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Nuclear Reactor Program

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23 December 2010

US Nuclear Regulatory Commission
Document Control Desk
Washington, DC

Re: Reportable Event 46484; Radiography Incident
License No. R-120
Docket No. 50-297

Attached please find a written report with a detailed explanation of a reportable event regarding a personnel exposure incident that occurred while performing neutron radiography. Corrective actions taken and planned to prevent recurrence are provided in the report. The event was reported under Technical Specification 6.7.1 as defined in Technical Specification 1.2.24h.

If you have any questions regarding this report or require additional information, please contact Gerald Wicks at 919-515-4601 or wicks@ncsu.edu .

I declare under penalty of perjury that the forgoing is true and correct. Executed on 23 December 2010.

Sincerely,

Ayman I. Hawari, Ph.D.
Director, Nuclear Reactor Program
North Carolina State University

cc: Duane Hardesty, US NRC

IE70

Neutron Imaging Facility Personnel Exposure Incident Report

Facility Description:

The Neutron Imaging Facility (NIF) at the NCSU PULSTAR reactor was approved for installation and use in Dec 2004. [Refer to Attachment 1] The NIF description given in this section indicates the status of the NIF at the time of the personnel exposure incident on 13 Dec 2010.

The NIF is used for neutron imaging and radiography. The NIF radiation beam emanates from the reactor out through a reactor beam tube. The beam tube contains filters and a collimator. Radiation in the NIF beam is composed of mostly thermal neutrons, gamma photons, and a minor amount of fast neutrons. A beam shutter, beam stop, shielding, and secured entry door are in place.

A pneumatic cylinder causes the shutter to rotate 90° CW to open the beam. A three-way solenoid valve de-energizes, venting the pneumatic cylinder which allows the shutter to rotate back to the closed position. The shutter is specially weighted to rotate by gravity to the closed position. [Refer to Attachment 2]

The shutter control system consists of a 24 volt loop which ultimately controls the three-way solenoid valve. The main components of the systems are:

- Exit Permit Pushbutton
- Entry Permit Pushbutton
- Control Room Permit Switch
- Door Bond Sensor
- Door Magnet Lock
- Shutter Closed Limit Switch
- Shutter Open Limit Switch
- Shutter Position Light Indicator
- Shutter Moving Audible Alarm
- Shutter Control Computer
- Live Video of Shutter Position

The shutter will only open if the Entry or Exit Permit Pushbuttons are pulled out, the Control Room Permit Switch is closed, the Door Bond Sensor is closed and the Shutter

Control Computer timer is not at zero. If the shutter is open and if any of these items are interrupted the 24 volt circuit is de-energized, air is vented from the pneumatic cylinder and the shutter is counter-weighted to close by gravity. In addition to the shutter closing, the Door Magnet Lock will also be de-energized by pushing either the Entry Permit Pushbutton or the Exit Permit Pushbutton or opening the Control Room Permit Switch. An audible alarm sounds whenever the shutter is neither fully-closed nor fully-opened.

Entry is restricted to the High Radiation Area (HRA) by using a secured door. An exterior radiation monitor with an audible alarm is in place. Other controls include a camera that is used to provide a live display of the shutter position and a shutter position indicator light on the NIF computer. Shutter position lights are also present above the NIF entry door. Radiation survey meters are available outside the NIF for use by personnel entering the NIF and to survey irradiated items.

NIF operation occurs by pulling out the Entry Permit Pushbutton, the Exit Permit Pushbutton and toggling the Control Room Permit Switch in the reactor control room to operate. Then the door is secured and the timer is set. The NIF shutter will then open when the command is entered in the NIF computer. After the exposure is done, the experimenter is expected to check the shutter position by observing the NIF computer screen and shutter position indicator lights either on the NIF computer screen or by the NIF entry door. Upon entry, the experimenter is expected to verify the shutter is closed before continuing into the NIF either by observation or by radiation survey.

Individuals requiring access to the reactor and experimental facilities undergo training upon starting work. Training on use of experimental facilities is performed with experienced personnel.

Sequence of Events:

On 13 Dec 2010, a contract company employee was using the NIF to perform neutron radiographs. This individual has been trained for reactor access and NIF operation. He is in training to become a certified radiographer and was using the NIF under supervision of a certified radiographer. Radiography began at 10 am and the radiographer had performed a few radiographs on 13 Dec 2010 prior to the incident.

2:55 PM The shutter was opened to start a 7 minute radiography exposure

2:57 PM The radiographer left the reactor room

3:02 PM The time for the radiograph expired on the Shutter Control Computer and air was vented from the pneumatic cylinder. The shutter failed to close due the shutter end stop being hung up on the end-stop bolt.

3:03 PM The radiographer returned to the reactor room and saw that the timer read zero. He then pushed the Entry Permit Pushbutton to de-energize the Door Magnet. The radiographer failed to notice that the live video feed showed that the shutter was still open, that the Shutter Position Light Indicator was red (denoting DANGER – Shutter Open) and that the Shutter Control Computer indicated the shutter was still open.

3:05 PM The radiographer then entered the NIF to load the next radiograph. Once inside the NIF he heard the radiation monitoring alarm. [Refer to Attachment 3 for the NIF radiation monitor display. The alarm set point is 2 mR/h.] At this point he was in the NIF beam area and looked up and saw that the shutter was still open. He immediately exited the NIF, secured the door and notified reactor operations that the shutter was still open. Based on statements from the radiographer and confirmed by the surveillance video camera recording, the radiographer was in the NIF from 3:04:58 to 3:05:16 pm for a total time of 18 seconds.

3:08 PM The reactor staff arrived at the NIF and observed that the shutter was stuck open on the live camera feed and shutter position indicator lights. The reactor staff attempted to close the shutter by actuating the pneumatic cylinder without success.

3:10 PM The reactor was shutdown. After confirming that the reactor was shutdown, the reactor staff entered the NIF with a hand-held radiation detector (radiation levels were less than 100 mrem/h) to observe how and why the shutter was stuck. The staff remained behind the shields out of the beamline and observed that the shutter was stuck on the end-stop bolt. The staff member exited the beam cave and the NIF door was secured. The radiographer exited the reactor building to do a whole body frisk.

3:14 PM The Reactor Health Physicist (RHP) was called and asked to report to the NIF.

3:17 PM The RHP arrives at the NIF and was informed that the shutter was stuck open and the reactor was shut down.

3:20 PM The RHP then surveyed the NIF as he entered and closed the stuck shutter. Dose rates were 70 mrem/h (gamma) in the beam area and 10 mrem/h out of the beam area. The dose to the RHP was less than 1 mrem (as measured by an electronic dosimeter).

The RHP was informed that the radiographer had entered the NIF with the shutter open. The RHP then went to find the radiographer and observed the frisking of the head and body. The RHP asked about the frisking results and was informed that the keys and wallet were activated slightly and after 5 minutes decay both of these items were at background levels. These items were frisked again with the RHP present. The frisking results of the radiographer was reported and observed to be at background levels. No bioassay was performed based on frisking results for the body being at background levels.

3:23 PM The reactor staff then began to evaluate the incident to determine the dose received by the radiographer. It was also then learned that the radiographer was not wearing dosimetry. The reactor was restarted for dose rate measurements. Based on statements made by the radiographer, the NIF was surveyed and the beam dose rate for the area entered by the radiographer was measured to be approximately 10 rem/h (gamma) and 20 rem/h (neutron) [Refer to Attachment 4]. The radiographer re-enacted his actions and was timed at 10 seconds. Later the reactor staff reviewed the surveillance video of the NIF area and determined the exposure time to be 18 seconds. For conservatism the dose rate of 30 rem/h and 18 seconds were used to estimate the radiographer's dose. This gave 150 mrem as an estimate for the incident. [Refer to Attachment 6.]

4:00 PM The reactor staff irradiated two personnel dosimeters at 1 MW for evaluation by the dosimetry vendor; (1) in the beam without any items present and (2) in the beam with the film cassette and parts radiographed present and with the dosimeter mounted on a thick slab of polyethylene. The first test dosimeter was performed to evaluate the beam only and the second test dosimeter was performed to evaluate the beam with scattering media present. The polyethylene block was used to resemble a human body. The second test dosimeter was performed on 14 Dec 2010. Dosimeters were sent to the vendor on 14 Dec 2010 for immediate analysis.

5:00 PM (Approximately) The campus Radiation Safety Officer (RSO) was informed by telephone message of the incident by the Reactor Health Physicist (RHP). A detailed description was provided to the RSO by the RHP early in the morning on 14 Dec 2010. The RSO informed other University officials of the incident on 14 Dec 2010.

5:20 PM The reactor staff reviewed reporting requirements and discussed the incident with the Director of the Nuclear Reactor. The dose estimate of 150 mrem was discussed. A decision was made to keep the reactor shut down until further notice, that a written report of the incident was needed, interlocks based on the radiation monitoring system were needed, an evaluation on whether or not the incident was reportable needed to be made, and that the NRC Project Manager needed to be contacted.

The reactor staff met with the Director on 14 Dec 2010 and decided that the incident was not reportable. The NRC Project Manager was then contacted and recommended that an informational telephone call to the NRC Operations Center should be made. The NRC Operations Center was called at approximately 4:20 pm on 14 Dec 2010 as recommended.

On 15 Dec 2010 follow up calls were received from the NRC. Based on these discussions it was decided that the incident was reportable as defined in Technical

Specifications 6.7.1 and 1.2.24 h. The NRC Operations Center was called on 15 Dec 2010 at 4:24 pm with information about the reportable event.

Results of the test dosimeters were reported by telephone on 16 Dec 2010 and indicated a gamma dose rate of 8.46 rem/h and a fast neutron dose rate of 1.8 rem/h giving a total dose rate of 10.3 rem/h. [Refer to Attachment 5.] Thermal neutron dose was not reported for either of the test dosimeters.

The RHP calculated the thermal neutron dose using the reported neutron fluence rate on 16 Dec 2010 corrected for the location of the radiographer. A thermal neutron dose rate of 15.46 rem/h was calculated. Total dose rate using the dosimeter data and thermal neutron fluence rate is ~ 26 rem/h giving an estimated total dose for a 18 second stay time of 130 mrem. This is in good agreement with the survey data based dose estimate of 150 mrem. [Refer to Attachment 6]

Root Cause:

The root cause for this incident has been determined to be a shutter malfunction that prevented it from closing. Furthermore, the NIF lacked the appropriate shutter-door interlock.

In this incident when the timer reached zero minutes, the 24 volt circuit de-energized and air was vented from the pneumatic cylinder. Normally this would cause the shutter to close by gravity. In this incident the shutter failed to close because it hung-up on the end-stop bolt. [Refer to Attachment 2]

Due to a design flaw, the shutter got hung-up because the shutter drum had moved outward in the axial direction by approximately 0.5 inches over time from repeated opening and closing. This altered where the shutter end-stop was making contact with the end-stop bolt, and the end-stop became jammed on the end-stop bolt.

The shutter open and close position switches, lights, and alarms are powered separately. The shutter close position switch was not part of the door interlock system. In this incident after the pneumatic cylinder vented, the Entry Permit Pushbutton was depressed to de-energize the Door Magnet which allowed entry into the NIF. The failure mode with the shutter getting stuck open was not considered in the design. Therefore, a design flaw with the door interlock caused this incident.

Response:

The immediate response to this incident was to shutdown the reactor and close the NIF shutter. Upon learning that the NIF was entered by the radiographer, a dose evaluation began. Based on the survey data and stay time determined from the surveillance video recording, a dose estimate of 150 mrem was made. [Refer to Attachments 4 and 6] NVLAP accredited dosimetry and the thermal neutron dose estimated from the reported NIF neutron fluence rate data gives approximately 130 mrem. [Refer to Attachments 5 and 6]

Notifications were to the Director, Nuclear Reactor Program, RSO, and NRC Operations Center. The RSO informed University officials.

Area radiation monitor readings for the new fuel storage area for 13 Dec and 14 Dec 201 were reviewed and showed no abnormal readings. A radiation survey was performed on 21 Dec 2010 and indicated normal radiation levels for the new fuel storage area.

After the incident the surveillance video was reviewed to determine if the shutter closing was an isolated event or if there may have been other instances when the shutter failed to close. Operation of the NIF for radiography was viewed from 29 Nov 2010 to 13 Dec 2010 using the security surveillance video. A total of 40 shutter openings on 5 days of NIF operation were observed. All NIF shutter openings on the day of the incident were observed. In all instances, the shutter close indication occurred before any personnel entered the NIF. The time of the incident is the only time that any personnel entered the NIF with a shutter open indication.

Stay times inside the NIF by radiography personnel were determined from the observed 40 radiographs sequences to be 30 to 60 seconds. Based on a stay time of 60 seconds, the expected dose would be 500 mrem. Most stay times were under 60 seconds.

The location of the radiographer is based on his work activities and brief duration of this incident. The radiographer would have had no reason to approach the shutter and would have noticed the shutter position upon facing it. His work involves performing radiographs at the rear of the NIF. Re-enactment by the radiographer following this incident indicated he did not approach the shutter. He did abandon his materials upon seeing the open shutter and the location of these materials was towards the rear of the NIF. This location is depicted as number 7 on Attachment 4 and was used for the dose evaluation.

Corrective actions have been identified and are given below. Many of the actions are related to operation of the NIF and will need to be documented as a design change. All design changes are submitted to the Reactor Safeguards and Audit Committee (RSAC) for review and approval. Additional actions have been identified to address personnel dosimetry being worn and procedural controls and training on experimental facilities.

This incident report will be provided to the RSAC and the University Radiation Safety Committee at their next scheduled meeting.

The reactor has been shut down since this incident occurred except for dose evaluation of this incident. Reactor operations will resume as specified in Technical Specification 6.6.2.

Lessons Learned:

For all HRA, installation of redundant interlocks including ones interfaced with the radiation monitoring system needs to be evaluated for implementation. Component failures need to be considered in the design of interlocks. Interlocks may include control devices to reduce the area dose rates and restricting access to such areas if radiation set points are exceeded. Interlocks shall always be designed for the failsafe condition, e.g. shutter fully closed, acceptable radiation levels.

Use of a radiation monitoring device separately interlocked with the NIF door would have prevented this incident. This should have been part of the original design change. Use of installed radiation monitoring equipment in rooms capable of causing HRA is a good practice.

Alarming dosimeters (electronic dosimeters) are useful in alerting personnel about areas with elevated radiation levels. This is a good practice, especially for known HRA or potential HRA.

The radiographer failed to wear his dosimeter as required. Training on dosimetry requirements is provided in the radiation safety training conducted by the RHP and the University Radiation Safety Division. Postings, dosimetry audits, and requiring personnel to use their dosimeter for access to the reactor and experimental facilities are good practices.

The radiographer was familiar with NIF operation, but in this instance forgot to perform a visual check of the shutter. No written directions on NIF operation were posted. Reactor beams and experiments capable of producing HRA, HRA controls and procedures, and control devices need to be emphasized in training. Conducting and documenting specific training on written procedures for such experiments is a good practice that aids users in complying with radiation safety requirements. Posting written procedures at the experiment location for such experiments is a good practice.

Since 2004 when the design change for installation and use of the NIF was approved, the NIF has been upgraded with various collimators, improved shielding, shutter maintenance, and installation of new experimental equipment (e.g. sample positioning and imaging). These upgrades were considered maintenance and were made using existing procedures and experiment protocols. It would be prudent to re-evaluate the design of experimental facilities at the reactor whenever major maintenance is performed, especially if protective circuits are involved. This would typically involve re-evaluation of the experimental facility design and may identify design flaws or failure modes not previously considered.

Corrective Actions:

A shutter malfunction and a design flaw with the door interlock caused this incident. Facility procedures and 10 CFR 20 requirements for wearing dosimetry and HRA entry were violated. Several corrective actions have been identified as a result of this incident and are listed below:

1. The reactor has been shut down since this incident occurred except for dose evaluation of this incident. Reactor operations will resume as specified in Technical Specification 6.6.2.
2. The end stop bolt that prevented the NIF shutter from closing has been replaced with a cylindrical block that is unlikely to get caught on the shutter end stop.
3. A retaining bar has been installed at the base of the shutter to prevent the shutter rotating drum from moving outward.
4. The shutter closed position switch AND a radiation monitor have been connected to the NIF door interlock. The shutter must now be fully closed AND the radiation monitor reading must be below a radiation set point for the NIF door to open from the outside. For egress reasons, the Exit Permit Pushbutton on the inside of the NIF remains as designed causing the shutter to close and the NIF door to open. Similar arrangements with a radiation monitor interlock are being planned for installation at the Primary Piping Vault door and Positron Facility door.
5. A shutter opening delay circuit will be added, including warning lights and audible alarms. This delay will alert people that the shutter is about to open.
6. A "DANGER" message has been added to the NIF Shutter Control Computer while the shutter is not fully closed.

7. Additional shutter open indicator lights have been installed at the door handle and inside the NIF.

8. All NIF users will be trained on the NIF operation instructions, interlocks, dosimetry requirements, HRA controls, and emergency response before NIF operations resume.

9. Testing of the NIF interlock prior to each day of use will be performed by using an approved procedure. Interlocks at the Primary Piping Vault and Positron Facility will be performed using an approved procedure. RSAC review and approval is required for procedure changes.

10. Instructions for operation of experimental facilities, including emergency response, will be posted at experimental facilities capable of producing a HRA.

11. NVLAP and alarming dosimeters with a coded tag (bar code or proximity tag, etc) will be required for entry into the NIF. Equipment for this capability will be installed on or before 1 Mar 2011. Similar arrangements are planned for installation at the Primary Piping Vault door and Positron Facility door. In the interim, a Radiation Work Permit will be used to track personnel dose.

12. NVLAP dosimeters with a coded tag will be required for entry into the reactor bay. Equipment for this capability will be installed on or before 1 Mar 2011. In the interim, daily spot checks on wearing of personnel dosimetry will be conducted by the RHP.

13. Changes to the NIF shutter and interlock will be documented in a facility design change. This design change shall be approved by RSAC prior to placing the NIF in service. Similar design changes will be prepared for the Primary Piping Vault and Positron Facility. These design changes will include interlock testing.

14. Control room annunciation will be generated if the NIF door is not secure with the shutter not closed or if radiation levels are above the set point. Automatic protective actions (i.e. reactor trip) are being considered.

15. A modification review program using an approved procedure for major maintenance to the facility or experiments will be implemented by 1 Feb 2011.

16. The radiographer's access to the reactor building has been suspended until he completes remedial training.

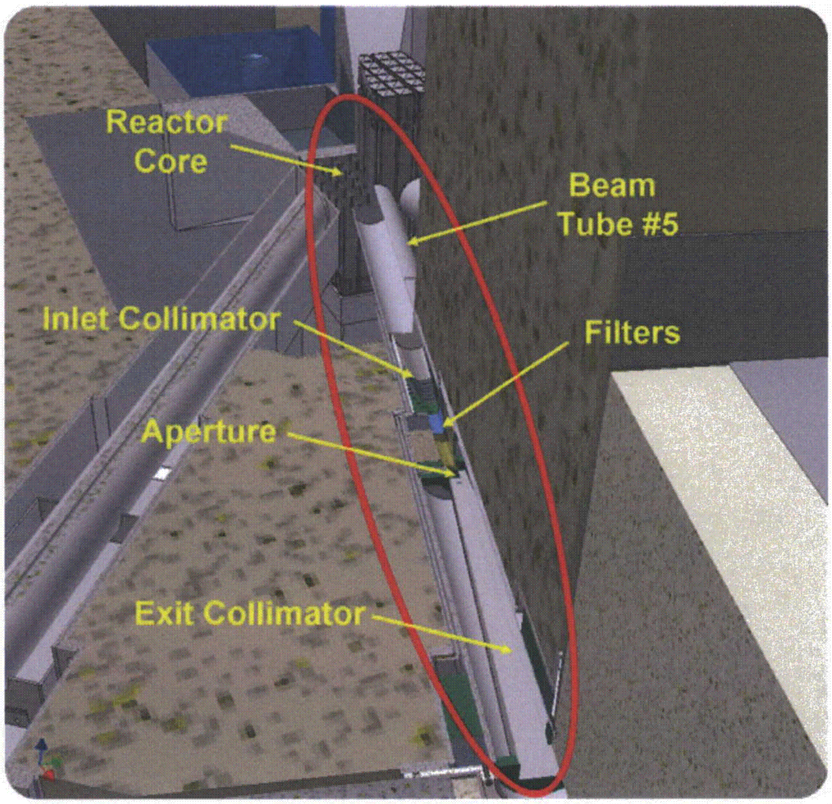
17. A dose estimate of 150 mrem has been assigned to the radiographer for this incident. The radiographer's administrative dose limit for 2011 will be reduced by 150 mrem.

18. Conducting and documenting training on written procedures for experimental facilities capable of producing HRA will be performed for all qualified experimental facility users by 1 Feb 2011.

ATTACHMENT 1 NCSU Neutron Imaging Facility (NIF)

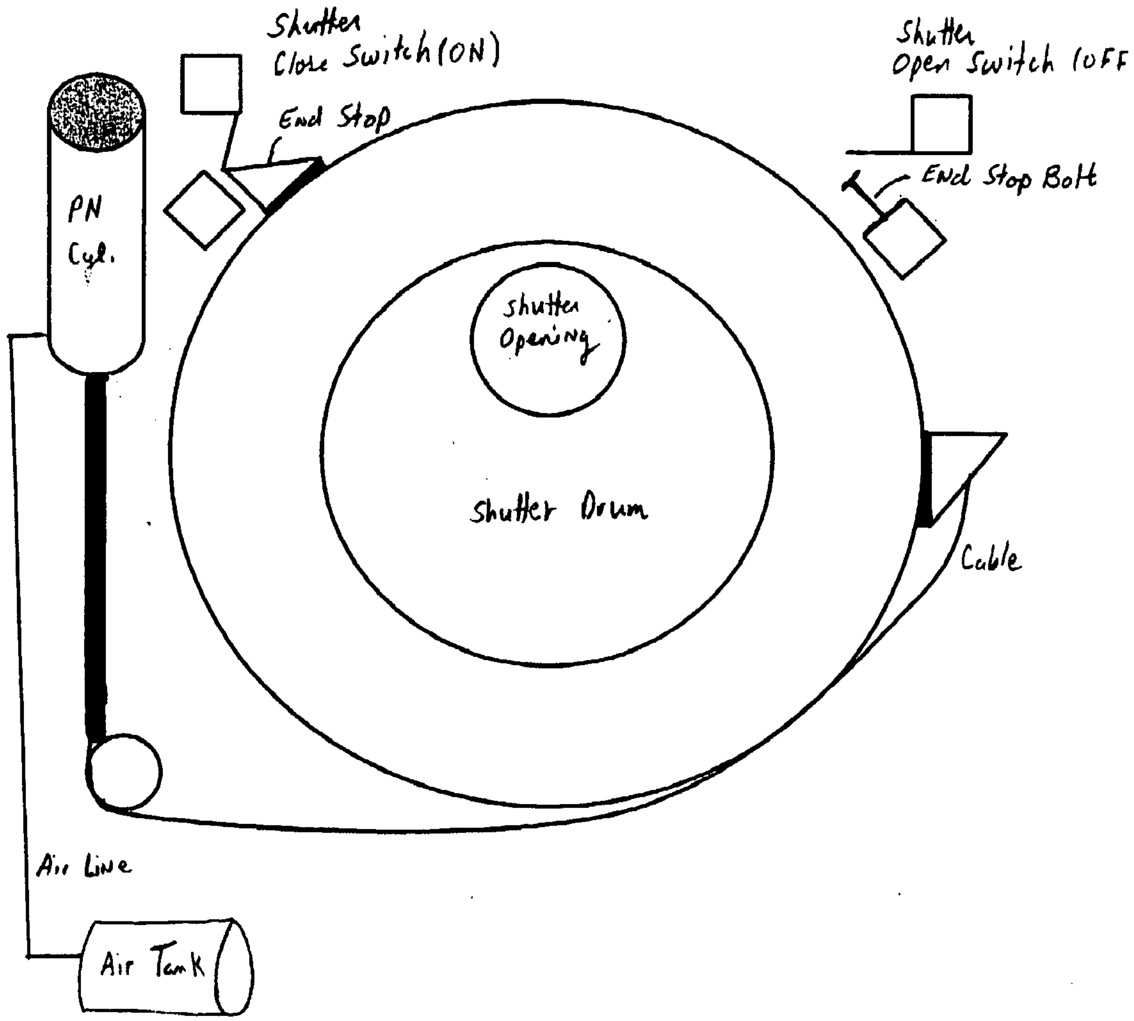
The Neutron Imaging Facility is installed at beamport #5 of the PULSTAR reactor. The beam is collimated and filtered.

Beam tube #5 – cutaway view of NIF collimator assembly

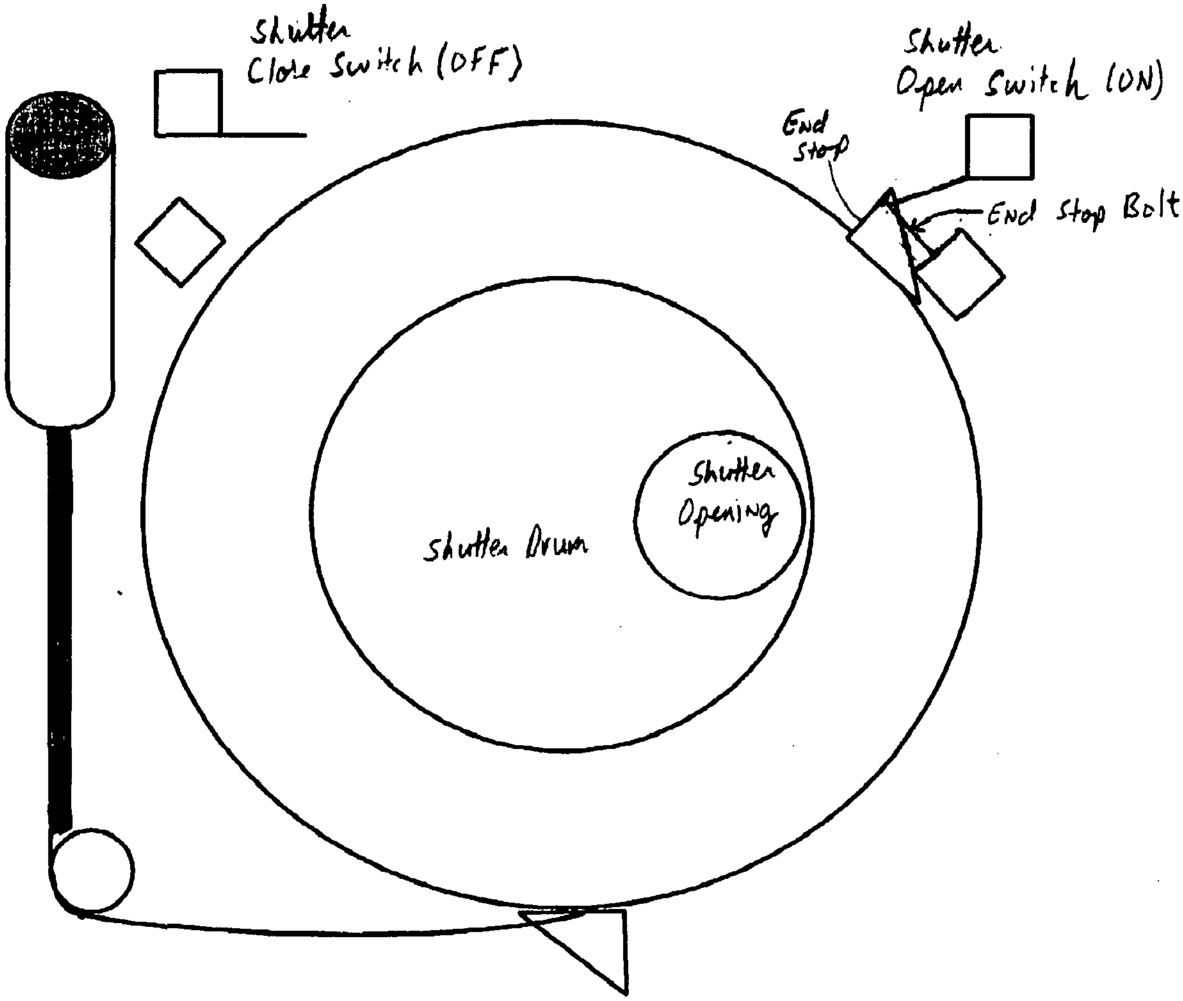


Fluence rate at the imaging plane in its current configuration is reported to be 1.8 E6 n/cm^2/sec.

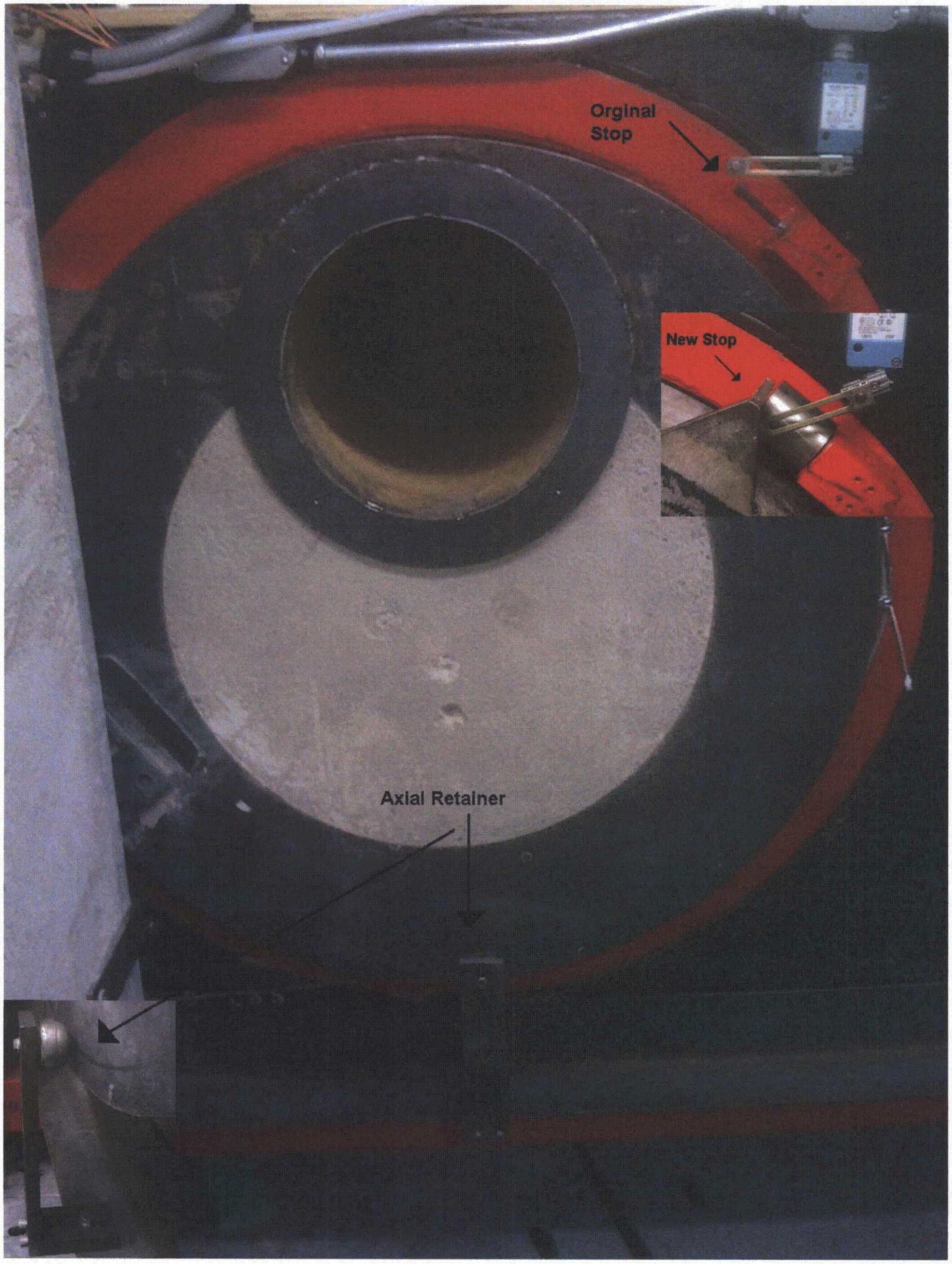
ATTACHMENT 2 NIF SHUTTER in CLOSED POSITION



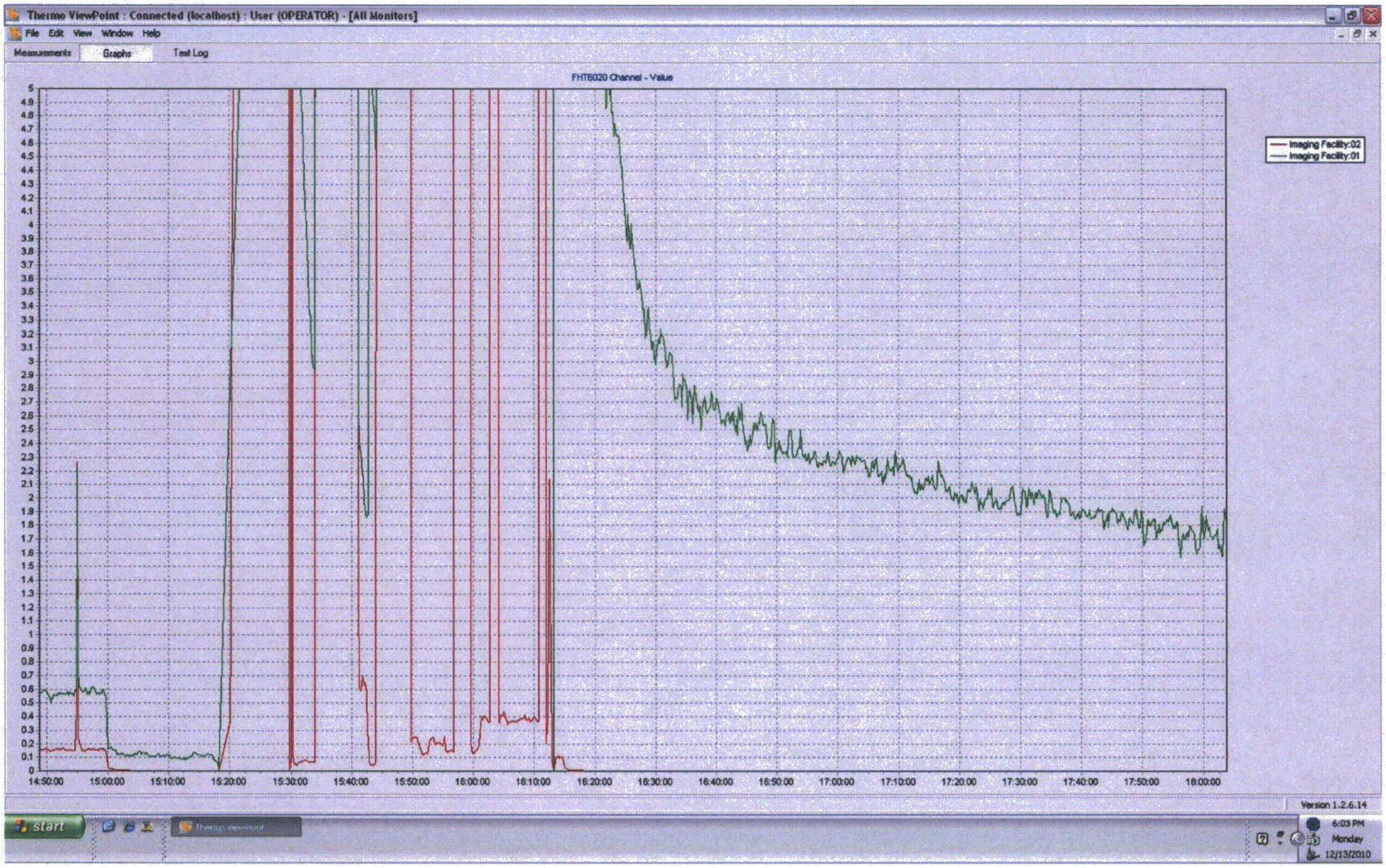
ATTACHMENT 2 NIF SHUTTER in OPEN POSITION



ATTACHMENT 2 NIF SHUTTER



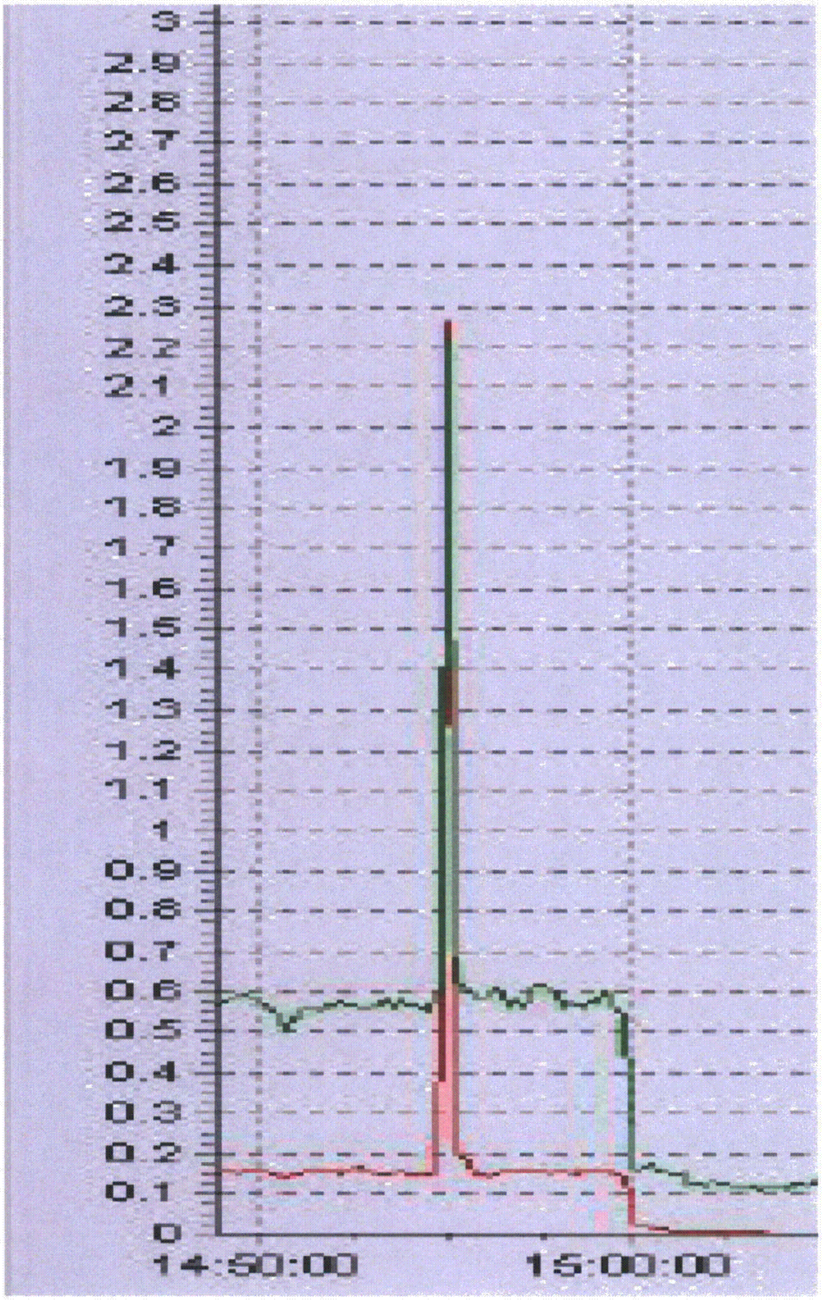
ATTACHMENT 3 **NIF Radiation Monitor Display (screenshot) for 13 Dec 2010**



The incident alarms (spikes) are shown on the left side of the display. The remaining display is from the dose evaluation with the radiation detectors located inside the NIF.

ATTACHMENT 3 **NIF Radiation Monitor Display (expanded screenshot)**

Alarm setpoints are 2 mrem/h for the gamma (green line) and neutron (red line) detectors. Both detectors went into alarm. The time stamp on the radiation monitor computer is 10 minutes slower than the security video computer. Therefore, the alarm (spike) occurred at approximately 3:05 pm, which matches the NIF entry time by the radiographer.



ATTACHMENT 4 **Radiation Survey**

ATTACHMENT 1
RADIOLOGICAL SURVEY

DATE: 13 Dec 2010 POWER: 0.1 to 1 MW

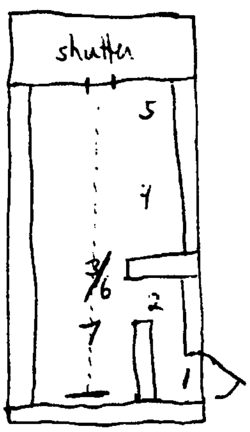
EQUIPMENT: MODEL SN CAL DATE

MODEL	SN	CAL DATE
(a) Ludlum 5	6211	Dec 2010
(b) Ludlum 12-4	19801	Sep 2010
(c) Thermo FH T6020	771	Jan 2010

LOCATION: NIF Cave

DATA:

Location	mR/h (γ)	Neutron mrem/h	Reactor Power (kW)
1	1 (a)	N/A	shut down
2	3	↓	↓
3	70	↓	↓
4	10	↓	↓
5	10 ↓	↓	↓
6	2200 (c)	2750 (c)	100
6	5200 (c)	off scale (c)	1000
7	750 (c)	2000 (b)	100
7	4250 (c)	8000 (b)	400
7	6200 (c)	offscale	1000 – cassette removed
cassette + parts	5 @ 1'	–	



COMMENTS: Locations 1-5 were made by entering the NIF
Locations 6+7 were made remotely and by use of cameras

over 2 →

PERFORMED BY: Gerald Wicks RHP: [signature]

IN mR. 32.4
OUT mR: 32.7

9

ATTACHMENT 5 Test Dosimeter Readings

NC STATE UNIVERSITY
RAD PROT ENV HLTH-SFTY
CAMPUS BOX 8007
2620 WOLF VILLAGE WAY
RALEIGH NC 27695

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RADIATION DOSIMETRY REPORT

** EMERGENCY PROCESSING **

ACCOUNT NO.	SERIES CODE	ANALYTICAL WORK ORDER	REPORT DATE	DOSIMETER RECEIVED	REPORT TIME IN WORK DAYS	PAGE NO.
44485	APQ	1034920001	12/17/10	12/15/10	2	1 OF 1

PARTICIPANT NUMBER	NAME	DOSIMETER	USE	RADIATION QUALITY	DOSE EQUIVALENT (MREM) FOR PERIODS SHOWN BELOW			QUARTERLY ACCUMULATED DOSE EQUIVALENT (MREM)			YEAR TO DATE DOSE EQUIVALENT (MREM)			LIFETIME DOSE EQUIVALENT (MREM)			RECORDS FOR YEAR	INCEPTION DATE (MM/YY)	SERIAL NUMBER	SEQUENCE NUMBER
	ID NUMBER BIRTH DATE SEX				DEEP DDE	EYE LDE	SHALLOW SDE	DEEP DDE	EYE LDE	SHALLOW SDE	DEEP DDE	EYE LDE	SHALLOW SDE	DEEP DDE	EYE LDE	SHALLOW SDE				
FOR MONITORING PERIOD:					10/01/10 - 12/31/10				QTR 4			2010								
10635	CLASS 3	Ja	WHBODY	*PH	105	105	98	105	105	98	166	168	169	1193	1198	1216	4	01/99	4510502	2
13251	TEST TEST	Ja	WHBODY	*PN	171	171	163	171	171	163	171	171	163	171	171	163	1	10/10	4510499	1
	000121410 01/01/1991 M			*PH	141	141	133													
				*NF	30	30	30													

M: MINIMAL REPORTING SERVICE OF 1 MREM
* - NO CONTROL SUBTRACTED, 6 MREM PER MONTH SUBTRACTED
ELECTRONIC MEDIA TO FOLLOW THIS REPORT

QUALITY CONTROL RELEASE: JAS 2S - PR 9657 - RPT1304- N1 C - 34901

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NVLAP LAB CODE 100518-0**

The values for 10/1/10-12/31/10 are from the dosimeter testing.

The CLASS 3 dosimeter was exposed for 60 seconds at 1,000 kW with no scattering media present. This gives a dose-equivalent rate of 6,300 mrem/h. No neutron dose was recorded.

The TEST TEST dosimeter was exposed for 60 seconds at 1000 kW with a beam target (cassette) present and mounted on a polyethylene slab. The gamma dose-equivalent rate is 8,460 mrem/h. The fast neutron dose-equivalent rate is 1,800 mrem/h.

ATTACHMENT 6 Dose-Equivalent Estimate

Gamma Dose-Equivalent Rate Estimate:

The gamma exposure rate is scaled from the 100 kW and 400 kW survey readings in Attachment 4 to 1,000 kW to give the following:

Survey reading / power in kW * 1,000 kW = Full power survey reading

(750 mR/h / 100 kW) (1,000 kW) = 7,500 mR/h

(4,250 mR/h / 400 kW) (1,000 kW) = 10,625 mR/h

The reading of 6,200 mR/h at 1,000 kW in Attachment 4 was taken without the cassette present. The cassette provides a scattering media and source of capture gamma photons.

The "CLASS 3" dosimeter results from Attachment 5 indicate a gamma dose-equivalent rate with no beam target present of 6,300 mrem/h (105 mrem/min * 60 min/h) This is good agreement with the survey reading from Attachment 4 of 6,200 mR/h.

From Attachment 5 data, the "TEST TEST" dosimeter vs. the "CLASS 3" dosimeter gives a factor of 1.343 increase (141/105) with scattering media present. Using this factor and the exposure rate in mR/h without scattering media present estimates the exposure rate in mR/h with scattering media present at 1,000 kW:

mR/h without scattering media * 1.343 = mR/h with scattering media present

where, 1.343 = 141 mrem / 105 mrem

(6,200 mR/h)(141 mrem / 105 mrem) = 8,327 mR/h

The "TEST TEST" dosimeter results from Attachment 5 indicate a gamma dose-equivalent rate of 8,460 mrem/h (141 mrem / min * 60 min /h). This is in good agreement with the adjusted survey reading of 8,326 mR/h at 1,000 kW.

Based on the above data, the gamma dose-equivalent rate is estimated to be 10 rem/h.

ATTACHMENT 6 Dose-Equivalent Estimate

Neutron Dose-Equivalent Rate Estimate:

The neutron dose-equivalent rate is scaled from the 400 kW survey reading in Attachment 4 to 1,000 kW to give the following:

$(H / 400 \text{ kW})(1{,}000 \text{ kW}) = H_{FP}$

Where, H is neutron dose-equivalent rate in mrem/h and

H_{FP} is neutron dose-equivalent rate in mrem/h at full power

8,000 mrem/h (1,000 kW/400 kW) = 20,000 mrem/h

The survey meter is calibrated for thermal and fast neutrons.

The fast neutron dose-equivalent rate is taken from Attachment 5 to be 1,800 mrem/h (30 mrem / min * 60 min/h).

The thermal neutron dose-equivalent rate is estimated to be 18,200 mrem/h (20,000 – 1,800 mrem/h).

The reported neutron flux at the image plane is 1.8 E6 $cm^{-2}s^{-1}$. The imaging plane is located at 6.5 m from the beam aperture. The radiographer was located at 4.25 m from the aperture as determined by his re-enactment and the location of his abandoned items. Based on inverse square law, the neutron flux at the radiographer's position is estimated to be 4.21 E6 $cm^{-2}s^{-1}$ [1.8 E6 $*(6.5/4.25)^2$]

Using the dose conversion factor (DCF) for thermal neutrons from 10 CFR 20 of 980 E6 cm^{-2} rem^{-1} or 1.02 E-9 rem cm^2 and a fluence rate of 4.21 E6 $cm^{-2}s^{-1}$ for the radiographer's location, the resulting thermal neutron dose-equivalent rate is estimated as follows:

DCF * neutron fluence rate = neutron dose-equivalent rate

$(1.02E\text{-}9 \text{ rem cm}^2)(4.21E6 \text{ cm}^{-2}\text{s}^{-1})(1000 \text{ mrem/rem})(3600 \text{ s/h}) = 15{,}460 \text{ mrem/h}$

Combining the thermal neutron estimated dose-equivalent rate with the measured fast neutron dose-equivalent rate from the "TEST TEST" dosimeter gives a total neutron dose-equivalent rate of 17,260 mrem/h (15,460 + 1,800). This is in good agreement with the scaled survey meter reading from Attachment 4 of 20,000 mrem/h shown above.

Therefore, the total neutron dose-equivalent rate is taken to be 20 rem/h.

ATTACHMENT 6 Dose-Equivalent Estimate

Dose-Equivalent Estimate for the Incident:

Using the estimated dose-equivalent rates for gamma photons and neutrons and a maximum stay time of 18 seconds gives the following total dose-equivalent for this incident:

Neutron:	100 mrem (20,000 mrem / 3600 s * 18 s)
Gamma photon:	50 mrem (10,000 mrem/ 3600s *18s)
Total:	150 mrem