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Radiation Predictions and Shielding Calculations for RITS-6

John E. Maenchen, John O' Malley, Ron Kensek, Wesly Fan, and Lance Bollinger

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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RADIATION PREDICTIONS AND SHIELDING CALCULATIONS FOR RITS-6

John Maenchen, John O'Malley*, Ron Kensek, Wesley Fan, and Lance Bollinger
Sandia National Laboratories
Albuquerque, New Mexico 87185
Atomic Weapons Establishment, Aldermasten, Berkshire, United Kingdom RG7 4PR

ABSTRACT

The mission of Radiographic Integrated Test Stand-6 (RITS-6) facility is to provide the underlying science and technology for pulsed-power-driven flash radiographic X-ray sources for the National Nuclear Security Administration (NNSA). Flash X-ray radiography is a penetrating diagnostic to discern the internal structure in dynamic experiments. Short (~50 nanosecond (ns) duration) bursts of very high intensity X-rays from mm-scale source sizes are required at a variety of voltages to address this mission. RITS-6 was designed and is used to both develop the accelerator technology needed for these experiments and serves as the principal test stand to develop the high intensity electron beam diodes that generate the required X-ray sources.

RITS is currently in operation with three induction cavities (RITS-3) with a maximum voltage output of 5.5 MV and is classified as a low hazard non-nuclear facility in accordance with CPR 400.1.1, Chapter 13, *Hazards Identification/Analysis and Risk Management*. The facility will be expanded from three to six cavities (RITS-6) effectively doubling the operating voltage. The increase in the operating voltage to above 10 MV has resulted in RITS-6 being classified as an accelerator facility. RITS-6 will come under DOE Order 420.2B, Safety of Accelerator Facilities.

The hazards of RITS are detailed in the "Safety Assessment Document for the Radiographic Integrated Test Stand Facility". The principal non-industrial hazard is prompt x-ray radiation. As the operating voltage is increased, both the penetration power and the total amount (dose) of x-rays are increased, thereby increasing the risk to local personnel. Fixed site shielding (predominantly concrete walls and a steel/lead skyshine shield) is used to attenuate these x-rays and mitigate this risk. This SAND Report details the anticipated x-ray doses, the shielding design, and the anticipated x-ray doses external to this shielding structure both in areas where administrative access control restricts occupation and in adjacent uncontrolled areas.

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RITS PULSED POWER DRIVE

RITS-6 is a high-energy, linear induction machine designed to study both pulsed power and high-intensity electron beam diode technologies required for flash X-ray radiography. The configuration utilizes six induction cavities to achieve a theoretical maximum of 12 MV with either a single (80 ohm) or double (45 ohm) pulse formation structure.

RITS has been operated with up to three induction cavities with a maximum 5.5 MV pulse (RITS-3), Figure 1 provides a schematic of the 60 ft wide, 30 ft long, and 16 ft high six cavity, double-sided-drive RITS-6 facility that is being updated from RITS-3. The RITS-6 pulsed power technology has been thoroughly described elsewhere[1],[2].

Each pulse formation line provides a 1.5-MV, 190 kA, 60-ns output pulse which are applied in a variety of ways. In RITS-3 (the red portion of Figure 1b) and in the initial configuration of RITS-6, only the north tank will be utilized so a single 190-kA pulse will be delivered to each induction cavity. In another configuration (the red and blue portions together), each of the six pulses from the North PFLs will be combined with the matching pulses from the south set to drive each induction cavity at the same voltage but with twice the current (about 380 kA). Finally, one tank may be delayed with respect to the other, driving each cell with two temporally-separated 190-kA pulses to investigate multi-pulse flash radiographic sources.

[1] "Advances In Pulsed Power-Driven Radiography Systems", Maenchen, J; Cooperstein, G; O'Malley, J; and Smith, I., Proceedings of the IEEE; July 2004; vol.92, no.7, p.1021-1042.
[2] "Safety Assessment Document for the Radiographic Integrated Test Stand Facility – 6", 2005.

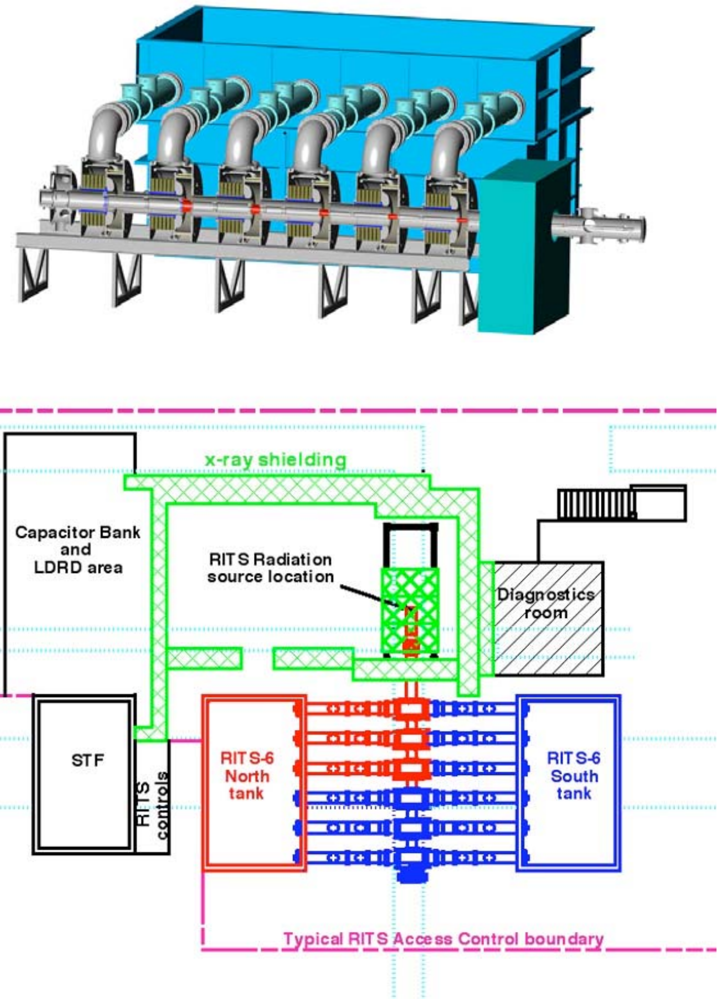

Figure 1 (a) RITS-6 Accelerator cutaway, (b) Plan view showing existing RITS-3 (red) and planned expansion (blue) in the context of the surrounding radiation shielding

Each induction cavity serves as a primary turn in a transformer coupled to a common vacuum coaxial transmission line secondary. Thus the voltages from each cavity add only in the vacuum region, providing high voltage to an electron beam diode in the heavily shielded radiation cell.

RITS-6 is designed as a balanced-risk accelerator, where the probability of performance failure is roughly constant through the power-compression chain. However, the weakest link is designed (and has been determined) to be the oil-vacuum dielectric barrier within the induction cavity. This barrier shorts at voltage pulses approaching 2 million volts, so the six cavity RITS-6 accelerator will be unlikely to produce voltages in excess of 12 MV.

A short duration (60-ns), high voltage (>10 MV), high current (>125 or > 250 kA) electromagnetic pulse is applied to an evacuated coax operating as a Magnetically Insulated Transmission Line (MITL). In this structure about half of the current is carried in the cathode conduction band, and half in vacuum electrons drifting as a sheath between the electrodes at about 80% the speed of light. MITLs can operate as a special kind of transformer when mismatched to transitions or to the termination load. The MITL impedance cannot support a voltage larger than that impressed by the accelerator since the sheath is a free boundary[3]

[3] J. M. Creedon, "Magnetic cutoff in high current diodes," J. Appl. Phys., vol. 48, no. 3, pp. 1070-1077, March 1977.

and becomes a parallel load when the load does not accept adequate current. When a transition or load is undermatched, some fraction of the sheath may be retrapped into the cathode conduction band with a relatively small voltage loss. Since radiographic diodes typically only utilize this cathode current and shunt the sheath flow away to low damage and low-radiation-producing regions, retrapping can significantly increase the "useful" power available for high intensity dose production[4]. Figure 2 shows the relationship between the load voltage and the total and the boundary (cathode) currents for RITS-6 in the single and double-tank configurations, respectively, for normal charge voltage operation.

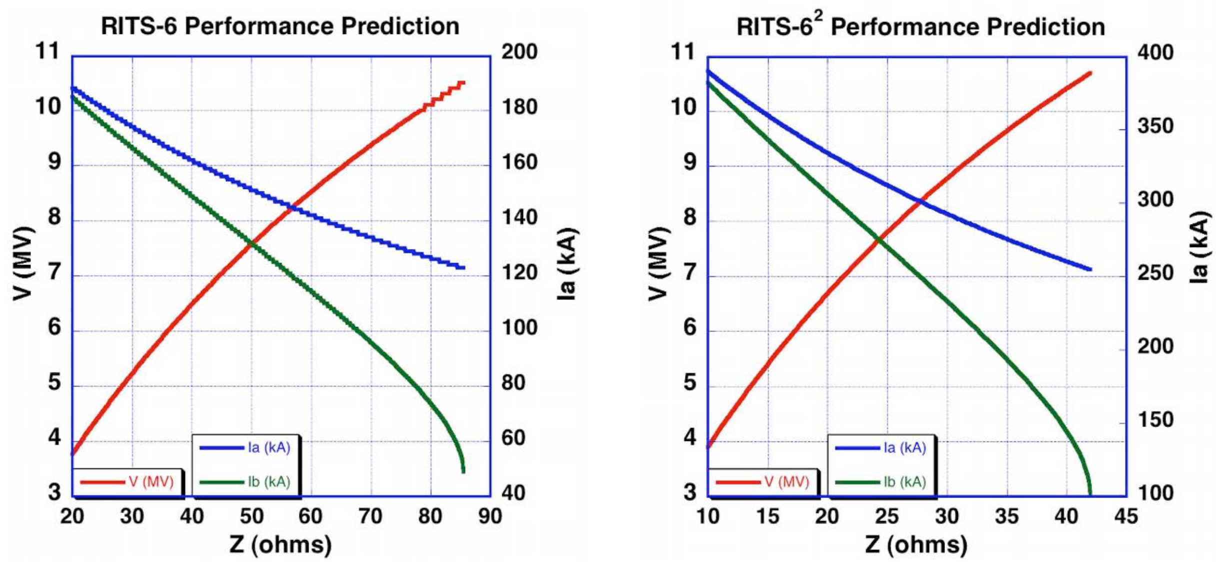

Figure 2 Voltage and Current amplitudes for varying load impedances
(left) One tank (8-ohm) drive into a 9-ohm MITL step
(right) Two tank (4-ohm) drive into a 7-ohm MITL step

RADIATION PRODUCTION

When this composite pulse arrives at the termination of the coax MITL, the "diode" load converts the electromagnetic pulse into a directed electron beam designed to address specific mission deliverables. The two generic diodes we will discuss are a "blade" and a "radiographic" load. The blade load couples all the current (both conduction and sheath) as a large area, low intensity configuration into an anode (grounded) electrode. The several radiographic diodes under development convert the conduction current into a highly focused electron beam which impinges at great intensity on the anode electrode, while the sheath current is shunted at large radius and low intensity to ground. These radiographic diodes typically operate at impedances much greater (~200 ohms) or less (~40 ohms) than the RITS MITL, resulting in electron beam diode voltages from 7 to 12-MV.

When these relativistic electrons are suddenly stopped in the anode electrode (or, in some cases, pass through a very thin anode foil to stop in a distant grounded x-ray converter), Bremsstrahlung x-ray radiation is produced[5]. The Bremsstrahlung yield (dose) scales roughly as the square root of the target atomic number. Therefore low-Z targets such as Carbon minimize dose, while high-Z targets such as Gold,

---

4 V. Bailey et. al. "Retrapping of Vacuum Electron Current in Magnetically Insulated Transmission Lines", Proceedings of the 15th International Conference on High-Power Particle Beams, St. Petersburg, Russia, 7/18-7/23, 2004.

5 J.D. Jackson, Classical Electrodynamics, J. Wiley and Sons, 1962.

Tungsten, and Tantalum maximize dose. These x-rays are both the desired outcome of the experiments (the radiographic x-ray source) and the principal hazard in operating this facility.

A series of MCNP[6] calculations were performed to characterize this radiation source for RITS-6 parameters[7]. A typical code deck is provided in Appendix A. The electrons are assumed to be mono-energetic at 12 MeV (the maximum credible operating voltage on RITS-6) and forward directed (aimed toward 0 degrees), which maximizes the forward dose. This configuration is correct for the blade load and ideal for radiographic diodes. The resulting photon spectra and polar dose profiles for Carbon and Tungsten converters are shown in Figures 3 and 4. Converter thicknesses of 10mm and 1.2mm were used for carbon and tungsten targets respectively. For carbon this is a typical thickness of converter used in repetitive blade load applications. For tungsten this was based on the nominal optimal target thickness to maximise the intensity of Bremsstrahlung radiation production. Note that the photon spectral shape is largely independent of angle – only the amplitude changes significantly. The severe dose reduction orthogonal to the beam direction is due to the assumption of an extended x-ray converter, which provides self-absorption only in this direction. Since radiographic diodes loads illuminate 3D converters from a variety of angles, this 90° data point was removed and the polar profile was interpolated for all subsequent calculations, thereby creating a more general (and more conservative) x-ray angular distribution estimate.

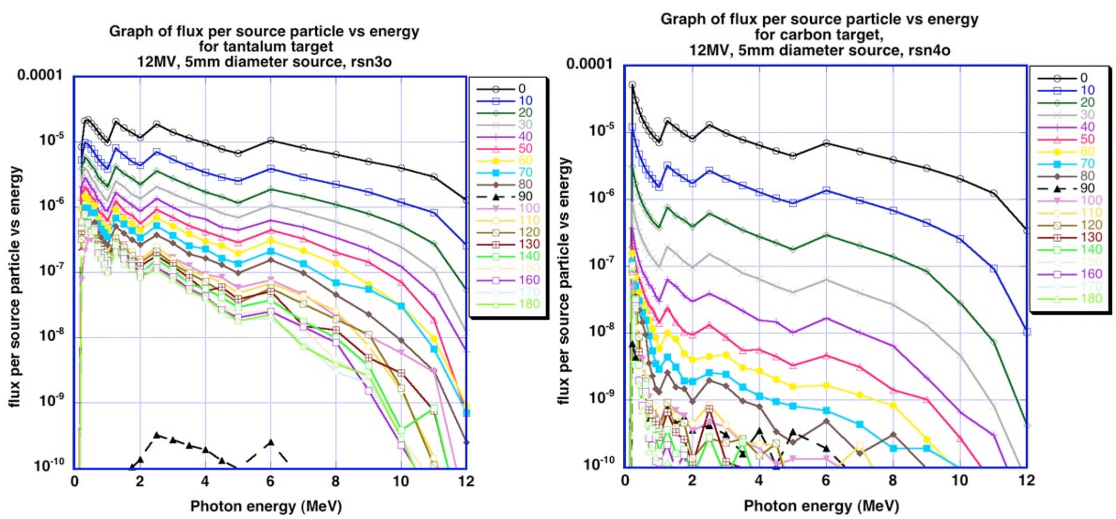

Figure 3 Calculated x-ray spectrum from a 12-MV electron beam onto a Carbon converter. Angles are indicated in degrees referenced from the initial electron direction (0°)

[6] X-5 Monte Carlo Team .MCNP-A General Monte Carlo N-Particle Transport Code, Version 5 Volume 1: Overview and Theory, LA-UR-03-1987

[7] John O'Malley, private communication

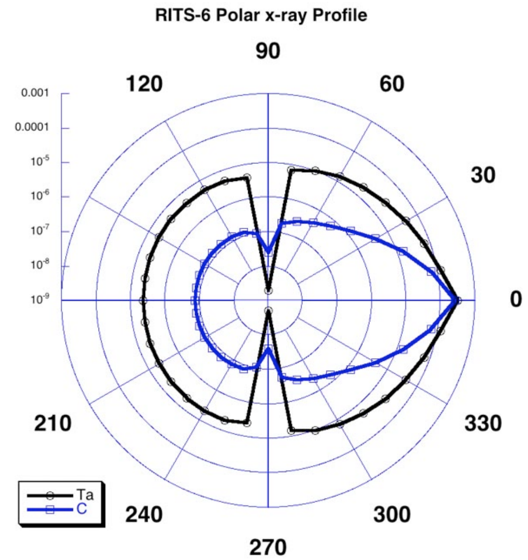

Figure 4 Resulting polar dose production profile into Carbon and Tantalum x-ray converter targets.

The above Monte Carlo calculations generated photon angular-dependent flux distributions and spectra calculated on a per-12-MV-electron basis. To extend these results to dose requires multiplying these results by the number of electrons in the RITS beam pulse. Typically the measured currents are binned against the changing voltage waveform to create a source electron spectrum. Here we calculate assuming the entire beam current is at the maximum credible voltage which overestimates the potential x-ray dose and is therefore taken as a conservative approach. Extensive investigations quantitative x-ray dose production from these diode loads have been developed over the past 30 years by the pulsed power community, using both empirical scaling and Particle-in-Cell simulations. We have compared both approaches[8] and the relevant dose scaling relationships for RITS-6 regimes can be summarized as:

Blade Diode: $\text{Dose} = Q * 150 * V^{2.8} * Z^{1/2}$
Pinched Diode: $\text{Dose} = Q * (-40.99V^3 + 1817V^2 - 1797V)$
Paraxial Diode: $\text{Dose} = Q * 1700 * V^{2.6} * \exp(-(V+0.511)*\beta_{\perp}/2)$

Where V is the voltage in MV, Q is the electron beam charge in coulombs at that voltage, and Z is the atomic number of the Bremsstrahlung target. Dose is measured in Rads 1-meter from the x-ray converter target in the forward (0°) direction. Applying these relationships to the RITS-6 drive capabilities yields the anticipated single-shot x-ray production estimates shown in Figure 5. The blade load produces more radiation than either radiographic load because it utilizes all the current (both cathode and sheath). An example of how experimenters can manage total dose is seen by comparing the blade diode with a Tantalum (high atomic number) versus a Carbon (low atomic number) converter. Both radiographic diodes assume a Tantalum converter (to maximize the dose) and are seen to produce approximately the same total yield although they operate at dramatically different impedances and function in rather different manners. These then can be used to generically bound the x-ray dose produced by all radiographic load experiments.

[8] Ian Crotch, private communication, and David Book, “NRL Plasma Formulary”, Naval Research Laboratory, Washington DC 20375, 1980.

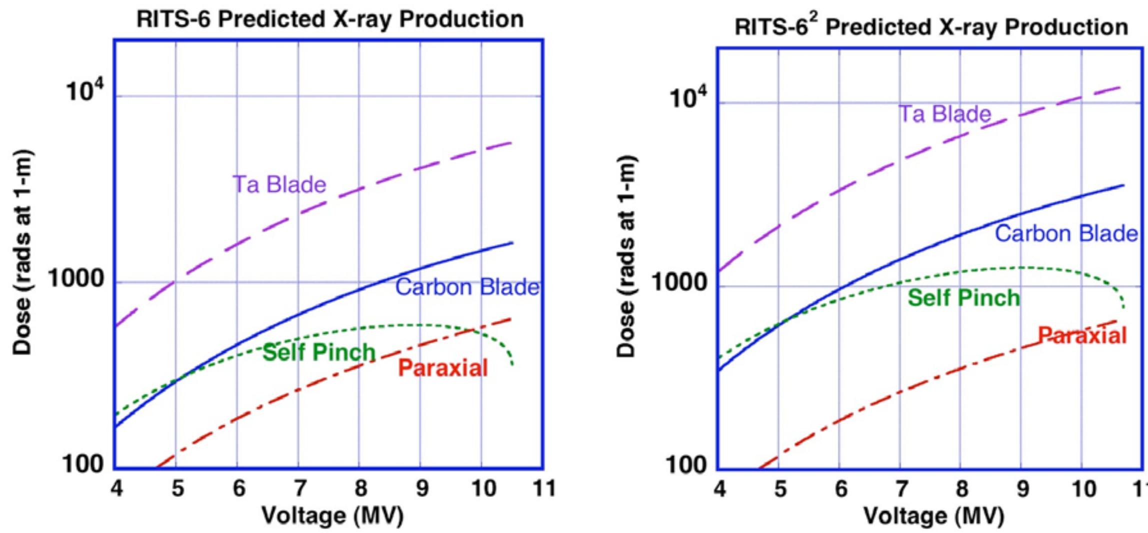

Figure 5 Radiation Production for the breadth of RITS-6 experimental configurations
One-sided-drive (8-ohm) into a 9-ohm MITL step
Two-sided-drive (4-ohm) into a 7-ohm MITL step

Recognizing that the higher voltage operation of RITS-6 will create more prompt radiation and more counter-streaming ion induced transmutation activation of the cathode materials[9], radioactivity will limit access to the diode region more than past experience on RITS-3. Blade loads do not require personnel access between shots, so multiple blade load experiments may be performed each day. Radiographic loads by definition deposit energy densities into the x-ray converter exceeding the material survivability limits, and are single shot devices. Experience suggests one shot per day is a sensible estimate. Combining these accelerator operations based again on past experience, an estimate (Table 1) of 200 diode shots per year and 60 blade load shots per year has been made. These estimates are considered typical and not absolute, as the experimental program goals and progress will determine the actual mix and sequence of shots. This combination of experiments is expected to produce about 284 kRads per year, measured 1-meter in front of the x-ray source. The possible future two-sided-drive configuration could produce about twice the dose, as seen in Figure 5. This total dose estimate will be used, along with the polar distribution and spectrum discussed earlier, in the design of the RITS-6 shielding system.

[9] F. Young and D. Rose, "Radioactivities Produced In Commonly Used Materials By Proton And Deuteron Beams Up To 10 MeV", Atomic Data And Nuclear Data Tables 64, 223–251 (1996).

Table 1 RITS anticipated shot distribution and dose		
RITS-6 blade load highest plausible operational dose	2000	R@m
Maximum blade load shots per year	60	
RITS-6 radiographic diode highest plausible dose	800	R@m
Maximum radiographic diode shots per year	205	
total annual dose	284,000	R@m
Shot number estimate basis		
year	52	wks/yr
holiday	3	wks/yr
facility maintenance	4	wks/yr
available weeks	45	wks/yr
Blade load	15	shots/wk
Diode load	5	shots/wk
Blade load time	4	weeks
Blade load shots	60	shots
Diode time	41	weeks
Diode shots	205	shots
Shot history on RITS		
2002 = 216; 2003 = 198; 2004 = 255; 2005 = 103 as of 4/21/05		

RITS X-RAY SHIELDING DESIGN

Sandia's Radiation Protection Program[10] specifies that occupational workers and the general public are allowed up to 100 mrem per calendar year doses without supervisory permission. The SNL ALARA (As Low As Reasonably Achievable) program[11] further guides radiation exposure controls to reduce worker doses to the extent possible. The x-ray shielding controls on RITS are designed to meet these guidelines.

An extensive series of Monte Carlo calculations were performed by Ron Kensek, Wesley Fan, and Diana Wrobel using the ITS code[12] to assess the effectiveness of variations in the RITS-6 proposed shielding structures. An existing CAD model of the facility was imported in ACIS™ format to become the baseline ITS geometry, iterated to adjust units and to separate structures such as the trenches in the floor, and modified to investigate shielding variations with the use of Sandia National Laboratories' CUBIT software.

ITS was modified in two ways to perform these calculations. The source was a coupled energy/angular distribution corresponding to the Ta converter shown in Figure 3. First the sampling was performed on the total angular distribution for the Ta converter shown in Figure 4 (modified as already discussed to remove the depression at 90°). Point values were given from previous MCNP flux calculations – a distribution was obtained by interpolating linearly in the cosine of the angle. Once the angle was determined, the spectrum was sampled from those from Figure 4.

Since this was a deep shielding calculation requiring many histories to obtain reliable statistics, a last-flight estimator was added to the ITS flux tally as had already been done to a previous version for similar calculations.[13.] This included a flux fold with the flux-to-dose human absorption factors. The 1977 standard[14] values were used to provide a worse-case compared to the 1991 standard[15].

---

[10] Radiological Protection Procedures Manual, Corporate Process Requirement No: CPR400.1.1.32, Revision Date: April 6, 2005.
[11] (RPPM) Chapter 7, Radiological Design and Control and ALARA Application.
[12] Brian C. Franke, Ronald P. Kensek, and Thomas Laub, "ITS Version 5.0: The Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Codes with CAD Geometry", Sandia National Laboratories Report SAND2004-5172, (2005).
[13] M.A. Sweeney and J.N. Olsen, "Monte Carlo Calculations of the Bremsstrahlung Radiation Environment Expected in the Future Particle Beam Fusion Accelerator Facility PBFA II", Nucl. Sci. Eng. pp233-246 (1985).
[14] ANSI/ANS-6.1.1-1977, American National Standard Neutron and Gamma-Ray Flux-to-Dose-Rate Factors (1977).
[15] ANSI/ANS-6.1.1-1991, American National Standard Neutron and Gamma-Ray Fluence-to-Dose Factors (1991).

While using the CAD model expedites the problem setup, it also slows the code down by a couple of orders of magnitude. Even with the variance reduction offered by the last-flight estimator, each job required sizeable resources. Hence, the calculations were performed on the Los Alamos ASC-Q machine, each typically running a total of $6x10^8$ histories on 300 processors in about 10 hours. A few calculations were run with four times as many histories (to reduce the variance by a factor of two). Confidence of the results is obtained from obtaining the expected general scaling of the variance in these longer runs and the lack of statistical anomalies over the set of results. It was also desired to keep the values of the statistical uncertainties reasonably low (about 10% or less) – but this was relaxed by running most of the calculations with somewhat higher statistics and having a few longer running jobs. The results of a typical run can be seen in Figure 7.

Figure 1b displays the final x-ray shielding structure in green, and Figure 6 provides more detail. The predominant shielding is the test cell boundary wall, where 2' x 3' x 6' concrete blocks are stacked into walls which surround the diode region. Trenches under the walls (marked by blue dotted lines) are filled with concrete to prevent shine and re-emission outside the cell. A 2" steel, followed by 1" lead, shield is located immediately above and beside the diode region to prevent any unattenuated x-rays from leaving this test cell. This dramatically reduces both the photon-induced transmutation of Nitrogen in the air and "skyshine", where x-ray scattering processes in the air can produce a shower of lower energy x-rays from

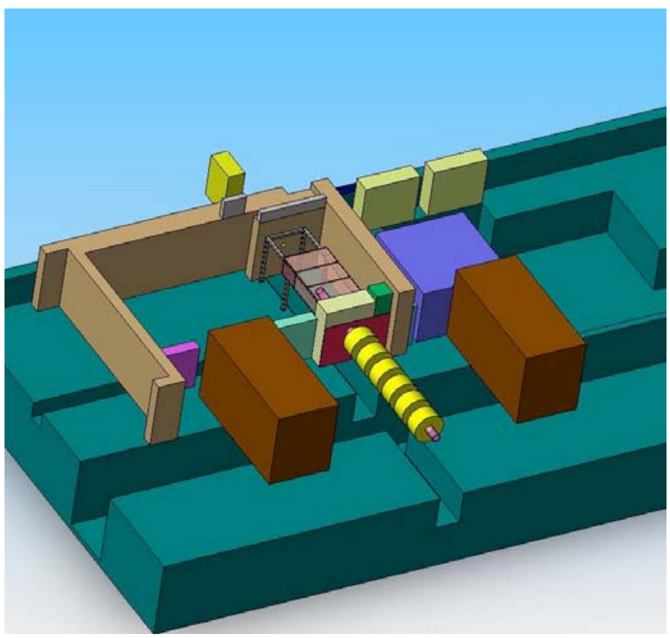

Figure 6 Detail of the RITS x-ray shielding configuration

distant and diffuse sites to increase personnel exposure in locations which would otherwise be well shielded by the test cell walls. Two 2' thick concrete walls are added to the west test cell to reduce scattered x-ray dose to populated locations outside the access control boundary, and a 1" lead barrier is placed outside the test cell wall directly to the west to attenuate direct shine in this direction. The MITL threads the entire accelerator with a vacuum coax, and would present a serious radiation hazard. An 8" thick lead shield is therefore placed at the west end of the MITL.

Two locations have 100% occupancy factors: the RITS operator console to the northwest, and the diagnostic room immediately south of the radiation source. Occasional access is allowed outside the RITS access control boundary to the west and south. The Monte Carlo runs therefore calculated x-ray attenuation at locations of concern in every direction, shown in Figure 7.

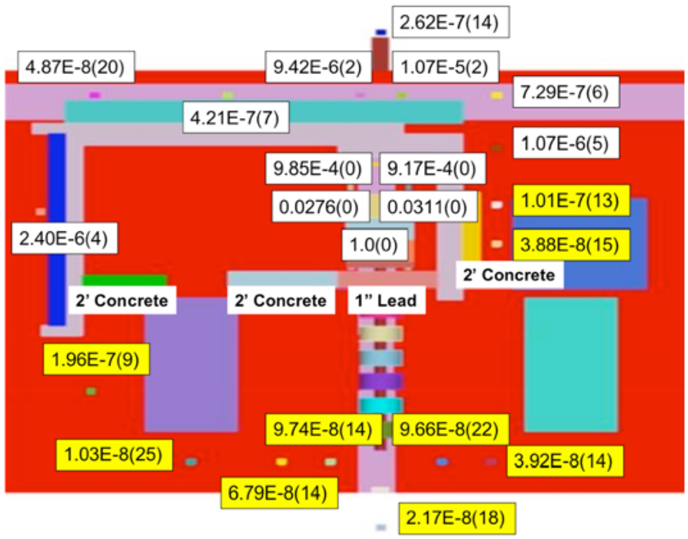

Figure 7 Monte Carlo attenuation factors at monitor locations

These Monte Carlo calculations also produced the dose and spectrum escaping from the steel and lead skyshine shield above and adjacent to the diode. Lance Bollinger used this source information to estimate the skyshine doses in the same personnel regions of concern[16]. Figure 8 shows that the skyshine contribution at personnel locations outside the access control boundary are approximately equal to (or a few times larger than) the direct penetration dose calculated by ITS (above). Prior data-skyshine calculation comparisons have shown that this approach tends to overestimate the measured dose, but serves as a sensible baseline to establish initial control levels. If measurements confirm these calculated levels, additional material may be added to the skyshine shield adjacent to the x-ray source to reduce the personnel dose per shot and therefore increase the shot count per calendar year.

[16] Lance Bollinger, private communication

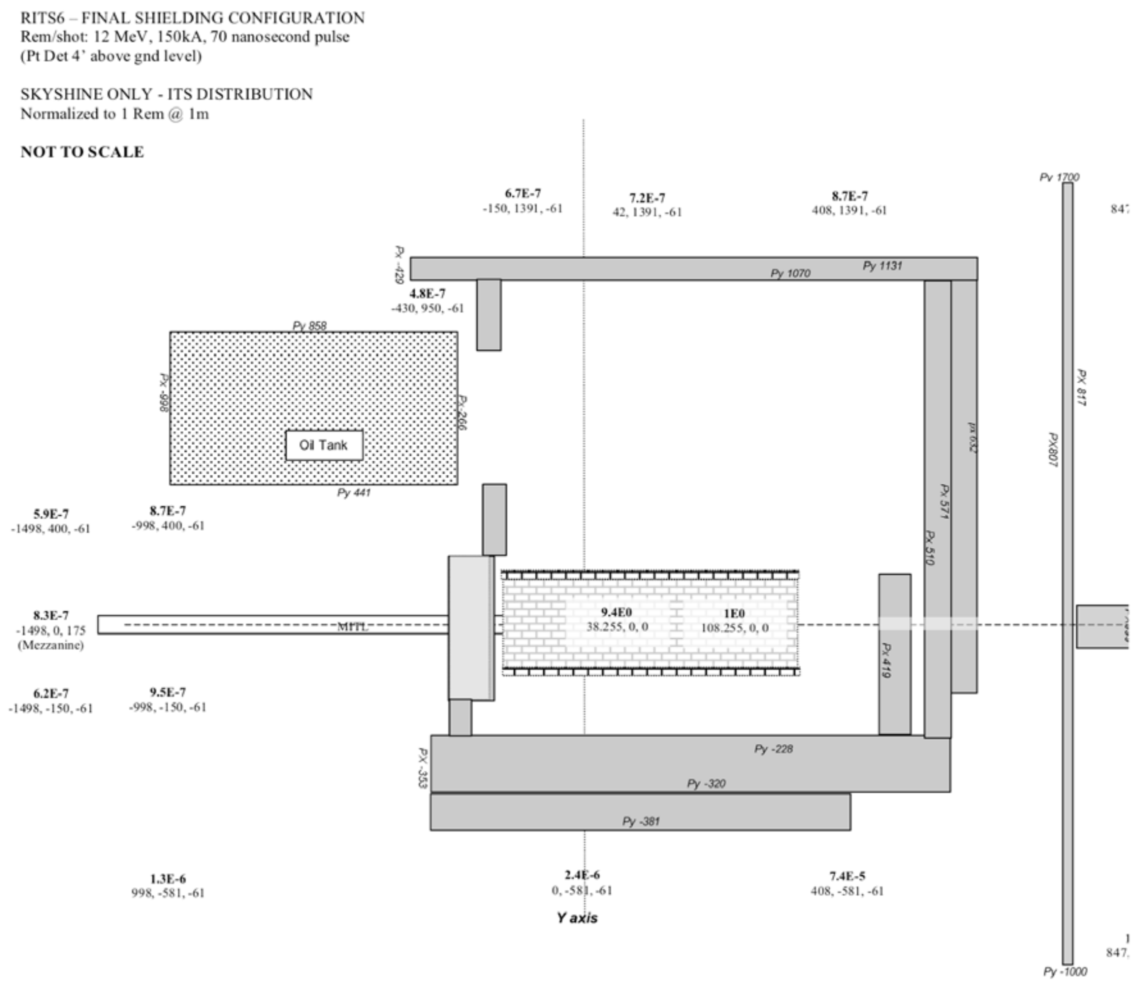

Figure 8 Skyshine dose (in terms of attenuation factors as above)

The design x-ray attenuation in 100% occupied areas is 0.1 Rad personnel dose / 284 kRad at 1-m annual prediction = 3.5e-7. Figure 8 shows that this x-ray shielding system meets this design goal for the anticipated shot sequence per calendar year. The skyshine term is additive and of about the same magnitude as the direct plus scattered x-ray dose, Experience on past pulsed power driven radiological generating devices shows that shielding calculations such as those described here are conservative but can provide general guidance, while that careful dosimetric measurements are required to verify these predictions. In general dosimetry has shown that such calculations are overly conservative.

CONCLUSIONS

The expansion of Sandia's Radiographic Integrated Test Stand (RITS) from a 5.5 MV 3-cavity facility to a > 10 MV six cavity accelerator will increase the hazard of prompt ionizing radiation. A study has been performed to estimate the x-ray dose production, the photon spectrum and angular distribution, then to design an x-ray shielding structure adequate to protect personnel. Both direct and indirect (skyshine) radiation has been considered in this design, and the calculations suggest the proposed shielding will be adequate for the anticipated RITS performance. The proposed RITS Accelerator Safety Envelope does not rely on the accuracy of these linked calculations, but rather limits RITS operation to be safe as measured by fixed site dosimetry in occupied locations.

Appendix A MCNP electron to photon conversion calculation sample deck

```
RITS 6 source term calculation
c cells
1 0 3 -10 -1 imp:p=1 imp:e=1 $ void cell, machine side
11 0 10 -5 -1 imp:p=1 imp:e=1 $ 2nd void cell, machine side
2 0 5 -6 -1 imp:p=1 imp:e=1 $ void in e-beam space
3 1 -2.3 6 -7 -9 imp:p=1 imp:e=1 $ carbon target, 2.3g/cc
4 0 6 -7 9 -1 imp:p=1 imp:e=1 $ void outside target
5 0 7 -8 -1 imp:p=1 imp:e=1 $ void cell, x-ray beam propagation side to tally
6 0 8 -4 -1 imp:p=1 imp:e=1 $ void cell, tally plane to end
7 0 -3:4:1 imp:p=0 imp:e=0 $ world cell
c surfaces
1 cy 110
2 so 100
3 py -110
4 py 110
5 py -1
6 py -0.5
7 py 0.5
8 py 100
9 cy 10
10 py -50
c physics
mode p e
c source, 12MV, 50mm (~ 2 inch) diameter beam, normally incident on target
sdef sur=5 rad=d1 ara=0.1963495408 erg=12 nrm=1 vec=0 1 0 par=3
    dir=d2 pos 0 -1 0
si2 0.9999999
si1 0.25
sp2 -21 $ ensures correct area sampling from source
m1 6000 -1 $ pure carbon target
e0   .1 .2 .3 .4 .5 .6 .7 .8 .9 1 1.25 1.5 1.75 2 2.5
     3 3.5 4 4.5 5 6 7 8 9 10 11 12 13
cut:p   j 0.1 $ don't transport sub 100keV photons, energy dumped locally
cut:e   j 0.1 $ don't transport sub 100keV electrons, energy dumped locally
c tally photons vs energy every ten degrees
f5:p 0 100 0 0
f15:p 17.36482 98.48078 0 0
f25:p 34.20201 93.96926 0 0
f35:p 50 86.60254 0 0
f45:p 64.27876 76.60444 0 0
f55:p 76.60444 64.27876 0 0
f65:p 86.60254 50 0 0
f75:p 93.96926 34.20201 0 0
f85:p 98.48078 17.36482 0 0
f95:p 100 0 0 0
f105:p 98.48078 -17.36482 0 0
f115:p 93.96926 -34.20201 0 0
f125:p 86.60254 -50 0 0
f135:p 76.60444 -64.27876 0 0
f145:p 64.27876 -76.60444 0 0
f155:p 50 -86.60254 0 0
f165:p 34.20201 -93.96926 0 0
f175:p 17.36482 -98.48078 0 0
f185:p 0 -100 0 0
ctme 60
print
```

Appendix B ITS Shielding Monte Carlo Calculation Sample deck

The following is a control deck for ITS. This file is divided up into different sections separated by the character string "{eor}" followed by a name. These different sections will be separated into different files using the name after the "{eor}".

The first ("defs") section defines how the code was built, namely with the ACCEPT (3D) option, using RNG3 (a particular option for a portable random-number generator), MPI to run on a parallel platform – in particular the Los Alamos ASC "Q" machine, and using the version 12 of the ACIS (a commercial product from Spatial Technologies) CAD libraries. The codes were built with optimization level 3.

The "prmfile" section gives input particular to the CAD portion of the code. The KD_TREE_PARAMS is an efficiency mechanism to help the slow CAD code perform geometry queries with a binary search in space. The CAD geometry files (in ACIS format, which is nearly unintelligible) are listed between the "ACIS_BEGIN" and "ACIS_END" statements. In this case, each file represents one ITS input zone.

Finally, in the last section ("mdat"), is the usual ITS keyword input. Notice the "geometry" section is empty which simply means the entire geometry is being specified through the CAD input, while the materials for each zone are listed as usual in the ITS input-keyword section.

The lines beginning "SOURCE-ENERGY-ANGLE" indicate special input for the coupled energy/angle distribution of the source for an application-specific modification of the software.

```
*include $HOME/bin/nmCVS
{eor}defs
#-------------#
# Definitions #
#-------------#
# rng  should be one of RNG1, RNG2, or RNG3
# code should be one of TIGER, CYLTRAN, or ACCEPT
# geom should be one of CAD or CG
# opt1 should be one of MITS, PCODES, or blank
# opt2 should be one of MCODES or blank
# opt3 should be one of MPI, SERIAL, or PLOTS
# opt4 should be one of DYNAMIC or blank
# opt5 should be one of ITSINP or blank
# cadv should be one of ACIS6 or ACIS12
# brep should be one of ACIS, CHOLLA, or ALL
rng=RNG3
code=ACCEPT
geom=CAD
opt1=
opt2=
opt3=MPI
opt4=
opt5=
cadv=ACIS12
brep=ALL
#----------------#
# Script options #
#----------------#
```

```
# flags can be -O, -O2, -O3, -O4, -g, -w, or blank
# email should be "no" for no email notification.
# interactive should be "no" for an uninterrupted script.
ccompileflags=-O3
fcompileflags=-O3
email=no
interactive=yes
#
# The prm, sat, and facet sections only need to be included for CAD
{eor}prmfile
ITS_BEGIN
INPUT_FILE mdat
OUTPUT_FILE output
MODE CAD_ONLY
KD_TREE_PARAMS 12 5 12 2 2 -1 0
ITS_END

ACIS_BEGIN
/chome/dlwrobe/SATELLITES/RITS/satfile2.sat 1
/chome/dlwrobe/SATELLITES/RITS/satfile4.sat 2
/chome/dlwrobe/SATELLITES/RITS/satfile7.sat 3
/chome/dlwrobe/SATELLITES/RITS/satfile18.sat 4
/chome/dlwrobe/SATELLITES/RITS/satfile19.sat 5
/chome/dlwrobe/SATELLITES/RITS/satfile24.sat 6
/chome/dlwrobe/SATELLITES/RITS/satfile27.sat 7
/chome/dlwrobe/SATELLITES/RITS/satfile33.sat 8
/chome/dlwrobe/SATELLITES/RITS/satfile39.sat 9
/chome/dlwrobe/SATELLITES/RITS/satfile40.sat 10
/chome/dlwrobe/SATELLITES/RITS/satfile44.sat 11
/chome/dlwrobe/SATELLITES/RITS/satfile49.sat 12
/chome/dlwrobe/SATELLITES/RITS/satfile56.sat 13
/chome/dlwrobe/SATELLITES/RITS/satfile61.sat 14
/chome/dlwrobe/SATELLITES/RITS/satfile62.sat 15
/chome/dlwrobe/SATELLITES/RITS/satfile71.sat 16
/chome/dlwrobe/SATELLITES/RITS/satfile73.sat 17
/chome/dlwrobe/SATELLITES/RITS/satfile78.sat 18
/chome/dlwrobe/SATELLITES/RITS/satfile83.sat 19
/chome/dlwrobe/SATELLITES/RITS/satfile86.sat 20
/chome/rpkense/explore/dlwRITS/satfile94.sat 21
/chome/rpkense/explore/dlwRITS/satfile95.sat 22
/chome/dlwrobe/SATELLITES/RITS/satfile1.sat 23
/chome/rpkense/explore/dlwRITS/fixedSats/satfile3.sat 24
/chome/dlwrobe/SATELLITES/RITS/satfile5.sat 25
/chome/dlwrobe/SATELLITES/RITS/satfile6.sat 26
/chome/dlwrobe/SATELLITES/RITS/satfile8.sat 27
/chome/dlwrobe/SATELLITES/RITS/satfile9.sat 28
/chome/dlwrobe/SATELLITES/RITS/satfile10.sat 29
/chome/dlwrobe/SATELLITES/RITS/satfile11.sat 30
/chome/dlwrobe/SATELLITES/RITS/satfile12.sat 31
/chome/dlwrobe/SATELLITES/RITS/satfile13.sat 32
/chome/dlwrobe/SATELLITES/RITS/satfile14.sat 33
/chome/dlwrobe/SATELLITES/RITS/satfile15.sat 34
/chome/dlwrobe/SATELLITES/RITS/satfile16.sat 35
/chome/dlwrobe/SATELLITES/RITS/satfile20.sat 36
/chome/dlwrobe/SATELLITES/RITS/satfile21.sat 37
/chome/dlwrobe/SATELLITES/RITS/satfile22.sat 38
/chome/dlwrobe/SATELLITES/RITS/satfile23.sat 39
/chome/dlwrobe/SATELLITES/RITS/satfile25.sat 40
```

```
/chome/dlwrobe/SATELLITES/RITS/satfile26.sat 41
/chome/dlwrobe/SATELLITES/RITS/satfile28.sat 42
/chome/dlwrobe/SATELLITES/RITS/satfile29.sat 43
/chome/dlwrobe/SATELLITES/RITS/satfile30.sat 44
/chome/dlwrobe/SATELLITES/RITS/satfile31.sat 45
/chome/dlwrobe/SATELLITES/RITS/satfile32.sat 46
/chome/dlwrobe/SATELLITES/RITS/satfile34.sat 47
/chome/rpkense/explore/dlwRITS/fixedSats/satfile35.sat 48
/chome/dlwrobe/SATELLITES/RITS/satfile36.sat 49
/chome/dlwrobe/SATELLITES/RITS/satfile37.sat 50
/chome/dlwrobe/SATELLITES/RITS/satfile38.sat 51
/chome/dlwrobe/SATELLITES/RITS/satfile41.sat 52
/chome/dlwrobe/SATELLITES/RITS/satfile42.sat 53
/chome/dlwrobe/SATELLITES/RITS/satfile43.sat 54
/chome/dlwrobe/SATELLITES/RITS/satfile46.sat 55
/chome/dlwrobe/SATELLITES/RITS/satfile47.sat 56
/chome/dlwrobe/SATELLITES/RITS/satfile48.sat 57
/chome/dlwrobe/SATELLITES/RITS/satfile50.sat 58
/chome/dlwrobe/SATELLITES/RITS/satfile51.sat 59
/chome/dlwrobe/SATELLITES/RITS/satfile52.sat 60
/chome/rpkense/explore/dlwRITS/fixedSats/satfile53.sat 61
/chome/dlwrobe/SATELLITES/RITS/satfile54.sat 62
/chome/dlwrobe/SATELLITES/RITS/satfile57.sat 63
/chome/dlwrobe/SATELLITES/RITS/satfile58.sat 64
/chome/dlwrobe/SATELLITES/RITS/satfile59.sat 65
/chome/dlwrobe/SATELLITES/RITS/satfile60.sat 66
/chome/dlwrobe/SATELLITES/RITS/satfile63.sat 67
/chome/dlwrobe/SATELLITES/RITS/satfile64.sat 68
/chome/dlwrobe/SATELLITES/RITS/satfile65.sat 69
/chome/dlwrobe/SATELLITES/RITS/satfile66.sat 70
/chome/dlwrobe/SATELLITES/RITS/satfile67.sat 71
/chome/dlwrobe/SATELLITES/RITS/satfile68.sat 72
/chome/dlwrobe/SATELLITES/RITS/satfile69.sat 73
/chome/dlwrobe/SATELLITES/RITS/satfile70.sat 74
/chome/dlwrobe/SATELLITES/RITS/satfile72.sat 75
/chome/rpkense/explore/dlwRITS/fixedSats/satfile74.sat 76
/chome/dlwrobe/SATELLITES/RITS/satfile75.sat 77
/chome/dlwrobe/SATELLITES/RITS/satfile76.sat 78
/chome/dlwrobe/SATELLITES/RITS/satfile77.sat 79
/chome/dlwrobe/SATELLITES/RITS/satfile79.sat 80
/chome/dlwrobe/SATELLITES/RITS/satfile80.sat 81
/chome/dlwrobe/SATELLITES/RITS/satfile81.sat 82
/chome/dlwrobe/SATELLITES/RITS/satfile82.sat 83
/chome/dlwrobe/SATELLITES/RITS/satfile85.sat 84
/chome/dlwrobe/SATELLITES/RITS/satfile87.sat 85
/chome/dlwrobe/SATELLITES/RITS/satfile88.sat 86
/chome/dlwrobe/SATELLITES/RITS/satfile89.sat 87
/chome/dlwrobe/SATELLITES/RITS/satfile90.sat 88
/chome/dlwrobe/SATELLITES/RITS/satfile91.sat 89
/chome/dlwrobe/SATELLITES/RITS/satfile93.sat 90
ACIS_END

CHOLLA_BEGIN
CHOLLA_END
{eor}diffs
# ***************
# * Differences *
# ***************
```

```
# Note that only this type of comment line is allowed.
#
#  Lines starting with "Index: <Directory/Filename>" are used for
#  identification of diff files to be patched to repository files.
#
#  Lines starting with "New file: <Directory/Filename>" will be
#  used to produce a new file with the given name and directory.
#
#  Lines starting with "# ", "=====", "RCS file:", "retrieving",
#  and "diff -r" are deleted.
#
# The prm and sat sections only need to be included for CAD
{eor}mdat
*/ *************
*/ * ITS INPUT *
*/ *************
ECHO 1
TITLE
RITS calculation test
POSITION
POINT -2602.2299805 182.879997 911.406433
PHOTONS 1
************************* GEOMETRY ******************************
GEOMETRY  3
  END
  END
  END
* MATERIAL
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 2 * 0.
 2 * 0.
 3 *   0.
 4 *   0.
 3 *   0.
 2 *   0.
 0 *   0.
 4 *   0.
 1 *   0.
 2 *   0.
```

```
 1 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 1 *   0.
 1 *   0.
 1 *   0.
 2 *   0.
 3 *   0.
 3 *   0.
 6 *   0.
 1 *   0.
 2 *   0.
 1 *   0.
 2 *   0.
 2 *   0.
 1 *   0.
 7 *   0.
 7 *   0.
 4 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 7 *   0.
 7 *   0.
 3 *   0.
 2 *   0.
 1 *   0.
 1 *   0.
 1 *   0.
 4 *   0.
 1 *   0.
* 0 *   0. now 61, Body 55 has volume problems (void anyway, so removed)
 1 *   0.
 1 *   0.
 1 *   0.
 2 *   0.
 1 *   0.
 1 *   0.
 3 *   0.
 2 *   0.
 2 *   0.
 1 *   0.
 2 *   0.
 2 *   0.
 2 *   0.
 1 *   0.
 1 *   0.
 1 *   0.
 6 *   0.
 1 *   0.
 1 *   0.
 1 *   0.
 4 *   0.
 3 *   0.
 2 *   0.
 7 *   0.
 1 *   0.
```

```
 2 *   0.
 7 *   0.
 1 *   0.
0
  0 * escape zone
************************ OTHER OPTIONS ************************
HISTORIES-PER-BATCH 1e6
BATCHES 300
photon-flux 1 22
nbine 27 user
   11. 10. 9. 8. 7. 6. 5.
   4.5 4. 3.5 3. 2.5 2.
   1.75 1.5 1.25 1.
   .9 .8 .7 .6 .5 .4 .3 .2 .1 .01
nbint 1
BIAS-GLOBAL
  PHOTRAN
SOURCE-ANGLE-ENERGY  19 27
 * ANGLES:
  0.00E+00  1.00E+01  2.00E+01  3.00E+01  4.00E+01
  5.00E+01  6.00E+01  7.00E+01  8.00E+01  9.00E+01
  1.00E+02  1.10E+02  1.20E+02  1.30E+02  1.40E+02
  1.50E+02  1.60E+02  1.70E+02  1.80E+02
 * ANGULAR PROBABILITIES:
  3.05E-04  1.20E-04  6.44E-05  3.99E-05  2.68E-05
  1.88E-05  1.39E-05  1.01E-05  6.75E-06  5.375E-06
  4.00E-06  4.85E-06  4.97E-06  4.86E-06  4.72E-06
  4.53E-06  4.42E-06  4.31E-06  4.28E-06
 * ENERGIES
  1.00E-01  2.00E-01  3.00E-01  4.00E-01  5.00E-01
  6.00E-01  7.00E-01  8.00E-01  9.00E-01  1.00E+00
  1.25E+00  1.50E+00  1.75E+00  2.00E+00  2.50E+00
  3.00E+00  3.50E+00  4.00E+00  4.50E+00  5.00E+00
  6.00E+00  7.00E+00  8.00E+00  9.00E+00  1.00E+01
  1.10E+01  1.20E+01
 * SPECTRAL PROBABILITIES:
  0.00E+00  8.49E-06  2.10E-05  2.20E-05  1.93E-05
  1.67E-05  1.44E-05  1.23E-05  1.10E-05  9.82E-06
  2.08E-05  1.65E-05  1.38E-05  1.17E-05  1.87E-05
  1.42E-05  1.15E-05  9.63E-06  7.84E-06  6.75E-06
  1.07E-05  8.18E-06  6.42E-06  5.05E-06  3.96E-06
  2.91E-06  1.28E-06
  0.00E+00  5.35E-06  9.83E-06  9.25E-06  7.75E-06
  6.68E-06  5.55E-06  4.82E-06  4.34E-06  3.84E-06
  8.05E-06  6.35E-06  5.06E-06  4.43E-06  7.06E-06
  5.41E-06  4.19E-06  3.45E-06  2.85E-06  2.51E-06
  3.90E-06  2.90E-06  2.26E-06  1.72E-06  1.20E-06
  8.24E-07  2.57E-07
  0.00E+00  3.90E-06  5.87E-06  5.19E-06  4.28E-06
  3.82E-06  2.95E-06  2.59E-06  2.32E-06  2.03E-06
  4.21E-06  3.31E-06  2.78E-06  2.26E-06  3.59E-06
  2.77E-06  2.17E-06  1.71E-06  1.43E-06  1.16E-06
  1.90E-06  1.46E-06  1.10E-06  7.90E-07  5.25E-07
  2.76E-07  5.31E-08
  0.00E+00  2.82E-06  3.97E-06  3.49E-06  2.74E-06
  2.41E-06  1.90E-06  1.64E-06  1.36E-06  1.27E-06
  2.50E-06  2.07E-06  1.58E-06  1.36E-06  2.06E-06
  1.61E-06  1.26E-06  1.04E-06  8.16E-07  7.00E-07
```

1.08E-06 8.21E-07 5.94E-07 4.16E-07 2.45E-07
1.11E-07 1.19E-08
0.00E+00 2.07E-06 2.81E-06 2.41E-06 1.97E-06
1.71E-06 1.32E-06 1.14E-06 9.25E-07 8.82E-07
1.68E-06 1.34E-06 1.08E-06 8.82E-07 1.35E-06
9.97E-07 7.48E-07 6.60E-07 4.91E-07 4.49E-07
6.35E-07 4.95E-07 3.43E-07 2.28E-07 1.24E-07
4.52E-08 6.10E-09
0.00E+00 1.42E-06 2.04E-06 1.77E-06 1.40E-06
1.33E-06 8.96E-07 8.09E-07 7.08E-07 6.06E-07
1.23E-06 8.83E-07 7.49E-07 5.68E-07 9.28E-07
7.01E-07 5.24E-07 4.24E-07 3.47E-07 2.88E-07
4.48E-07 3.27E-07 2.03E-07 1.43E-07 7.15E-08
1.88E-08 6.91E-10
0.00E+00 9.62E-07 1.48E-06 1.33E-06 1.09E-06
1.06E-06 7.21E-07 5.61E-07 5.20E-07 4.38E-07
9.30E-07 6.70E-07 5.59E-07 4.44E-07 6.90E-07
5.09E-07 3.89E-07 3.00E-07 2.55E-07 1.95E-07
3.13E-07 2.15E-07 1.35E-07 6.60E-08 3.14E-08
9.59E-09 9.11E-10
0.00E+00 5.61E-07 9.82E-07 9.64E-07 8.22E-07
8.26E-07 5.61E-07 4.63E-07 4.03E-07 3.46E-07
6.80E-07 5.53E-07 4.41E-07 3.45E-07 5.22E-07
3.69E-07 2.55E-07 2.28E-07 1.66E-07 1.37E-07
2.13E-07 1.37E-07 7.01E-08 5.56E-08 3.05E-08
6.72E-09 7.11E-10
0.00E+00 2.18E-07 4.75E-07 5.70E-07 5.33E-07
5.81E-07 4.04E-07 3.40E-07 2.90E-07 2.61E-07
5.16E-07 4.00E-07 3.17E-07 2.67E-07 3.73E-07
2.82E-07 1.94E-07 1.65E-07 1.32E-07 9.89E-08
1.56E-07 9.86E-08 4.52E-08 2.29E-08 9.14E-09
3.08E-09 2.47E-10
0.00E+00 1.47E-07 3.44E-07 4.40E-07 4.24E-07
4.72E-07 3.27E-07 2.78E-07 2.39E-07 2.19E-07
4.23E-07 3.33E-07 2.61E-07 2.13E-07 3.06E-07
2.25E-07 1.61E-07 1.29E-07 1.08E-07 7.88E-08
1.16E-07 7.23E-08 3.35E-08 1.68E-08 7.49E-09
3.05E-09 1.34E-10
0.00E+00 7.61E-08 2.12E-07 3.09E-07 3.15E-07
3.62E-07 2.50E-07 2.16E-07 1.88E-07 1.77E-07
3.30E-07 2.65E-07 2.04E-07 1.59E-07 2.39E-07
1.68E-07 1.27E-07 9.20E-08 8.48E-08 5.86E-08
7.60E-08 4.61E-08 2.17E-08 1.07E-08 5.84E-09
3.02E-09 2.11E-11
0.00E+00 1.95E-07 4.63E-07 5.07E-07 4.27E-07
4.80E-07 2.86E-07 2.47E-07 2.09E-07 1.80E-07
3.55E-07 2.59E-07 2.09E-07 1.55E-07 2.52E-07
1.60E-07 1.08E-07 8.78E-08 7.15E-08 4.79E-08
6.82E-08 4.43E-08 2.56E-08 7.33E-09 1.52E-09
1.44E-10 1.40E-11
0.00E+00 3.21E-07 6.22E-07 5.73E-07 4.45E-07
5.05E-07 2.72E-07 2.31E-07 2.02E-07 1.75E-07
3.34E-07 2.44E-07 1.80E-07 1.43E-07 2.13E-07
1.35E-07 9.82E-08 7.20E-08 5.14E-08 3.40E-08
5.72E-08 3.32E-08 1.94E-08 1.13E-08 1.67E-09
1.10E-10 9.01E-12
0.00E+00 4.28E-07 7.04E-07 5.80E-07 4.36E-07
4.96E-07 2.62E-07 2.26E-07 1.80E-07 1.52E-07

```
  2.85E-07  2.05E-07  1.50E-07  1.27E-07  1.81E-07
  1.27E-07  8.23E-08  5.24E-08  5.92E-08  3.90E-08
  5.07E-08  1.51E-08  1.31E-08  4.92E-09  2.87E-09
  7.58E-10  8.31E-12
  0.00E+00  5.00E-07  7.48E-07  5.88E-07  4.36E-07
  4.81E-07  2.48E-07  1.91E-07  1.68E-07  1.35E-07
  2.65E-07  1.91E-07  1.37E-07  9.57E-08  1.60E-07
  1.11E-07  6.76E-08  5.62E-08  4.11E-08  2.94E-08
  3.76E-08  1.78E-08  9.95E-09  3.70E-09  3.87E-10
  8.33E-10  6.86E-12
  0.00E+00  5.66E-07  7.75E-07  5.70E-07  4.16E-07
  4.72E-07  2.25E-07  1.87E-07  1.52E-07  1.15E-07
  2.39E-07  1.59E-07  1.19E-07  9.99E-08  1.32E-07
  9.71E-08  6.43E-08  3.77E-08  3.19E-08  2.33E-08
  2.66E-08  1.37E-08  4.60E-09  2.59E-09  2.93E-10
  5.71E-11  4.53E-12
  0.00E+00  5.89E-07  7.89E-07  5.72E-07  4.16E-07
  4.59E-07  2.01E-07  1.67E-07  1.36E-07  1.07E-07
  2.08E-07  1.62E-07  1.26E-07  9.05E-08  1.20E-07
  8.56E-08  5.62E-08  4.28E-08  2.65E-08  2.02E-08
  2.52E-08  1.47E-08  8.38E-09  1.53E-09  2.26E-10
  3.52E-11  7.10E-12
  0.00E+00  6.01E-07  7.90E-07  5.74E-07  4.03E-07
  4.39E-07  1.91E-07  1.60E-07  1.27E-07  1.08E-07
  1.96E-07  1.53E-07  1.12E-07  9.80E-08  1.12E-07
  7.75E-08  5.16E-08  4.14E-08  2.16E-08  1.85E-08
  1.95E-08  8.80E-09  2.99E-09  2.01E-09  3.04E-10
  2.46E-11  7.20E-12
  0.00E+00  6.17E-07  7.81E-07  5.68E-07  3.84E-07
  4.32E-07  2.00E-07  1.64E-07  1.17E-07  1.02E-07
  2.14E-07  1.37E-07  1.15E-07  8.55E-08  1.12E-07
  7.75E-08  5.32E-08  4.04E-08  2.68E-08  1.83E-08
  2.24E-08  7.36E-09  4.01E-09  2.63E-09  2.85E-10
  2.39E-11  5.44E-12
* READ-FOLD-XS parameter1 parameter2
* parameter1=1 => Next-event (really, last-flight) turned on, otherwise off
* parameter2= number of xs's to be read in
*   (but only 1st will be used for now)
READ-FOLD-XS 1 1
  1 5  * one table (no discontinuities) with 5 energies
  1.e3 1.0 0.1 0.01 0.001 * 5 energies decreasing from 1GeV to 1keV
  1.0  1.0 1.0 1.0  1.0 * same number of XS values
```

Appendix C Activation of the air by RITS-6 prompt x-ray radiation

Photon interaction with air can produce radioactive gases if the accelerator operates above the minimum threshold level of 10.55 MeV.[17] In the case of RITS-6, the primary air activation product of concern is N^{13} resulting from a (γ,n) reaction with the N^{14} parent since the nominal operating voltage is anticipated to be 11 MeV or just slightly above the N^{13} production threshold but well below the thresholds for other air activation products (e.g O^{15}). The production of N^{13} can be estimated with the equation[18] shown below.

$$A_{0_{RITS6}} = A_s P_t l_{av} \lambda t_{shot}$$

$$A_{s_{N-13}} = \text{Saturation activity} = 14{,}000\ \mu\text{Ci}\Big/\text{m}-\text{kW}$$

$$P_t = \textit{total machine power} = \textit{12 MeV X 250E6 mA} = \textit{3E9 kW}$$

$$l_{av} = \text{beam path length} = \approx 2\text{m (first shield wall)}$$

$$\ddot{e}_{N^{13}} = N^{13}\ \textit{decay constant} = 0.001155\Big/sec$$

$$t_{shot} = \text{shot duration} = 50\ \text{nano} - \text{sec}$$

$$\therefore A_{0_{RITS6}} = \left[1.4E4\,\mu Ci\Big/m - kW\right]\left[3E9kW\right]\left[2m\right]\left[0.001155\Big/sec\right]\left[50E - 9sec\right] = 4.85E3\,\mu Ci\Big/shot$$

$$\left[4.85E3\,\mu Ci\Big/shot\right]\left[300shots\Big/y\right] = 1.45E6\,\mu Ci\Big/y = 1.45Ci\Big/y$$

Although the production of N^{13} appears significant, practical modifying factors need to be noted regarding the calculated production and subsequent potential dose. Most importantly, the calculation assumes all photons exceed the requisite threshold energy of 10.55 MeV. Photon distributions from Integrated Tiger Series (ITS) calculations show that less than 1% of the photons produced exceed the threshold. Assuming 1% is more realistic yet still conservative, resulting in a N^{13} production of approximately 48.5 µCi per shot and 0.014 Ci per year based on 300 shots.

The potential dose consequence from N^{13} was assessed for both co-located occupational workers within the RITS-6 high bay operational area and to personnel at points external to the high bay. Assuming the N^{13} is immediately dispersed within the high bay volume (approximately 3E10 cm^3) and neglecting any high bay air exchange or decay (which would reduce these values further) results in a concentration of 1.6E-9 µCi/cm^3. In comparison, the ICRP[19] recommended maximum permissible concentration (MPC) for a continuous 40-hour week occupational exposure to a semi-infinite cloud at constant concentration is 2E-6 µCi/cm^3. The production and dispersal of N^{13} from RITS-6 operation is therefore 1000 times lower than the ICRP limits.

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[17] [1] International Atomic Energy Agency Technical Reports Series No. 188, *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*, 1979.

[18] JW VanDenburg and DV Rao, *SNL/NM HERMES III Air Activation analysis and Dose Assessment*, December 23, 1994.

[19] International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2, 1960.

Extrapolation of previous N^{13} dose calculations by SNL's Environmental Management Department shows potential doses of approximately 7E-6 mRem/year at an on-site location 657 meters NW and approximately 3E-7 mRem/year for locations 2000 meters NNE. These values should be compared to 100 mRem/year dose limit for members of the general public. The production and dispersal of N^{13} from RITS-6 operation therefore creates a risk 14 million times lower than the acceptable limits for the public.

We conclude that air activation due to RITS-6 operation does not pose a significant risk to workers, co-located workers, or to the general public.

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John O'Malley (AWE), Atomic Weapons Establishment
Aldermasten
Reading, RG7 4PR
United Kingdom
John.O'Malley@awe.co.uk

Veronica Martinez (DOE), NNSA/DOE
Service Center
P.O. Box 5400
Albuquerque, NM 87185-5400