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LANSCE DESIGN BASIS BEAM SPILL ACCIDENT

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ABSTRACT

A one-hour, full power point spill was the design basis beam spill accident for shielding at the Los Alamos Neutron Science Center (LANSCE) from 1991 to 2008. This was consistent with accelerator safety community and U.S. regulatory guidance developed in the early 1990s. Superseding guidance issued in 2004 is to design accelerators to safely accommodate transient events with the recommendation to consider the maximum credible incident (MCI). A number of developments in 2008 prompted LANSCE to evaluate the credibility of the one-hour, full power spill and to redefine its anticipated design basis beam spill accident as a 30 MJ spill regardless of beam power. While considering designs that safely accommodate transient events, policy for crediting active versus passive protection systems was also revisited. Historically LANSCE has given passive shielding and some active systems more credit in the mitigation of accidents than others of the same pedigree. Operating experience however does not justify this. In this paper the development of the new LANSCE design basis beam spill accident is described with subsequent discussion of the role of active protection systems.

1. Introduction

It was LANSCE policy that the unmitigated design basis beam spill accident is an anticipated one-hour, full power point spill that may occur anywhere along the accelerator or various beam lines. This was based on recommendations of a 1991 prompt radiation protection workshop held at Los Alamos National Laboratory (LANL) and the 1993 implementation guidance for the U.S. Department of Energy (DOE) accelerator safety order [1,2]. Prior to the workshop, shielding at LANSCE was designed for normal beam losses and target operations. In the early 1990s many very costly shielding upgrades were made to become compliant with this policy. Implementation guidance for the latest DOE accelerator safety order does not define the design basis accident [3,4]. Instead, the concept of the MCI is introduced and direction is provided that “accelerators should be designed to accommodate transient events… without degradation of safety.”

In 2008 three developments prompted LANSCE to revisit the unmitigated design basis beam spill accident. The first was shielding assessments, being performed in support of a new Safety Assessment Document (SAD), were identifying areas of noncompliance where the capability for beam power on the order of a megawatt existed. The second was designers of a new high power beamline and target station challenged that a one hour megawatt beam spill was not credible and that shielding for such an event would be unnecessarily costly. The third development was the identification of accelerator beam line life-safety egress issues that required shielding modifications and additional entrance mazes, changes in which it would be prohibitively expensive or impossible to accommodate the one-hour, full power beam spill design criterion.

The design basis accident was redefined in order to ensure that radiation safety controls were not overly conservative and could be balanced with life safety controls. The new definition was based on a risk assessment that included accelerator community operational experience and MCI's. Actual beam spill events were investigated for agreement with implications of the new definition to check its reasonableness. The LANSCE MCI, a derivative of the re-defined design basis accident, was compared with MCIs of other accelerator facilities to check for consistency. Finally the role of active protection systems for the mitigation of the design basis accident at LANSCE is discussed in light operating experiences.

2. Design Basis Accident

Reference 5 documents a probabilistic risk assessment (PRA) for occupancy of the LANSCE Lujan Center's Experimental Rooms 1 and 2 (ER1 and ER2). It analyzed a single event initiator, failure of a high-field 90-degree bending magnet with C-type configuration, that had a historical rate of approximately 0.01 failures per year. The failure probability was for an individual magnet. LANSCE has hundreds of magnet-years of operating experience and thus could base failure rates on experience. With "anticipated" likelihood being defined as 1 to 1E-2 events per year, the PRA initiator frequency was at the threshold between anticipated and unlikely. But, considering all beam spill initiators (multiple magnets, possible operator errors, etc.) in an area, the total likelihood was something higher and clearly in the anticipated frequency bin.

Though the initiators may occur frequently, the accelerator is designed to prevent significant beam spills. These normal preventative features are part of the Run Permit (RP) and Fast Protect (FP) systems at LANSCE. These systems only terminate beam spill events—they do not prevent them. Therefore, it is not justifiable that they will in general reduce the event frequency on beam lines from the anticipated bin to the unlikely. Beam spill events that challenge safety systems beyond RP and FP do occur on LANSCE beam lines. Accepting this logic, the design basis accident's unmitigated likelihood is reasonably binned as anticipated.

In addition to event frequency, the 2008 beam spill event analysis questioned what beam spill current, and for how long, could be considered bounding or "safe" if adequately shielded. Included was whether a one-hour spill at full power should be anticipated. It was recognized that, as power increases, the likelihood of accelerator equipment failures increases. Therefore, the more safety significant beam spills could be the lower power, longer duration events—not the high power beam spills. Additionally, at LANSCE, full beam power was sometimes defined by a beam current limiting device (a Radiation Security System [RSS] transmission limiter [XL]) and not by accelerator design and beam physics. Consequently, there was the possibility for higher than "full power" beam spill events if an XL failure was postulated. The implications were that, for any operating beam current, there were events that may have durations longer or shorter than one hour and that may have more or less than the full power beam current being spilled. The one-hour, full power event was accepted as being reasonably bounding of all of possible events, but this may not be the case.

The challenge was to define event likelihood as a function of the spilled beam current and event duration noting that, for any operating beam current, there is some probability of spilling some or all of it for any length of time, from fractions of a second to days. The first thing to note is that, as events are postulated with longer durations and higher currents, they become inherently less likely simply by the fact that it is more likely that systems and/or operators will react to a variety of problem indications. Physically however, this is bounded by noting that a significant localized beam loss is going to result in melting through the beam pipe wall and that the vacuum loss will shut down the beam ending the event. A very localized spill could occur in a bending magnet failure event, where even at relatively low current the beam pipe is expected to burn through quickly. For focusing magnets, whether failed or misfocused, spill may occur over some length of beam line, but even in this case vacuum seals quickly fail as the beam pipe heats up.

Though it is impossible to prove exactly how long burn through or seal failure takes for the essentially infinite number of possible spill scenarios, it clearly becomes increasingly more likely that vacuum failure will occur as more beam energy is deposited in components not designed to take it. This is illustrated in the context of beam plugs in Figure 1, taken from analysis supporting a past LANSCE beam plug standard. The analysis provided that, for powers over 9 kW, steel plugs will have a finite lifetime. For a design basis beam spill accident duration of one hour the energy deposited at this power is about 30 MJ. This is the amount of energy that it takes to raise about 30 kg of steel to the melting point. Two meters of 10 cm (4-inch) diameter schedule 40 stainless steel beam pipe is also about 30 kg.

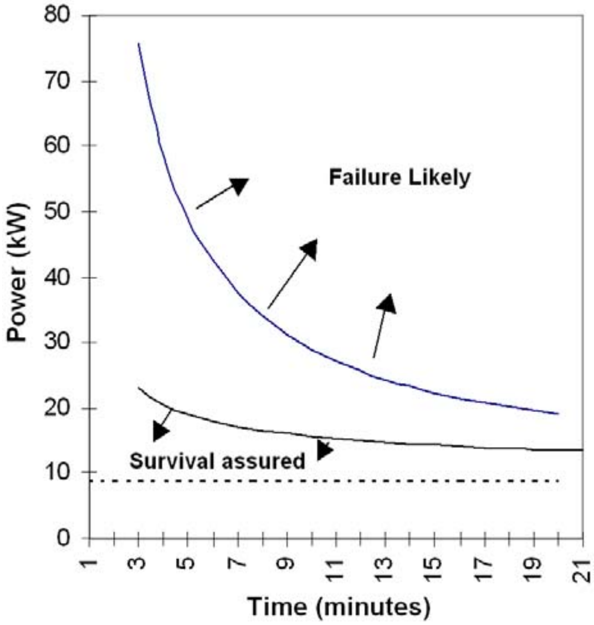


Figure 1. Illustration of beam plug thermal limitations.

Figure 2 is a plot showing the time it takes to deliver 30 MJ of beam energy as a function of 800 MeV beam current, the LANSCE maximum. Beam spill events falling below the line in Figure 2 are more likely than beam spill events falling above it. Considering the generally qualitative nature of hazard analysis, this plot was proposed as a conservative and reasonable definition of the boundary between anticipated and unlikely beam spill events. If reasonable, one should, upon inspection, find that the most significant beam spill events that have occurred at LANSCE and other facilities have all been less than 30 MJ. If conservative, one should find that loss of vacuum and beam shutdown due to burn through and seal failure has occurred with the spills of much less than 30 MJ. Burn through in the transition region between the 100 MeV drift tube linac and 800 MeV coupled cavity linac at LANSCE occurred with only an estimated 40 J of spill in 2 beam pulses [6]. At the Paul Scherrer Institut (PSI), a 600 MeV proton facility [7], “Experience showed, that already with proton beam intensities as low as 10 µA a leak at a vacuum seal may occur after overheating it for only a few seconds.” This is on the order of 30 kJ. LANSCE has similar experience though not formally documented. At the 2008 DOE Accelerator Safety Workshop other facilities were asked in a breakout session how beam spill event experiences compared with 30 MJ. One significant beam spill event was discussed. This was an activation event at Thomas Jefferson National Accelerator Facility (TJNAF) resulting from losses about 100 times normal for 80 hours along approximately 30 meters of beamline [8]. The estimated energy for this spill is 10 MJ. No spill events involving greater than 30 MJ were identified, supporting this energy as being used to bound anticipated transient beam events.

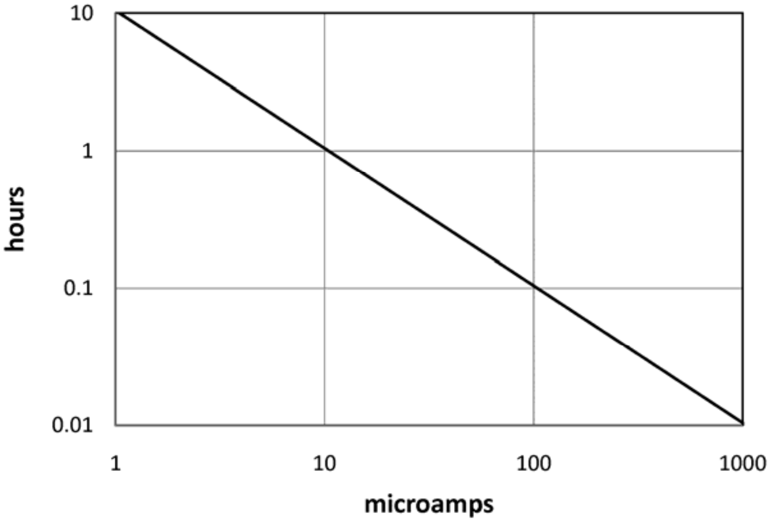
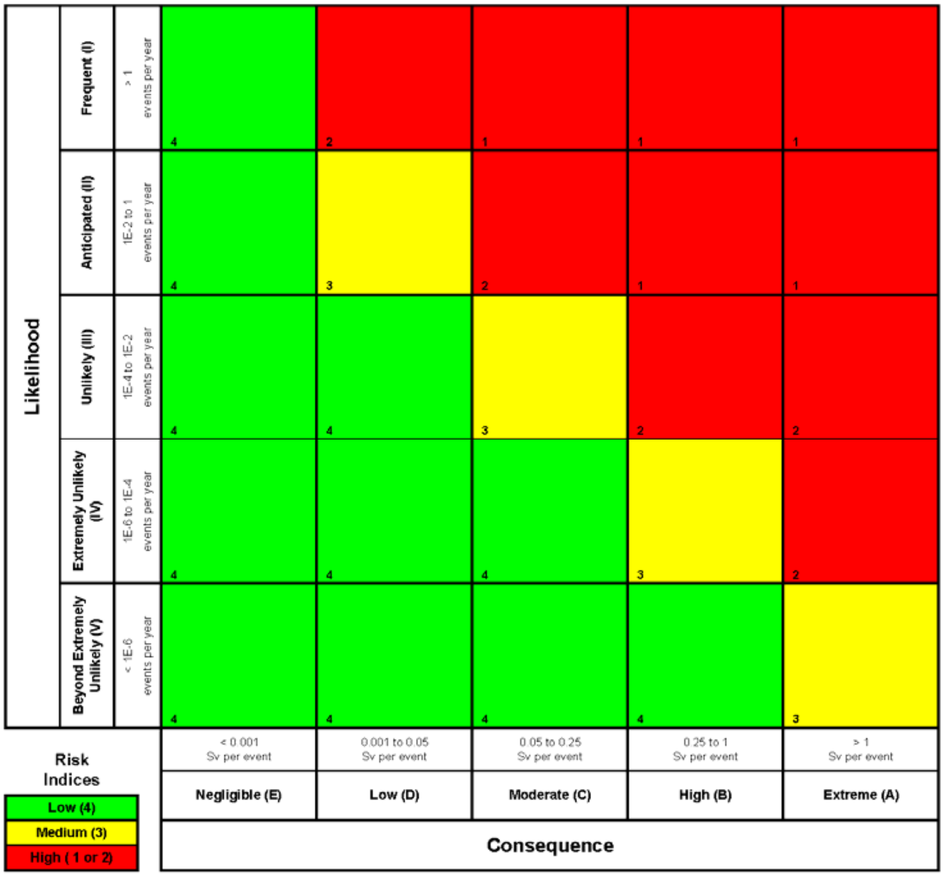


Figure 2. Time to spill 30 MJ as a function of 800 MeV beam current.

Figure 2 only provides one boundary, that between the anticipated and unlikely events, and more resolution was desired for the LANSCE policy. For example, an unmitigated one-hour full power spill remains anticipated for 10 µA but for 100 µA it is in a lower undefined likelihood bin. A LANL risk matrix (Table I) was used to define five likelihood bins. Figure 3 proposes the other three frequency bin boundaries, those between frequent and anticipated, unlikely and extremely unlikely, and extremely unlikely and beyond extremely unlikely. The likelihood bin boundaries in Figure 3 correspond to spills of 0.6 MJ, 30 MJ, 150 MJ, and 600 MJ. The ratios between these spilled energy boundaries were assumed to be the same as the ratios between the consequence bin boundaries of the Table I risk matrix. This was considered reasonable since consequence is proportional to the amount of beam spilled, which by the underlying assumption is also proportional to event frequency. What it resulted in was a beam spill design criteria of 5 mSv/µA/h at 800 MeV that satisfied the Table I risk requirements that consequences for frequent events be less than 1 mSv, anticipated events be less than 50 mSv, unlikely events be less than 0.25 Sv, and extremely unlikely events be less than 1 Sv, regardless of the operating beam current. All events identified in LANSCE operating history fall below the 0.6 MJ boundary for frequent events.



Likelihood		Negligible (E) < 0.001 Sv per event	Low (D) 0.001 to 0.05 Sv per event	Moderate (C) 0.05 to 0.25 Sv per event	High (B) 0.25 to 1 Sv per event	Extreme (A) > 1 Sv per event
Frequent (I)	> 1 events per year	🟩 4	🟥 2	🟥 1	🟥 1	🟥 1
Anticipated (II)	1E-2 to 1 events per year	🟩 4	🟨 3	🟥 2	🟥 1	🟥 1
Unlikely (III)	1E-4 to 1E-2 events per year	🟩 4	🟩 4	🟨 3	🟥 2	🟥 2
Extremely Unlikely (IV)	1E-6 to 1E-4 events per year	🟩 4	🟩 4	🟩 4	🟨 3	🟥 2
Beyond Extremely Unlikely (V)	< 1E-6 events per year	🟩 4	🟩 4	🟩 4	🟩 4	🟨 3

Consequence

Risk Indices
- 🟩 Low (4)
- 🟨 Medium (3)
- 🟥 High (1 or 2)

Table I. Onsite beam spill risk evaluation matrix.

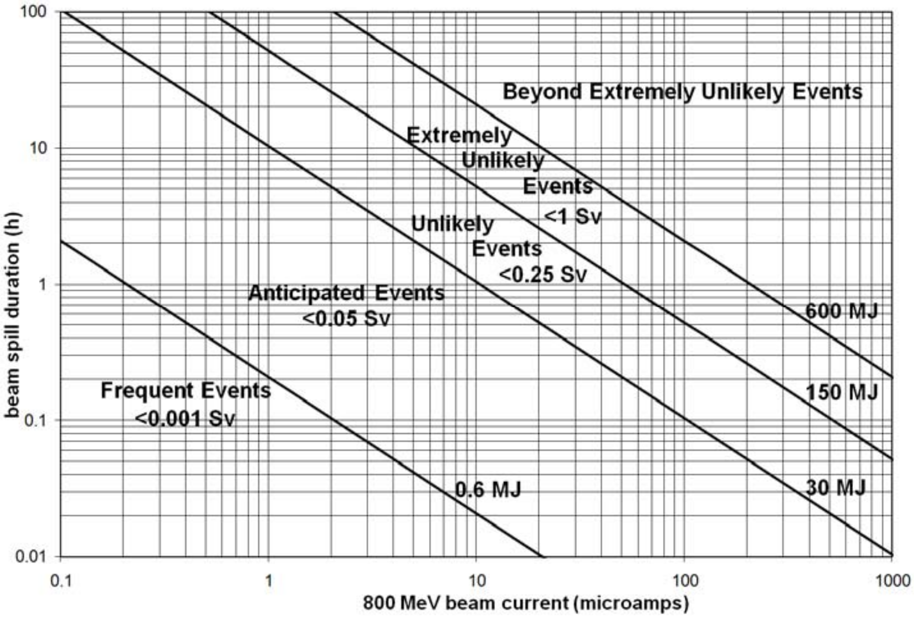


Figure 3. Beam spill event likelihood as function of current spilled and event duration.

Qualitative hazard analysis generally involves binning event frequencies and consequences using engineering judgment. In other words the implications of Figure 3 should sound reasonable given some operating current. Taking Line D operations in the LANSCE switchyard for example, where there are no FP ion chambers (IRs) or RSS gamma detectors (GDs) monitoring spill, beam is transported normally on the order of 100 µA for operation of the 1L target at the Lujan Center. For this beam transport operation Figure 3 says it is extremely unlikely that all 100 µA would be lost for more than a half-hour. This sounds reasonable. In this time frame someone or something can be expected to intervene. The something can very reasonably be expected to beam line failure in the bounding case. The figure also indicates that loss of all 100 µA for up to about 6 minutes is anticipated and should be expected to occur in the lifetime of the facility. This also sounds reasonable. The figure also says the loss of 10% of the beam, 10 µA during 100 µA operations, for up to one hour should be anticipated, but that spilling 10 µA for much longer than that is unlikely. Again, it sounds reasonable. A final note on Figure 3 is that is does not say any beam spill is impossible. It does not reject the one-hour, full power spill of past policy, it simply provides a more reasonable binning of its likelihood while accounting for the virtually infinite number of spill scenarios that could be postulated for any given beam operation.

3. Maximum Credible Incident

The MCI is the set of beam spills on the line separating extremely unlikely from beyond extremely unlikely events in Figure 3. A 600 MJ spill is the MCI and the LANSCE consequence limit is 1 Sv. This is equivalent to the design basis of 5 mSv/µA/h at 800 MeV. It could be a 1.5 mA spill for 8.3 minutes or a 10 µA spill for 21 hours. The 600 MJ MCI compares reasonably with policy at other facilities [9].

At the Tri-University Meson Facility (TRIUMF) “the policy is to consider the worst-case credible beam loss scenario, which is full, instantaneous beam loss at a point with rated (i.e. maximum approved) beam power and the dose limit outside shielding is 1 Sv/h.” TRIUMF is a 500 MeV, 250 µA proton facility. In one hour this is a 450 MJ spill for which the limit is 1 Sv. It is a little less conservative than what has been defined for LANSCE.

The SLAC B-Factory, a 333 kW electron facility, initially wanted shielding to limit dose rates to 0.25 Sv/h for a full power spill. This is limiting a 1200 MJ spill to 0.25 Sv. However, SLAC found this requirement too conservative for B-Factory design and credited burn through for limiting the MCI to 110 kW. This is a 400 MJ spill in one hour being limited to 0.25 Sv. With the lower dose limit this design basis is a little more conservative than the LANSCE design basis. The SLAC Linac Coherent Light Source (LCLS) shielding design basis was limiting a 150 kW spill to 0.25 Sv in one hour [10]. This is 0.25 Sv for 540 MJ, which again is a little more conservative than the LANSCE design basis.

At other facilities the shielding design basis is for normal beam losses and active protection is creditted for accident mitigation. Examples include TJNAF, Duke Free Electron Laser Laboratory (DFELL) and the Spallation Neutron Source (SNS). SNS identified a 2 MW beam loss for 10 minutes as the MCI for its safety basis. Extrapolating from Figure 3 the threshold for 2 MW, 800 MeV beam loss going from extremely unlikely to beyond is 5 minutes. This is reasonable consistency considering the qualitative nature of the hazard analyses.

Comparing the design basis for TRIUMF, SLAC and that of LANSCE by dividing the maximum allowed dose by the energy of the MCI shows they are all within a factor of 4. TRIUMF is 2.2 mSv/MJ, SLAC is 0.6 mSv/MJ, and LANSCE is 1.7 mSv/MJ. The consequence bins in the LANSCE risk matrix are all a factor of 4 or more wide suggesting all of the design bases are essentially equivalent. TRIUMF as a proton facility could be a better LANSCE comparison than the SLAC electron facilities. Its MCI is slightly less conservative than that developed for LANSCE while the SLAC MCIs are more conservative. SLAC however is a DOE facility while TRIUMF is not. But electron beam spill can be easier to shield than proton spill since the neutron yields are lower, so the cost of being more conservative may be appropriate.

4. Crediting Active Protection

There are three subsystems of RSS that provide active protection from accelerator radiation hazards at LANSCE. GDs are beam loss detection interlocks that measure radiation levels created by spill inside beam tunnels and trip the beam before dose rates in outside occupiable areas exceed posted limits. The Personnel Access Control System (PACS) uses door interlocks that shutdown the beam if exclusion areas are entered. XLs limit beam current, which for the past one-hour, full power design basis accident, defined full power where installed. All of the RSS subsystems are designed to be redundant and fail-safe.

Under the redefined design basis accident, full power is not relevant and XLs are not credited for beam spill accident mitigation. They are still relied upon for target operations where radionuclide inventory, heating or target shielding design bases must be enforced. As fail-safe devices XLs were credited for making higher power events incredible. Likewise door interlocks in the PACS system are effectively credited for making it incredible that one could enter very high radiation areas that exist in beam tunnels during operation. Historically, however, the same credit was not given to GDs though they share the same design pedigree. It was policy to only credit GD coverage for reducing the beam spill likelihood by one frequency bin. This was not consistent with the other RSS subsystems.

The credited protective function of GDs was reconsidered for the present policy. GD performance was compared to other credited active components and also to the credit given to passive shielding. Like PACS door interlocks, GDs are fail-safe and redundantly interlocked. 10 CFR 835, DOE’s occupational radiation protection rule, requires physical controls to prevent workers from being exposed to high and very high radiation areas. PACS door interlocks prevent people from entering these areas; similarly, GD radiation interlocks prevent these areas from reaching people. It was recognized that giving commensurate credit to GDs would imply that passive shielding for beam lines equipped with GDs can be designed to accommodate normal beam losses alone.

It has been suggested that the reliance on passive shielding could be better than reliance on active protection, but experience suggests otherwise. Experimental, maintenance, and construction activities all routinely make temporary shielding changes that must be administratively controlled. Earthen shields erode and must be monitored and maintained. Unlike fail-safe interlocked radiation monitors that must be operable to run beam, passive shielding is not generally interlocked. Since 1992 LANSCE has accumulated over 600 device operating years experience with GDs as beam loss detection interlocks and there have been approximately 200 documented instances of safe response to challenges and failures and zero unsafe responses. In only the past seven years there have been two LANSCE events where passive shielding configuration control has failed. One of these resulted in the creation of an uncontrolled high radiation area [11]. The conclusion reached was that GDs could be credited exclusively for beam spill accident mitigation in revised policy.

5. Conclusions

The LANSCE unmitigated design basis beam spill accident is that a 30 MJ spill will not result in consequences >50 mSv in occupiable areas. This was derived from risk analysis guidance. The underlying assumption is that the probability of an event is proportional to the total beam energy spilled. Long duration, low power spills and short duration, high power spills are the most likely events and are of comparable energy. As duration and power increase it becomes more likely that interlocks, accelerator failure, or operator intervention terminates the event. The design basis does not say that all higher energy events are incredible. It defines the MCI as a 600 MJ event, for which the design basis proportionally limits consequence to 1 Sv. The new design basis is reasonable when compared with accelerator beam spill event experience and MCIs of other facilities.

Also considered was the role of active protection systems in the design of accelerators to safely accommodate transient events. Under the LANSCE design basis accident definition, devices that limit beam power are not credited for mitigating beam spill events. Beam loss detection devices with RSS required redundancy and fail-safe pedigree can be credited for maintaining dose rates to posted levels. They are not seen as being any less reliable than passive shielding for this purpose.

6. References

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