access to the MER and MER mezzanine during plasma operation.

Action: Restrict access to the MER and MER mezzanine during plasma and beam operations.

NTC floor neutral beam penetrations (Penetrations 506, 504)

The NB water penetrations are shown in Fig. 2-14. No measurements were taken directly below these penetrations either during the run or during the D-T neutron generator tests.

Based on the discussion in the previous section, the recommendation is to post and restrict access to areas beneath those penetrations.

Action: Restrict access to the MER and MER mezzanine during operations.

NTC flow OH water heater penetration (Penetration 510)

There are unshielded penetrations associated with the OH water heater electrical power feed. While no D-T neutron generator tests were done for these penetrations, it is clear that these penetrations allow neutrons to pass from the test cell into the MER.

Action: Restrict access to the MER and MER mezzanine during operations.

Cable penetrations under the Power Cable Termination Structure (PCTS) (Penetration 6093)

There is a large floor penetration beneath the power cable termination structure, where the majority of cables for the TF, OH, and PF coils pass from the MER to the test cell. This large penetration is filled with a combination of large cables and fire bricks.

Action: Restrict access to the MER and MER mezzanine during operations.

4.2.5 South and West Walls

There are no intended shielding augmentations on these walls in Phase I

4.3: Methods for Shielding Design

NSTX-U radiation shielding will be designed to alleviate the problematic radiation areas assessed in Phase I. The assessment will be an iterative calculation cycle using a conservative neutron source that will converge on an acceptable shielding design. The calculation will be done with an acceptable particle transport code (e.g. MCNP or Attila). The models will be built to incorporate a modeled NSTX-U neutron source or a worst case neutron source. The source will be placed in such a way as to incorporate any streaming and single interaction deflections through the shielding region of interest. The code will be run with the current NSTX-U shielding (baseline) and multiple improved shielding configurations. The improved shielding configurations will be compared to the baseline, and the proper shielding configuration will be confirmed.

5: Phase II Shielding Overview

In general, the intent of Phase II is to twofold:

- assess the efficacy of the remediation steps undertaken in Phase I by repeating relevant tests, and
- assess if additional penetrations need remediation once the leakage from the large Phase I penetrations have been attenuated

The doors and penetrations listed in Table 4-1 may be found to require remediation as part of Phase II. This table lists all penetrations and doors that were identified during the Phase I testing but deferred to Phase II, as well as all other test cell penetrations of significant size that are not addressed in Phase I.

This details of this section will be completed once the Phase II DT tests are completed.

Table 5-1*: Doors and penetrations that may require remediation as part of Phase II.*

	Penetration Number	Penetration Location & Notes
1		NBPC Door from South High Bay
2	1586	North Wall
3	1586a	North Wall
4	1586	North Wall
5	1586A	North Wall
6	1591	North Wall
7	1592	North Wall
8	1593	North Wall
9	1594	North Wall
10	6310	East wall
11	6172	East Wall
12	6173	East Wall
13	6174	East Wall
14	6360	East Wall
15	6243	East Wall
16	6297	East Wall
17	6296	East Wall
18	6146	East Wall
19	6145	East Wall
20	6291	East Wall
21	6273	East Wall
22	6272	East Wall
23	6335	East Wall
24	6062	East Wall
25	1633	East Wall
26	6139	East Wall
27	1622A	East Wall
28	6138	East Wall (this is the MPTS laser entrance penetration)
29	---	All South and West Wall Penetrations

6: Phase III - Testing When Operations Resume

The phase III plan will be based on measurements made during the FY2016 run as described in Section 3, and refined based on the output of Phase I and Phase II activities. During the Phase III testing to be performed during plasma operation, the following activities shall be performed to further assess the effectiveness of the Test Cell shielding.

- Mobile integrated ^{3}He neutron detectors will be used to monitor the neutron flux outside the Test Cell. They will be located in the similar positions to those used during the initial NSTX-U startup operation from Section 3. These locations include but may not be limited to the north and east galleries, the neutral beam power conversion building, and other areas adjacent to the NSTX test cell.

- A single neutron detector will be placed inside the north test cell door prior to daily plasma operation, and another integrating neutron detector will be placed outside the closed tritium seal door to make a comparison measurement of potential neutron exposure inside the test cell versus exposure outside the north door shield wall.

- Three integrating neutron monitors will be located in the existing North, East and South boundary trailer locations. Backup neutron monitors will be provided in each location.

- Passive dosimetry will be deployed in a grid formation from ground elevation up to 10 feet above floor level along the North and East outside walls of the gallery. This data will be normalized and compared to data taken during the NSTX-U startup run.

The NTC dose rate monitors will also be deployed as during the 2016 run campaign.

Appendix 1: Penetration Drawings with Planned Remediation

In the drawings below, color coding is as follows:

***Table A1-1**: Color coding in Figs. A1-1 through A1-4.*

red	Penetrations to be addressed in Phase I, by additional shielding as appropriate (see Section 4.2)
green	Doors where remedial action is required
purple	Penetrations to be addressed in Phase I, by access restrictions
black	Other penetrations

***Figure A1-1**: Penetrations in the test cell north wall*

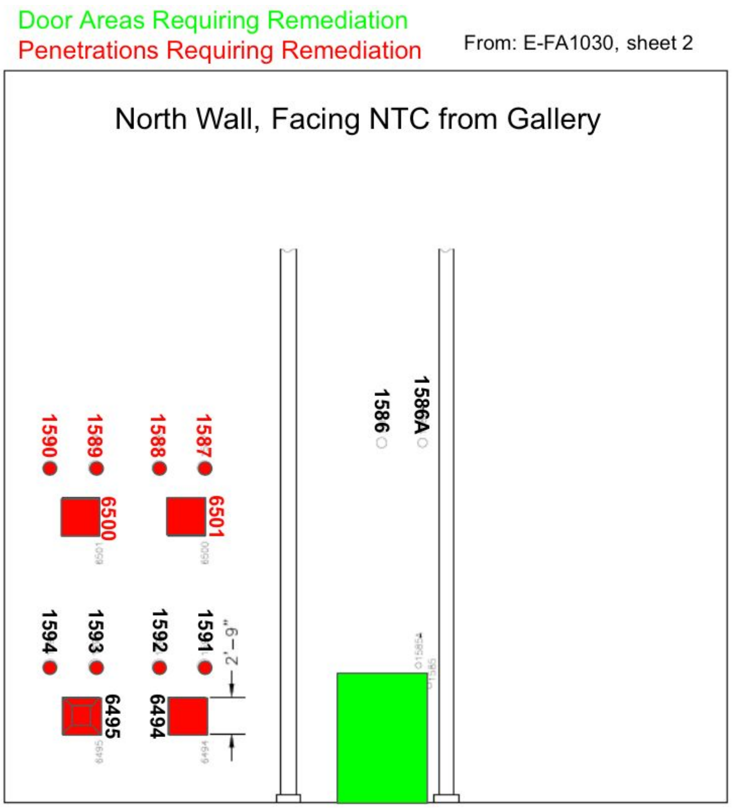


__Figure A1-2__: Penetrations in the test cell north east wall

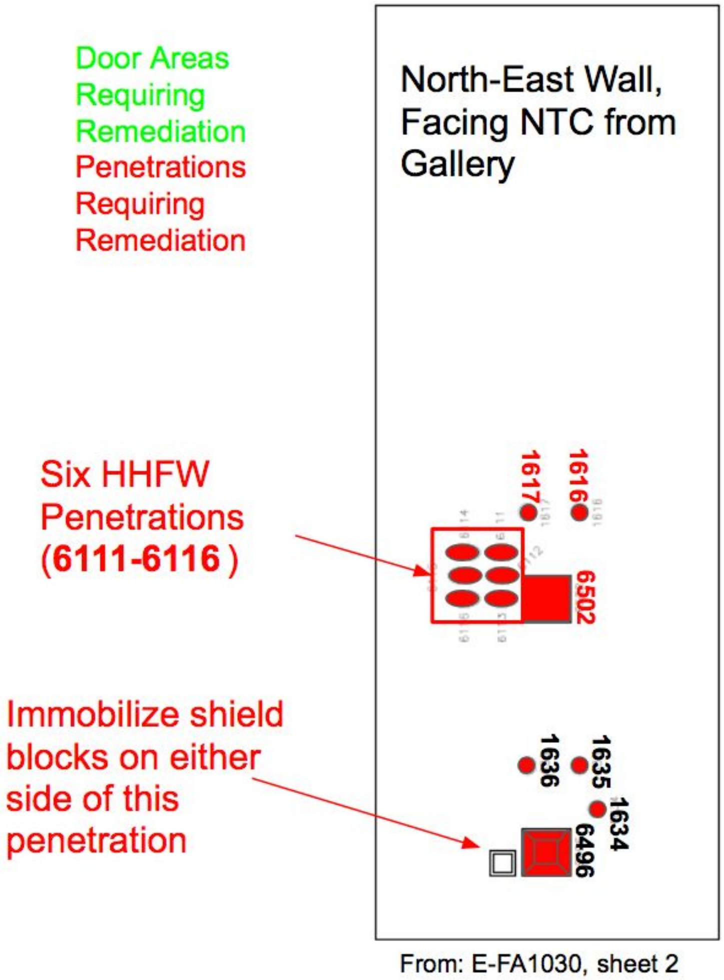


***Figure A1-3**: Penetrations in the test cell east wall*

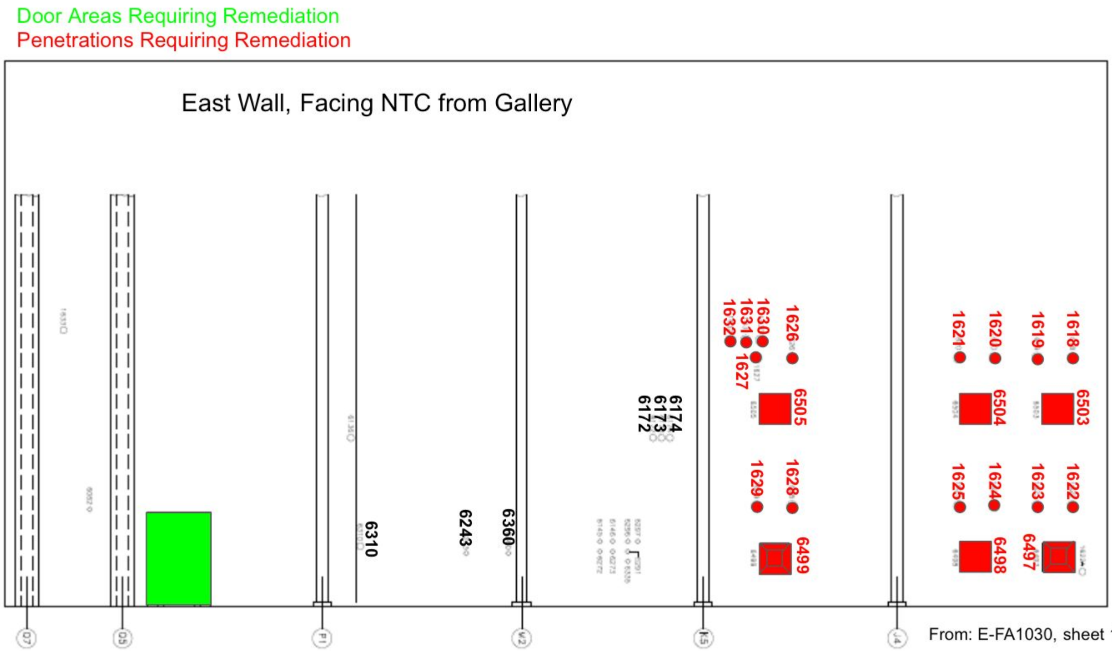
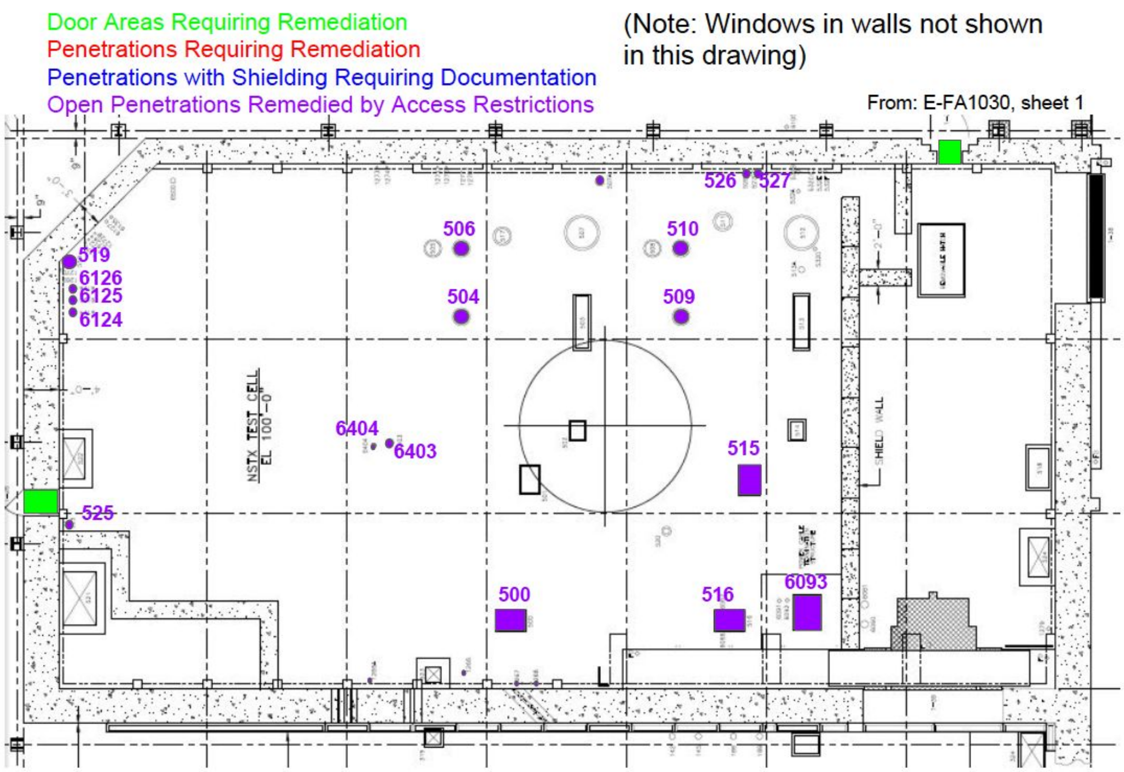


***Figure A1-4**: Open penetrations in the Test Cell floor. Note that the majority of penetrations in the Test Cell floor are already filled with concrete, and the open ones are indicated in purple (open implies that they have fire stops and physical covers, but no dedicated shielding installation)*



Appendix 2: Trade-Offs for Comprehensive Neutronics Modeling vs. Penetration Testing For Identification of Problematic Penetrations

The first question asked when approaching the problem of remediating neutron leakage through penetrations in the NSTX-U test cell walls is "which penetrations are allowing the neutrons to leave?" At the start of this process, a qualitative assessment was made regarding two options for determining which penetrations to remediate: i) comprehensive 3-D neutronics analysis of the test cell, or ii) experimental assessments with the D-T generator. The second option was chosen for reasons provided below.

Full neutronics analysis with D-D neutrons might be called for in a number of scenarios. For example, if PPPL/NSTX-U were embarking on the design of a new facility and test cell, neutronics analysis may allow a first-principle determination of shield wall design and penetration requirements. Similarly, if for some reason it were not possible to make measurements on the outside of the test cell due to an access restriction, then modelling may be the acceptable fall-back position. Alternatively, if a specific dose or flux or energy value must be met at a given location during operations, then full neutronics analysis with D-D fusion neutron energies may be required. Examples of the latter would be relevant if the tests were targeting a specific dose in the south and east galleries, or for studies of the effects of neutrons on electronics within the test cell. While NSTX-U has made some low level effort at assessing neutron effects on test cell electronics via calculations, none of these examples *directly* address the fundamental question of "which penetrations are allowing the most neutrons to leave?".

Furthermore, full 3-D neutronics analysis of the test cell would be extremely time consuming, requiring detailed models of the test cell, including the numerous small items within the test cell. The initial calculations would likely have large errors and require model calibration data based on D-T generator tests. Hence those D-T generator tests would have been required under either approach described in the first paragraph of this Appendix. Additional information from modelling beyond that determined directly from the D-T neutron generator testing would likely not have been worth the delay and expense, given the ability of the neutron generator to rapidly identify problematic penetrations.

In contrast, the D-T neutron generator is well suited to identification of problematic penetrations, for a number of reasons. Tests with the generator inherently utilize the "full model" of the test cell, in the sense that they assess the as-found condition of all penetrations and the effects of scattering and shielding from objects in the NTC. These tests also allow rapid identification of problematic areas: by scanning detectors across penetrations in the gallery, the impact of specific penetrations could in some, but not all, cases be determined. Furthermore, these higher-energy neutrons have a longer residence time within the test cell relative to lower energy D-D neutrons, implying that they are more likely to ultimately escape via problematic penetrations; in this sense, the use of neutrons from D-T reactions is partially advantageous. All of these features make the D-T neutron generator source with detection outside the test cell walls the test ideal for the specific test goals in this report.

Sub-model neutronics calculations are useful for determining the appropriate thickness or properties of shielding materials to be used in specific configurations. These sub-model calculations will be applied to assess the efficacy of particular shielding solutions, as described in Section 4.3.

Ultimately, the shielding must ensure that specific maximum doses are not exceeded, with i) 10 mrem/year at the site boundary a requirement and ii) <50 microrem/hour in occupied areas in the vicinity of the test cell a project goal [1]. As described in Section 6 of this document, a comprehensive plan has been made to survey critical areas following resumption of operations, in order to verify compliance with these requirements and goals. Based on dose levels observed during operations in 2016 (see Section 3), before the shielding remediation program described here, evidence indicates that steps taken in Phase I & II of this program should be sufficient to meet these metrics.

In summary, the intent of the D-T neutron generator measurement is to assess penetrations through which neutrons leave the test cell, with the goal of appropriately shielding or filling these penetrations to eliminate this effect. The method of utilizing the D-T neutron generator is the most effective means to do this. Neutronics modelling will then be used to define the appropriate shielding methods to remediate the problematic penetrations.

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