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Spallation Neutron Source

A U.S. Department of Energy Multilaboratory Project

SNS

Spallation Neutron Source Accident Terms for Environmental Impact Statement Input

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August 1998

Argonne National Laboratory - Brookhaven National Laboratory - Lawrence Berkeley National Laboratory - Los Alamos National Laboratory - Oak Ridge National Laboratory

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SPALLATION NEUTRON SOURCE ACCIDENT SOURCE TERMS FOR ENVIRONMENTAL IMPACT STATEMENT INPUT

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CONTENTS

LIST OF TABLES

ACRONYMS

A	anticipated
ABC	automatic beam cutoff
ac	alternating current
A/C	air conditioning
ACGIH	American Congress of Government Industrial Hygientists
BDB	beyond-design basis
BP	beam pulse/beam permit
CDR	conceptual design report
DAC	derived air concentrations
DOE	U.S. Department of Energy
EIS	environmental impact statement
EU	extremely unlikely
FP	fast protect
HEPA	high-efficiency particulate air
HOG	hot off-gas
HT	tritiated hydrogen
HTO	tritiated water
HVAC	heating, ventilation, and air-conditioning
LLLW	liquid low-level waste
MCNP	monte carlo neutron photon
NA	not applicable
NIOSH	National Institute for Occupational Safety and Health
NRC	Nuclear Regulatory Commission
NSNS	National Spallation Neutron Source
ORNL	Oak Ridge National Laboratory
PPS	personnel protection system
R&D	research and development
SNS	Spallation Neutron Source
TBD	to be determined
TLV	threshold limited value
TPS	target protection system
TWA	time-weighted average
U	unlikely

SPALLATION NEUTRON SOURCE ACCIDENT SOURCE TERMS FOR ENVIRONMENTAL IMPACT STATEMENT INPUT

1. INTRODUCTION

This report is about accidents with the potential to release radioactive materials into the environment surrounding the Spallation Neutron Source (SNS). As shown in Chap. 2, the inventories of radioactivity at the SNS are dominated by the target facility. Source terms for a wide range of target facility accidents, from anticipated events to worst-case beyond-design-basis events, are provided in Chaps. 3 and 4. The most important criterion applied to these accident source terms is that they should not underestimate potential releases. Therefore, conservative methodology was employed for the release estimates. Although the source terms are very conservative, excessive conservatism has been avoided by basing the releases on physical principles.

Since it is envisioned that the SNS facility may eventually (after about 10 years) be expanded and modified to support a 4-MW proton beam operational capability, the source terms estimated in this report are applicable to a 4-MW operating proton beam power unless otherwise specified. This is bounding with regard to the 1-MW facility that will be built and operated initially. See further discussion below in Sect. 1.2.

1.1 OTHER TYPES OF ACCIDENTS

The accidents addressed in this report do not consider two types of accidents that could occur at the SNS: accidents involving nonradiological hazards and accidents involving external exposure to penetrating radiation. The nonradiological hazards are not included because, as explained in Sect. 9 of the *SNS Conceptual Design Report*[1] (CDR), the nonradiological hazards present at an accelerator site during construction or operation can be characterized as standard industrial hazards. None of the SNS nonradiological accident hazards have any potential for harming people away from the immediate vicinity of the SNS buildings.

1.1.1 Toxic Materials

The presence of a nominal 1-m^3 volume of mercury could be considered to be a nonroutine industrial hazard, but two factors mitigate against such a conclusion: (1) the SNS mercury target is kept inside a closed system maintained at temperatures well below the boiling point of mercury, which is located inside a nonoccupied, ventilated hot cell and (2) the degree of containment and surveillance dictated by its radioactivity is more than sufficient to prevent excessive human contact. As shown in Exhibit A, the air concentration limit necessary to prevent occupational mercury poisoning exceeds by a factor of ~10 (i.e., is 10 times more permissive than) the limit that would be necessary to prevent excessive exposure to radiation after only one year of operation of the accelerator at the initially planned 1 MW of proton beam power. As the facility undergoes the planned upgrading to 2 MW, followed by the eventual upgrade to 4 MW, the specific radioactivity content of the mercury increases in direct proportion. Therefore,

controlling the airborne radioactivity of mercury will be more limiting than controlling airborne mercury toxicity throughout the planned life of the facility.

1.1.2 Flammable Gases

The SNS target facility cryogenic neutron moderator employs a small quantity of hydrogen gas (about 1.5 kg), normally in the liquid form. Accidents of this system are considered in Sect. 3.10 of this report and are shown not to form a significant source term for release of radioactive material. The conceptual design, as discussed in Sect. 5.3.2 of the SNS CDR, provides a double-barrier (triple-boundary) hydrogen containment concept (hydrogen surrounded by vacuum surrounded by helium), monitoring instrumentation with alarm annunciation and controls to minimize the risk presented to workers involved in the operation and/or maintenance of this system. The installed hardware, safety and warning devices, automatic alarms and controls, and administrative procedures are expected and intended to make serious work injury by hydrogen combustion an extremely unlikely event.

1.1.3 External Exposure

Accidents involving external exposure to penetrating radiation are not specifically addressed in this report because beam control accidents or other accidents involving external irradiation have no potential for injuring members of the public at the well shielded SNS. The SNS proton beam is at every point, and for every possible beam misdirection, separated from the outside of the facility by many feet of concrete, steel, and/or dirt. The SNS shielding is designed in accordance with a shielding design policy (J. A. Alonso et al., "NSNS Shielding Policy," NSNS/97-9, May 1997) that requires shielding sufficient to render radiation levels very low on the exterior of the shield. For example, the external radiation exposure rate must not exceed 10 mrem/year at the site boundary.

There is a nonnegligible possibility for radiation injury to workers, but the SNS design and operational teams plan to make full use of the successful approaches to personnel protection that have been worked out during the past 50 years of accelerator development in the United States. The SNS is proposed to be built for scientific investigations, but the accelerator design involves concepts that have been proven at other facilities. Each of the candidate laboratories for SNS siting currently has active radiological control programs for accelerators. As explained in Sect. 9 of the SNS CDR, the SNS worker radiological protection program will use shielding, automatic beam cut-off devices, entry control devices, warning devices, and operator radiological training to ensure minimal risk to workers during operation of the SNS.

The Department of Energy (DOE) Regulation 10 CFR 835, "Occupational Radiation Protection," provides standards that must be followed in order to minimize the risk of excessive radiation exposure at DOE facilities. This includes requirements that must be followed for controlling access to and posting of radiation areas, high radiation areas, and very high radiation areas. The 10 CFR 835 definition of very high radiation areas is >500 rads in 1 h at 1 m, which is clearly in the potentially lethal range. During beam operation at high beam power, the SNS high energy tunnels meet the definition of a very high radiation area. In addition to training, use of procedures, posting, and other administrative safety features and programs, the SNS will have a high integrity automatic safety system, the personnel protection system, that will discontinue the proton beam whenever anyone tries to gain access to the interior of the proton beam tunnel.

Considering both administrative and automatic control functions, the risk of fatality or radiation injury because of external radiation (e.g., attempting tunnel access during beam operation) is judged to be in the extremely unlikely category. Moreover, this risk is well understood and accepted by those who operate accelerators in the DOE complex. The risk of tunnel access during beam operation is addressed above because it involves the highest radiation levels and is the most "dramatic" throughout the SNS facility.

There are other lesser risks involving direct radiation, such as the possibility for excess exposure during movement of highly activated components inside the target hot cell, for example, or when loading highly activated components into shipping casks. These risks are controlled within 10 CFR 835 by administrative programs, automatic protective or warning devices, and/or facility design measures, as appropriate to each particular application. Movement of activated components in shipping casks on public roads is subject to the regulation of the U.S. Department of Transportation.

1.2 ACCIDENTS WITH POTENTIAL TO RELEASE RADIOACTIVE MATERIAL

The potential radiological consequence of an accident involving release of radioactive material is determined by the inventory of radioactivity present in the process, the available transport mechanisms, and the installed mitigative features. Section 2 discusses the inventories and dispersabilities of radioactive nuclides to be found in the SNS components and structures. Section 3 presents the spectrum of accidents for the target and target components and provides estimates of the source terms for reasonably foreseeable accidents involving the potential for release of radioactive material. Chapter 4 derives source terms for accidents involving the target facility hot off-gas system and other waste-related systems.

The initial design for the SNS is for a 1-MW accelerator with a 1-MW target facility, upgradable to a 2-MW operation with modest refitting (the goal is that the needed modifications should be able to be completed during a 6-month shutdown of the facility). It is expected that the 2-MW operation will be achieved within approximately 5 years. After that, it is planned that a second ring will be built and a target plug/cooling system will be installed in the target facility that will be capable of 4-MW operation. It will probably take more than 10 years for the 4-MW operation to be realized, and additional approvals from DOE will be required before its realization. An objective of this report is to specify bounding source terms that are applicable to the 4-MW operation that may eventually be achieved, provided that the extensive target modifications are made and that the additional ring is constructed. Unless indicated otherwise, the source terms were calculated for the 4-MW operation and, thus, bounding for the 1-MW operation. In some cases, source terms are given for both the 1-MW and the 4-MW configuration for comparison purposes. (Note: the target facility radionuclide inventory is directly proportional to the proton beam power, so the initial radioactivity for 4-MW target operation is four times higher than that for 1-MW operation.)

The evaluation of risk must consider the probability that a given hypothetical accident will occur during a given period of time. Quantitative probabilities have not been developed for the SNS accident sequences, but the various potential events have been placed in the frequency categories introduced in DOE-STD-3009-94: Anticipated, Unlikely, Extremely Unlikely, and Beyond Extremely Unlikely (beyond design basis). Probability per unit time (frequency) ranges are indicated in Chap. 3 based upon whether an accident is likely to occur at least once in the life

of the facility (anticipated event—frequency >0.025/year for a 40-year lifetime), not likely to occur even once in the facility lifetime (unlikely event—frequency range 0.025/year to 10^{-4}/year), or very unlikely to occur even during many facility lifetimes or longer (extremely unlikely event). All of these three categories are considered to be design-basis events. A fourth category is postulated for risk assessment purposes—the beyond-design-basis (BDB) category. Events in this category are physically plausible but are not considered credible events. The frequency range could, in a very approximate sense, be stated as being from 10^{-8}/year to 10^{-6}/year. The BDB category events are postulated in order to obtain full understanding of potential consequences without being constrained as to whether the event(s) are actually credible.

Events are assigned to a frequency category based on experience and on engineering judgement considerations such as whether the failure in question is something relatively likely, such as a pump stopping or a valve being inadvertently closed by an operator; something somewhat unlikely (e.g., a sudden major pipe break or other boundary failure); or something very unlikely (e.g., the total failure of a redundant, multichannel beam cutoff system.

A bounding approach has been used for accident analysis in this report. The objective of the methods used to estimate source terms is to provide accident release estimates that have enough conservatism to allow for design evolution that will occur as the design proceeds from conceptual to detail design and then to construction.

In the spirit of ensuring bounding source terms, the accident durations are typically much longer than would be the case if any of the hypothetical events actually occurred. This is true because very little or no credit has been taken for accident mitigation procedures that would be available to the facility operators. Therefore, some accident durations longer than 8-hours, for example, are listed. This is done only to maximize the calculated bounding source terms and does not imply that the facility operators would not be able to take action to curtail an actual release much sooner.

This report should be read in conjunction with the SNS CDR and the SNS Design Manual (to be published later this year). The extensive descriptions of facilities and drawings contained in these design documents are not repeated here. In addition, reference can be made to recent papers[2,3] addressing the use of mercury in spallation neutron source systems.

1.3 REFERENCES

1. The NSNS Collaboration, *National Spallation Neutron Source Conceptual Design Report*, NSNS/CDR-2/V1 and V2, Lockheed Martin Energy Research Corp., Oak Ridge Natl. Lab., May 1997.
2. D. Filges, R. D. Neef, and H. Schaal, "Nuclear Studies of Different Target Systems for the European Spallation Source (ESS)," ICANS-XIII, 13th Meeting of the International Collaboration on Advanced Neutron Sources, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland, October 11–14, 1995.
3. G. S. Bauer, "Mercury as a Target Material for Pulsed (Fast) Spallation Neutron Source Systems," ICANS-XIII, 13th Meeting of the International Collaboration on Advanced Neutron Sources, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland, October 11–14, 1995.

2. RADIONUCLIDE INVENTORIES

The purpose of this section is to acquaint the reader with the inventories of radioactive material that will accumulate in the SNS systems, structures, and components, and to point out which inventories of radionuclides could realistically be released in quantities sufficient to cause significant radiation exposure at a distance from the SNS facilities.

For the SNS, the greatest inventory of radioactive material is found in the target facility, more specifically in the mercury that is bombarded by the beam of 1000-MeV protons to produce neutrons by the spallation reaction. Activated mercury and radioactive spallation products (of atomic weight all the way down to tritium) are the byproducts of the intense neutron flux and the spallation reactions. Components other than the target become radioactive by virtue of spallation and/or activation, but at a much lower level and with a much more restricted list of radionuclides.

The methodology described in Sect. 5.4 of the SNS CDR was employed to calculate the inventories of radionuclides. This involved use of the HETC96 particle generation and hadronic transport code, the Monte Carlo neutron photon (MCNP) code for low energy (<20 MeV) neutron transport, and the ORIHET95 code to track isotope production and decay.[1] Only the radionuclides that are potentially significant are presented in Table 2.1.

The reported inventories are calculated under the assumption that the accelerator operates continuously at 4 MW for 30 years. This is a reasonable or conservative assumption for three reasons. First, the accelerator operation is not continuous. The total yearly operating time will actually be about 70% of the time (~6000 h per year). Typically, the proton beam will be on target for 3 or 4 weeks and then will be down for adjustment or experiment change-out. Once a year, there will be an approximately 6-week to 2-month outage for more time consuming maintenance and refurbishment. Thus, the nominal 40-year facility life will accumulate no more MW × years of proton beam time on-target than would 30 years of continuous service, if that were possible. Second, upgrading the SNS to a 4-MW power level will be a deliberate process, with the final upgrade from 2 MW to 4 MW requiring construction of a second accumulator ring (each ring will be capable of handling 2 MW of proton beam power). Thus, it may be 10 years before the power is upgraded to 4 MW. The reader is referred to the discussion in Sect. 1.3.5 of the CDR. Third, it is expected that a second target facility will be added early in facility life. This second target facility (a separate building) will operate at a lower pulsing rate (about 10/s instead of about 50 to 60/s) and also a lower beam power. This will take MW × years away from the higher-power main target building to which this report is addressed. These factors add a degree of conservatism to the Table 2.1 target system inventories.

DOE Standard 1027-1992 (Change Notice No. 1, September 1997) provides radioactivity thresholds for evaluating, on a quick, screening basis, whether the quantity of radioactivity in a facility is capable of causing only localized consequences (i.e., consistent with low hazard or Category 3 facilities), as opposed to being able to cause consequences that could cover a wider area on site (moderate hazard or Category 2 facilities). The Category 2 thresholds were used as a basis for comparison of inventories of radionuclides in different locations. For instance, where threshold values were not provided by STD-1027-92, the methodology defined in STD-1027-92 was used to calculate the appropriate thresholds.

Specifically, the Category 2 thresholds define how much radioactivity would have to be involved in a generic accident in order to cause a radiation dose of 1 rem at 300 m assuming a

ground level release and specified meteorological conditions. The source terms (release fractions) assumed by STD-1027-92 for the generic accident are based on the physical form of the radioactive material involved: 100% is assumed for gaseous and highly volatile materials; 50% is assumed for halogens (e.g., iodine); 1% is assumed for semivolatiles such as mercury; and 0.1% is assumed for all others. For nuclides not specifically addressed in STD-1027-92 or other DOE publications, one user must input dose conversion factor values. For example, updated dose conversion values,[2,3] were used for mercury and mercury daughter radionuclides.[2,3]

In this chapter, radioactivity inventory thresholds based on STD-1027-92 methodology are used to obtain a relative understanding of the potential radiological health impacts of amounts of radioactivity found throughout the SNS facilities.

The results of the radionuclide inventory hazard screening (Table 2.1) show very clearly that the radionuclides in the target mercury dominate the potential release hazards. For example, if all the radionuclides in the SNS target mercury are considered, the SNS target mercury's spallation/activation products are estimated after 30 years of continuous operation at the maximum 4-MW beam power to have an aggregate radioactivity inventory of about 9.5 times the DOE Category 2 threshold, whereas the corresponding aggregate for any accelerator component (e.g., the neutral beam stop) would be more than two orders of magnitude lower. This identifies the mercury target and its hot cell as a preliminary candidate Hazard Category 2 facility. Whether the preliminary Category 2 designation remains, or is changed to Category 3, will depend upon analyses to be done in the next phase of design. As explained in DOE-STD-1027-92, ". . . for facilities initially classified as Hazard Category 2, if credible release fractions can be shown to be significantly different than these values based only on physical and chemical form and available dispersive energy sources . . .," the facility may be placed in Category 3 instead. This designation must be approved by DOE, and the burden of proof is upon the contractor to demonstrate that the ground rule conditions exist. Chapters 3 and 4 of this report provide conservative, event-sequence-specific source terms for more detailed study of the consequences of radioactivity release accidents of the SNS target mercury and related off-gas system.

A conclusion that can be drawn from Table 2.1 is that radioactive material release accidents of the accelerator, including its beam stops, would not be capable of causing significant radiation exposures beyond the confines of the accelerator. Considering the most highly activated part of the accelerator, the ring injection beam stop, we see that the total inventory is about 10% of the Category 2 limit. The corresponding radiation exposure that could, per the DOE-STD-1027-92 methodology, be expected at 300 m as a result of a beam stop accident, with ground level release of the prescribed fractions of the radionuclide inventory, would therefore be about 10% of 1 rem, or about 100 millirem, which is comparable to the annual natural background. For this reason, the source terms reported for further analysis in Chap. 3 concentrate on the much more radioactive target and related systems.

Exhibit B presents the inventory of radionuclides in the target mercury after 30 years of continuous irradiation by a 1-MW proton beam, which is equivalent to about 40 years of actual operation (~6000 h/year of high power beam operation). The inventory corresponding to operation for the same period at a 2-MW or a 4-MW proton beam power can be accurately determined by multiplying by 2 or 4, respectively, since the buildup and decay of radioactive nuclides is linear with respect to the proton beam power level.

Table 2.1. SNS radioactivity inventories survey for operation with 4-MW proton beam

Area or component (Ref. Table 5.4-5, Fig. 5.4-6 in SNS CDR, NSNS/CDR-2/V1)	Radioactivity (Ci)			Dispersability assessment
	Decay energy (W)	Nuclides present in quantity >0.1% of DOE Cat. 2 hazard threshold[a]		
		Nuclide inventories[b] (Ci)	Fraction of DOE Cat. 2 threshold	
Per 10 m of linac or ring high energy beam tube and surroundings[c]	1.4 W in 680 Ci	None in quantity >0.1% of Cat. 2 threshold	None	N/A
Accelerator neutral (i.e., ring injection) beam stop Cu + H_2O. Irradiated by 200 kW proton beam continuously for 30 years; equivalent to nominal 40-year life. This is bounding with respect to the other beam stops, which are operated intermittently	300 W in 2.8E6 Ci	***Volatile/gaseous***		Most of the indicated H-3 inventory is bound in the copper metal of the beam stop and thus not readily releasable. The amount in beam stop coolant H_2O is estimated at well below 1000 Ci (this H_2O is periodically replenished). The gaseous isotopes of N and O are associated with the cooling water, and therefore subject to release
		H-3: 4.6E3	1.6E-2	
		N-13: 166	2.6E-3	
		N-16: 120	1.0E-2	
		O-15: 654	1.1E-2	
		Nonvolatile	3.0E-2	Release of these nuclides would require vaporization of the metallic beam stop (highly unlikely) combined with failure of the beam stop ventilation system HEPA[d] filters to eliminate any resulting aerosol from the exhaust air
		Cu-64: 2.8E6	1.6E-2	
		P-32: 1.6E2	9.6E-3	
		Co-60: 1.8E3	3.0E-3	
		Na-22: 2.2E1	2.4E-3	
		Co-56: 2.4E3		
Accelerator neutral beam stop, stainless steel + H_2O (i.e., inner shielding)	114 W in 2.8E5 Ci	***Nonvolatile***		Significant release would require vaporization of the stainless steel shielding structure combined with failure of the beam stop ventilation system HEPA filters
		Fe-55: 1.2E5	4.8E-3	
Target SS-316 after 1 year (expected replacement before 0.5-year)	3.3E2 W in 3.6E5 Ci	***Nonvolatile***		Nonvolatile elements held inside stainless steel. Not subject to release unless stainless steel is vaporized and HEPA filters fail
		P-32: 2.0E2	1.9E-2	
		Cr-51: 2.8E5	2.7E-3	
		Fe-59: 5.7E3	2.1E-3	
		Fe-55: 5.0E4	2.1E-3	
		Na-22: 1.1E1	1.7E-3	
		K-42: 7.4E1	1.6E-3	
		Mn-54: 4.6E3	1.1E-3	
Target, H_2O (shroud cooling water)	46 W in 4.7E3 Ci	N-13: 6.2E2	1.0E-2	Volatile/gaseous nuclides subject to release if water spill occurs
		N-16: 3.9E2	3.4E-2	
		O-14: 2.1E2	1.8E-2	
		O-15: 2.9E3	4.6E-2	

Table 2.1 (continued)

Area or component (Ref. Table 5.4-5, Fig. 5.4-6 in SNS CDR, NSNS/CDR-2/V1)	Radioactivity (Ci)			Dispersability assessment
	Decay energy (W)	Nuclides present in quantity >0.1% of DOE Cat. 2 hazard threshold[a]		
		Nuclide inventories[b] (Ci)	Fraction of DOE Cat. 2 threshold	
Target, moderator Al	540 W in 3.0E4 Ci	Na-22: 42 Na-24: 330 Al-28: 2.9E4	6.6E-3 9.8E-2 1.E-3	Structure made of nonvolatile aluminum that is not released unless vaporized
Target, cryogenic H_2 moderator	~0	None	None	N/A
Target, moderator H_2O	7 W in 488 Ci	***Volatile/gaseous*** N-13: 75 N-16: 110 O-15: 270	 1.2E-3 9.6E-3 4.4E-3	Gaseous nuclides could be released if target moderator water spilled
Target, Reg. IV & V, reflector Be/D_2O (As noted in the SNS CDR, lead is under consideration for use in reflector rods; due to the relatively low activation characteristics of lead, this does not increase the hazard profile of the reflector activation products substantially above what is shown here for Be)	4.3 kW in 2.7E6 Ci	***Volatile/gaseous*** H-3: 3200 N-13: 420 N-16: 520 O-15: 1700	 1.1E-2 6.8E-3 4.6E-2 2.7E-2	Gaseous nuclides could be released if reflector cooling water spilled
		Nonvolatile P-32: 2.0E1 Cr-51: 1.4E6 Mn-54: 1.E4 Fe-55: 1.1E6 Fe-59: 3.3E4 Co-60: 2.8E2 Ni-63: 1.3E5	 1.9E-3 1.4E-2 2.4E-3 4.5E-2 1.2E-2 1.5E-3 8.6E-3	Nonvolatile elements in the reflector metal structure. Release would require mass vaporization combined with failure of HEPA filtration
Target, Reg. VI & VII Ni reflector + D_2O coolant	0.64 kW in 2.5E5 Ci	***Volatile/gaseous*** N-16: 23 O-15: 74	 2.0E-3 1.2E-3	Gaseous nuclides could be released if reflector cooling water spilled
		Nonvolatile Co-56: 1.1E4 Co-57: 2.7E4 Co-58: 1.4E4 Co-60: 1.2E3 Ni-63: 1.2E5	 1.0E-2 7.2E-3 3.6E-3 6.1E-3 8.1E-3	Nonvolatile elements in the reflector metal structure. Release would require mass vaporization combined with failure of HEPA filtration

Table 2.1 (continued)

Area or component (Ref. Table 5.4-5, Fig. 5.4-6 in SNS CDR, NSNS/CDR-2/V1)	Radioactivity (Ci)			Dispersability assessment
	Decay energy (W)	Nuclides present in quantity >0.1% of DOE Cat. 2 hazard threshold[a]		
		Nuclide inventories[b] (Ci)	Fraction of DOE Cat. 2 threshold	
Target, Reg. VIII & IX Ni reflector + H_2O coolant	3.1 kW in 6.0E5 Ci	***Volatile/gaseous***		Gaseous nuclides could be released if reflector cooling water spilled
		N-13: 122	2.E-3	
		N-16: 87	7.6E-3	
		O-15: 860	1.4E-2	
		Nonvolatile		Nonvolatile elements in the reflector metal structure. Release would require mass vaporization combined with failure of HEPA filtration
		Na-22: 2.7E1	4.2E-3	
		Mn-52: 1.2E4	2.9E-3	
		Mn-54: 8.5E3	2.0E-3	
		Co-55: 1.4E3	1.3E-3	
		Co-56: 7.4E4	7.1E-2	
		Co-57: 1.5E5	4.1E-2	
		Co-58: 4.2E4	1.1E-2	
		Co-60: 6.3E3	3.3E-2	
		Ni-56: 3.6E3	1.3E-3	
		Ni-57: 4.1E4	3.7E-3	
		Ni-63: 1.4E4	9.1E-3	
Target, Reg. X Ni reflector + H_2O coolant	2.1 kW in 7.0E5 Ci	***Volatile/gaseous***		Gaseous nuclides could be released if reflector cooling water spilled
		N-13: 68	1.1E-3	
		N-16: 82	7.1E-3	
		O-15: 260	4.1E-3	
		Nonvolatile		Nonvolatile elements in the reflector metal structure. Release would require mass vaporization combined with failure of HEPA filtration
		Co-56: 3.13E4	3.0E-2	
		Co-57: 8.3E4	2.2E-2	
		Co-58: 5.3E4	1.4E-2	
		Co-60: 3.9E3	2.0E-2	
		Ni-57: 1.9E4	1.7E-3	
		Ni-63: 4.1E5	2.7E-2	
		Ni-65: 6.7E4	1.0E-3	
Target, Reg. XI and XII, Fe shielding + H_2O coolant	200 W in 2.0E5 Ci	***Volatile/gaseous***		Gaseous nuclides could be released if shield cooling water spilled
		N-16: 14 Ci	1.3E-3	
		Nonvolatile		Nonvolatile elements in the reflector metal structure. Release would require mass vaporization (not credible) and failure of HEPA filtration (unlikely)
		Na-22: 1.4E1	2.2E-3	
		P-32: 4.0E1	3.9E-3	
		Mn-54: 6.7E3	1.8E-3	
		Fe-55: 1.8E5	7.5E-3	

Table 2.1 (continued)

Area or component (Ref. Table 5.4-5, Fig. 5.4-6 in SNS CDR, NSNS/CDR-2/V1)	Radioactivity (Ci)			Dispersability assessment
	Decay energy (W)	Nuclides present in quantity >1.0% of DOE Cat. 2 hazard threshold[a]		
		Nuclide inventories[b] (Ci)	Fraction of DOE Cat. 2 threshold	
Target, Hg, after 30-year continuous irradiation by 4 MW proton beam (The mercury H_2O coolant does not become activated because it is outside the target plug. Double-walled heat exchanger tubes are used to prevent Hg from entering the cooling H_2O.) The target mercury is not changed during the facility life. The buildup of radioactivity is not dependent upon the total Hg volume (~1 m^3), or upon the rate of circulation of the mercury	9.6 kW in 3.6E6 Ci	**Volatile/gaseous**		The parentheses indicate that this inventory will not actually be present—a helium purge flow purges gaseous H-3 from the target Hg and transports it to a hydride bed in the hot off-gas system, where it is unlikely to be released (see Sect. 4). Some tritium will form stable, nonvolatile hydrides with spallation products in the Hg, but tritium in this state will not be readily releasable
		H-3: 2.4E5	(0.78)	
		Semivolatile		Iodine combines chemically with Hg to form Hg2I2, but the accident source terms assume 100% release to ensure conservatism (see Chap. 3)
		I-124: 6.8E1	0.052	
		I-125: 3.0E2	0.27	
		I-126: 1.4E1	0.023	
		Hg-189: 6.8E3	0.16	
		Hg-193:4.1E4	0.067	Hg is subject to evaporation in Hg spill accidents, which is considered in formulation of the source terms (see Chap. 3).
		Hg-194: 4.5E3	0.24	
		Hg-195: 6.9E4	0.13	
		Hg-197: 4.7E5	2.6	
		Hg-203: 3.3E5	3.0	

Table 2.1 (continued)

Area or component (Ref. Table 5.4-5, Fig. 5.4-6 in SNS CDR, NSNS/CDR-2/V1)	Radioactivity (Ci)			Dispersability assessment
	Decay energy (W)	Nuclides present in quantity >1.0% of DOE Cat. 2 hazard threshold[a]		
		Nuclide inventories[b] (Ci)	Fraction of DOE Cat. 2 threshold	
		Nonvolatile		Not subject to release: these elements have essentially zero vapor pressure at normal and accident temperatures. They are either dissolved in the Hg or have plated out on an interior Hg system surface or been filtered out of the Hg
		Gd-148: 7.6E2	2.2	
		Hf-172: 1.6E4	0.14	
		Au-195: 9.0E4	3.8E-2	
		Au-188: 1.3E4	3.1E-2	
		W-175: 1.3E4	3.0E-2	
		W-174: 1.2E4	2.8E-2	
		Hf-171: 9.4E3	2.2E-2	
		Os-183M: 8.76E3	2.0E-2	
		Lu-168: 7.2E3	1.7E-2	
		Ta-171: 7.2E3	1.7E-2	
		Lu-167: 7.0E3	1.6E-2	
		Os-179: 7.0E3	1.6E-2	
		Tb-152: 6.4E3	1.5E-2	
		Hf-168: 6.1E3	1.4E-2	
		Ho-158: 5.8E3	1.4E-2	
		Ta-170: 5.6E3	1.3E-2	
		Dy-153: 5.0E3	1.2E-2	
		Er-158: 5.0E3	1.2E-2	
		Tm-164: 4.9E3	1.1E-2	
		Dy-152: 4.8E3	1.1E-2	
		Yb-164: 4.8E3	1.1E-2	
		W-172: 4.8E3	1.1E-2	
		Ho-160: 4.5E3	1.1E-2	
		Tm-165: 4.4E3	1.0E-2	
		Er-160: 4.4E3	1.0E-2	

Table notes:

[a]DOE Standard 1027-1992 defines facility hazard categories and inventory thresholds for screening purposes. The Category 2 threshold for a nuclide is the quantity of that nuclide that, if involved in an accident, could impart a radiation dose of 1 rem at a distance of 300 m under average meteorological conditions. Published threshold values were available from STD-1027 or from DOE-STD-6003-96 for most of the nuclides in this table. Where neither published threshold values nor dose conversion factors were available, the thresholds were typically taken as the 4.3E5 generic threshold value suggested by STD-1027-1992 for beta-gamma emitters. (See also Exhibit B)

[b]Note "E" nomenclature used to indicate 10 raised to a power (e.g., E-3 means 10^{-3}). Reported inventories are for 4-MW operation for 40 years (40 years of on and off operational cycles is simulated as 30 years of continuous operation in the calculations). The beam stops are assumed to operate continuously at 0.2 MW for 30 years. Beam stops may be operated for short periods at higher beam power, but the 0.2 MW for 30 years is conservative with respect to inventory buildup over the life of the facility. Only the neutral beam stop (ring injection stop) operates continuously during normal operation.

[c]The high energy end of the linac and the ring operate with particle energy of ~1000 MeV. The activation levels become progressively lower from the high energy end to the low energy end. The activity calculations represented the beam tube and its immediate surroundings (e.g., magnets) as one lump of copper. The activation levels present in the linac and ring beam tube and surrounding structures depends on beam losses that are not a direct function of proton beam power. When the SNS is upgraded from 1 to 2 and/or to 4 MW, every attempt will be made to maintain the same beam losses in order to avoid increased structural activation that would complicate radiation protection for maintenance activities. No activation occurs in the ion-source facility because particle energies are below the coulomb barrier there.

[d]High-efficiency particulate air.

2.1 REFERENCES

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2. "Dose Coefficients for Intakes at Radionuclides by Workers," ICRP-68, Annals of the ICRP, 24(4), 1994.
3. K. Eckerman, Oak Ridge National Laboratory, E-mail letters dated June 18, 1998, and August 24, 1998, transmitting "Hg and Hg Daughter and Hg Spallation Product Dose Conversion Factors."

3. SOURCE TERM DEVELOPMENT: TARGET AND TARGET COMPONENTS

3.1 INTRODUCTION

This chapter provides detailed consideration of target and target component accidents that could release significant amounts of radioactive material to the environment (see Chap. 4 for target facility hot off-gas system accidents and liquid waste system-related accidents). Recommended source terms for target facility accidents are summarized in Table 3.1, and the major facts of the accident sequences are presented in Table 3.2. Individual sequences and source term development are discussed in Sects. 3.1 through 3.17. In some cases, the same source term applies—in a bounding sense—to several accidents. Table 3.1 indicates which events are bounded by each of the given recommended source terms.

The initial design for the SNS is a 1-MW target facility upgradable to a 2-MW operation with minimal refitting (e.g., up to a 6-month shutdown for any needed modifications). It is expected that the 2-MW operation will be achieved within approximately 5 years. After that, it is planned that a second ring will be built, and a target plug/cooling system will be installed in the target facility that will be capable of 4-MW operation. It will probably take more than 10 years for 4-MW operation to be realized. An objective of this chapter has been to specify source terms that are applicable to 4-MW operation. Unless indicated otherwise, the stated source terms are for 4-MW operation, and, therefore, bounding with respect to 1-MW operation.

3.1.1 Selection of Target Accident Sequences

As shown in Chap. 2, the target mercury has the most significant inventory of radioactive materials of all the SNS components and systems. Preventing release of those radioactive materials depends primarily upon three things: (1) maintaining control of the energy input to the mercury (i.e., the proton beam), (2) maintaining continuous cooling of the mercury during proton beam operation, and (3) maintaining the integrity of the mercury system itself. The first four accident sequences in this chapter evaluate potential source terms associated with these three important parameters. Section 3.2 examines beam control faults; Sect. 3.3, system integrity faults; Sect. 3.4, loss of mercury forced flow; and Sect. 3.5, loss of mercury cooling water. Depending on sequence-specific details and additional failures that are assumed, any of the first four sequences could involve release of mercury and/or its contained spallation and activation products. Section 3.14, loss of off-site power; Sect. 3.15, fire; and Sect. 3.16, natural phenomena, evaluate external events or common mode internal events that could affect mercury system integrity and/or cooling. The decay heat generation in the mercury after cutoff of the proton beam is sufficiently low that events such as loss of off-site power (Sect. 3.14) do not have the potential for compromise of mercury confinement integrity.

When the proton beam is operating, about 66% of the beam's energy ends up as thermal energy dissipation in the mercury held in the mercury vessel. The balance of the proton beam's energy supplies binding energy for the spallation process, escapes into the surrounding components, or is subtracted from the beam as it passes through the barriers between the accelerator-produced beam and actual target mercury: these barriers are the proton beam window, the water-cooled shroud, and the front face ("window") of the mercury vessel (see Fig. 5.3-6 in Chap. 5 of the CDR). Clearly, the beam has the potential to cause failure of mercury

Table 3.1. Source term summary—Hg target systems

(frequency ranges: $2.5(10)^{-2}$/year<**A**<10^{0}/year; 10^{-4}/year<**U**<$2.5(10)^{-2}$/year; 10^{-6}/year<**EU**<10^{-4}/year)

Frequency category	Event(s) (sequence number(s) as used throughout Chap. 3, Table 3.2)	Recommended source term		
		Material released	Time span[a]	Nuclides released to environment
A	1, 3, 4, 5, 6, 7, 13	None	NA	None
A	2.SL—Loss of Hg vessel or pipe integrity: slow leak to air inside target cell	Hg vapor	Indeterminant	Radiation exposure calculation not required since operation would be curtailed before exceeding EPA off-site airborne exposure limit
A	8.SL—Loss of H_2O or D_2O component cooling system integrity, slow leak	Tritiated H_2O or D_2O vapor, as applicable	Indeterminant	Radiation exposure calculation not required since operation would be curtailed before exceeding EPA off-site airborne exposure limit
A	8.SL—Slow leak into core vessel (this is an example of the sort of event that 8.SL can represent)	Tritiated H_2O or D_2O vapor, as applicable	30 d	18 L of H_2O or D_2O released over 30-d period. Source term is 90 Ci of tritium for D_2O cooling system and 9 Ci of tritium for H_2O cooling system
A	8.MF—Loss of H_2O component cooling system integrity, major failure	Tritiated H_2O plus N and O gaseous nuclides	First 5 min: mist release and N, O release. First 1/2 h: H_2O vapor release	150 L of H_2O evaporated over a ≥1/2-h period releasing 75 Ci of tritium. See Table 3.6 for N and I isotopes release. Mist entrainment release: 7.5 Ci tritium plus List 8 (Exhibit E) * [beam power/ (1 MW)] * 0.005
A	8.MF, 7/ABC/—Loss of D_2O component cooling system integrity, major failure	Tritiated D_2O plus N and O gaseous nuclides	First 5 min: mist release and N, O release. First 1/2 h: D_2O vapor release	150 L of D_2O evaporated over a ≥1/2-h period releasing 750 Ci of tritium. The N and O isotopes (see Table 3.4) released over a ≥5-min period. Mist entrainment releases: 75 Ci tritium plus List 8 (Exhibit E) * (beam power/ 1 MW) * 0.005
U	10—Loss of integrity of target core vessel (~3.5-m diam target containment vessel)	Gaseous products from spallation, activation of air	NA	Radiation exposure calculation not required since operation would be curtailed before exceeding EPA off-site airborne exposure limit
U	12—HEPA filter failure	Unfiltered target cell exhaust released	NA	Radiation exposure calculation not required since operation would be curtailed before exceeding EPA off-site airborne exposure limit
U	2.MF—Loss of Hg vessel or pipe integrity: major fault	Hg vapor, radio-iodine	Initial release specified for first 10 min; additional release over 8 d	1 L of nondrained Hg assumed to evaporate over 8-d (0.14% of total inventory). See Table 3.4. Iodine contained in 1 L of Hg assumed to be released

Table 3.1 (continued)

Frequency category	Event(s) (sequence number(s) as used throughout Chap. 3, Table 3.2)	Recommended source term		
		Material released	Time span[a]	Nuclides released to environment
U	Design basis natural phenomena—tornado, earthquake	Either no release or minor releases since natural phenomena in the unlikely range are within the target facility design basis		
EU	2.MF/mercury enclosure/—Major loss of Hg vessel or pipe integrity with assumed failure of mercury enclosure and/or its drainage system. Also bounds other EU events (e.g., EU filter fire, EU natural phenomena)	Hg vapor, radio-iodine	Initial release specified for first 10 min; additional release over 30 d	See Table 3.4. Total of 0.24% of Hg and 100% of iodine released
BDB	2/ABC/, 3/ABC/—Loss of Hg forced circulation with failure of the BP and TPS automatic beam cutoffs, plus Hg drainage path blocked, water-cooled shroud failure	Hg vapor, radio-iodine	Releases broken down for first 10 min, days 1–7, and days 8–30	Total of 1.1% (1-MW case) or 1.3% of Hg released (4-MW case). 100% of radioiodines released in either case. See Table 3.8

[a]The time spans listed are bounding and do not credit the full range of recovery actions that operations personnel would take to curtail or stop releases much sooner.

containment barriers and/or to cause elevated mercury temperatures in a short period of time. After cut off of the proton beam, the rate of decay heat dissipation within the mercury (~2.5 kW at 1 MW or 10 kW at 4 MW) does not require active cooling.

Other target systems (e.g., moderators and reflectors) have radioactive material inventories, and this chapter also considers accident sequences that could threaten release of radioactive material from those systems. Chapter 4 considers potential target facility off-gas and waste system accident sequences and source terms.

3.1.2 Proton Beam Cutoff

The single most important parameter in any target facility accident sequence is timely cut off of the proton beam when unusual conditions occur. In order to prevent damage, the cutoff must occur on a time scale consistent with the abnormal condition that is occurring. For example, following a loss of forced mercury flow, the beam must be cut off while the flow is coasting down if damage is to be avoided (i.e., within a few seconds). At the slower end of the spectrum, following a loss of cooling to the mercury heat exchanger, the beam must be cut off within a few minutes. Failure to cut the beam off can result in inadequate cooling of the mercury vessel walls with uncontrolled heat-up and over-temperature failure. Furthermore, continued proton beam operation following barrier failure would provide a driving energy for escape of radioactive material from the target system.

Table 3.2. Target accidents

(frequency ranges: $2.5*10^{-2}$/year<**A**<10^{0}/year; 10^{-4}/year<**U**<$2.5*10^{-2}$/year; 10^{-6}/year<**EU**<10^{-4}/year)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
Events that initially (by definition) or potentially involve Hg system integrity					
1.A—Loss of control of proton beam: too narrow beam focus (A)	•Focusing magnet diagnostic signals •Beam current density detector upstream of target	•Automatic beam cutoff (ABC) via beam permit (BP) system	No damage. High proton flux density for one or two pulses not sufficient to cause damage	NA	Proton beam cutoff, target facility in standby
1.A/ABC/—Too narrow beam focus, with failure of focusing magnet and beam focus alarms (EU)	•Same as above, plus possibility of Hg spill-related alarms •Change in neutron production	•Failure of BP beam trip(s) on focus fault •BP or TPS cutoff on Hg spill-related signals	Proton beam might overheat the Hg vessel and/or water-cooled shroud leading to H_2O and/or Hg spill(s)	•Mercury spill confinement and drainage system •Hot cell ventilation and air treatment systems •If water-cooled shroud fails, neutron beam windows prevent radioactive material from entering the neutron beam tubes/guides	Proton beam cutoff, and: •Passive dissipation of Hg decay heat (no pumping required) •Spilled mercury in collection tank or other closed location within hot cell or core vessel
1.B—Loss of control of proton beam: diffuse focus (A)	•Change in neutron production	NA—none needed	No damage expected—diffuse focus distributes proton beam over wider area, reducing heat flux	NA—none needed	May continue operating at near normal, or proton beam may be cut off
1.C—Misdirected proton beam (A)	•Magnet status alarm •Tunnel radiation level	•ABC—via BP	None. Beam cutoff occurs before any damage can occur	•The collimator prevents impingement of proton beam upon nontarget components (e.g., moderators or reflectors)	Beam off for troubleshooting
1.C/ABC/—Misdirected proton beam with failure of magnet status and tunnel radiation alarms (EU)	Same as above plus alarms on: •Loss of beam tube vacuum •Isolation valve closure	•ABC on magnet status, tunnel radiation fail •ABC on isolation valve closure after loss of vacuum	Proton beam may burn through the beam tube: •Resulting loss of beam tube vacuum initiates signal for auto closure of "upstream" isolation valve	•The collimator prevents impingement of proton beam upon nontarget components	Beam tube burned through and isolated from ring beam tube by closed isolation valve; some ablation of scraper

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
2.MF—Loss of Hg vessel or pipe integrity: major fault (U) (MF = major failure)	•Hg presence (e.g., conductivity alarm) •Low level in reservoir tank	•ABC by BP and/or TPS	Hg pump maintains Hg circulation until level too low. ABC occurs before circulation ceases or additional damage	•Mercury spill confinement and drainage system •Hot cell ventilation and air treatment systems	Spilled mercury drains to collection tank. Passive dissipation of decay heat
2.MF/ABC/—Loss of Hg vessel or pipe integrity with failure of mercury level and leakage alarms (EU)	Same as above, plus •Target cell radiation levels	•ABC by BP and TPS fail •ABC by the personnel protection system (PPS) based on high radiation levels in target hot cell	The initiating boundary failure plus possibly some additional ablation of otherwise uninvolved target structures	Same as above	Same as above
2.SL—Loss of Hg vessel or pipe integrity: slow leak to air (A) (SL = slow leak)	Radiation levels in cell exhaust, stack emission monitors	NA	No damage except spread of contamination	Operators take the target out of service to avoid exceeding annual emission limits	Proton beam is cut off with active or passive cooling to remove residual heat from the Hg
2.HXL—leak in Hg*H_2O heat exchanger (A)	Interspace between double-walled heat exchanger tubes is monitored	NA	NA	Operators shut down the operation when/if tube leakage excessive	•Shutdown in preparation for heat exchanger repair and cell cleanup
3—Loss of mercury pumping (A)	•Hg pump status •Hg flow, or pump ΔP •Hg temperature	•ABC by BP and/or TPS	No damage. Proton beam cut off before Hg temperature becomes excessive	NA	•Proton beam is cut off •Passive removal of nuclide decay heat from target Hg
3/ABC/—Loss of mercury pumping with failures of pump status/flow alarms (EU to BDB)	Same as above, plus spill-related signals: •Hg level inside Hg system •Hg presence outside Hg system	•ABC failure but back-up ABC on spill-related signal(s) occurs if Hg vessel fails	•Hg temp increases •Hg vessel may fail if Hg boiling occurs •Sequence after Hg vessel failure (if any) similar to other Hg spill events	If severe enough to cause Hg boundary failure, then Hg drainage and confinement features provide mitigation	•Proton beam is cut off •Passive removal of nuclide decay heat from target Hg
4—Loss of H_2O cooling of Hg*H_2O heat exchanger (A)	•H_2O cooling flow •H_2O pump status, or •Hg temperature	•ABC by BP and/or TPS	No damage. Hg temp. begins increasing, but proton beam is quickly cut off	None needed	•Proton beam is cut off •Passive removal of nuclide decay heat from target Hg

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
4/ABC/—Loss of cooling H_2O flow in Hg*H_2O heat exchanger with failure of cooling water pumping status alarm(s) (EU)	Same as above, plus spill-related signals: •Hg level inside Hg system •Hg presence outside Hg system	•ABC failure •Back-up ABC on spill-related signals	•Hg temp. increases •Burn through or rupture of Hg vessel could occur if localized Hg boiling occurs •Sequence after Hg vessel failure (if any) similar to other Hg spill events	•Heat-up rate (25°C/min for 1-MW operation) allows adequate time for operator cutoff of proton beam before damage (e.g., failure of Hg boundary)	•Proton beam is cut off before significant damage •Hg circulation continues with passive dissipation of decay heat-to-heat sinks surrounding the Hg system
Events involving target component cooling					
5—Loss of H_2O flow: water-cooled shroud (A)	Pump status and/or low flow alarm(s)	•ABC by BP and/or TPS	No damage due to prompt beam cutoff	NA	Proton beam cut off, target facility in standby
5/ABC/—Same as above, with failure of pump status and/or low flow alarm(s) (EU)	•Increase in neutron production •Increase in core vessel pressure	•ABC failure	•Shroud may fail if H_2O boils	Spilled H_2O, if any, drains to the collection tank or remains inside core vessel. Aluminum windows prevent radioactivity from entering the neutron beam tubes/guides	Proton beam cut off, target facility shut down for recovery and repair
6—Loss of H_2O flow to proton beam window (A)	•Cooling system status alarms •Cooling H_2O low flow alarm	•ABC	No damage due to prompt beam cutoff	NA	Proton beam cut off, target facility in standby
6/ABC/—Loss of H_2O flow to proton beam window with failure of proton beam cut off (EU or BDB)	The above, plus alarms related to loss of proton beam tube vacuum and isolation valve closure	•ABC by TPS and BP fail •ABC on isolation valve closure signal or inherent beam loss due to loss of vacuum	•Proton beam window may fail if H_2O boils, causing loss of vacuum inside the proton beam tube, resulting in automatic closure of "upstream" isolation valve (to preserve vacuum in ring tube, etc.) •H_2O spill if proton beam window fails	•Neutron beam windows prevent transport of radioactive material released inside core vessel (e.g., due to spilled H_2O, if any) from entering the neutron beam tubes/guides	•Proton beam cut off, target facility shut down for damage assessment. Cooling water may be spilled inside core vessel. •He from core vessel has filled the failed proton beam tube up to the upstream isolation valve

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
7—Loss of H_2O or D_2O flow to target component (reflector, moderator, etc.) (A)	•Cooling system status alarms •Cooling H_2O and/or D_2O flow alarms	•ABC by TPS and/or BP	•Proton beam cut off occurs before significant heat-up can occur •Active cooling not required for removal of radionuclide decay heat after proton beam cut off	NA	Proton beam cut off; target facility in standby
7/ABC/—Same, with failure of proton beam cut off (EU)	Same as above, plus: •Core vessel pressure alarm	•ABC failure	•If boiling occurs, component cooling pipe or vessel may burst, spilling H_2O or D_2O inside core vessel •Component may overheat, but heat losses to surrounding structures will prevent extensive melting	•If no automatic beam cutoff occurs, the operators would initiate manual beam cutoff in response to various alarms. There would be adequate time (>1 min for most components) for operator action •H_2O spillage drains to drain tanks or remains inside core vessel	Target facility shut down for damage assessment
8.MF—Loss of H_2O or D_2O system integrity [U for any given system, A for multiple systems]	•Cooling system status alarms •Cooling H_2O and/or D_2O flow alarms •Core vessel pressure alarm (possible)	•ABC	•Proton beam cut off before significant component heat-up. •Cooling H_2O or D_2O, as applicable released inside core vessel, target cell, or pump vault (depends on location of failure)	•Spillage drains to core vessel or to drain tank, depending on location of failure	Target facility shut down for damage assessment

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
8.MF/ABC/—Same with failure of proton beam cut off (EU)	Same as above	•ABC failure	•Cooling H_2O or D_2O, as applicable, released inside core vessel, target cell or pump vault •Component may overheat. Extensive melting unlikely	•If no automatic beam cutoff occurs, the operators would initiate manual beam cutoff in response to various alarms •H_2O spillage, if any, drains to drain tanks	Target facility shut down for damage assessment
8.SL—Loss of H_2O or D_2O system integrity (A)	Depending on location, one or more of following: •Core vessel pressure alarm •Exhaust radiation alarm(s) •Affected cooling system low-water-inventory-related signal(s)/alarm(s)	Probably none, until or unless coolant system flow affected	Slow leak does not affect coolant flow initially (or until significant inventory loss has occurred)	•Drainage paths and drain tanks or sumps are provided for coolant leaking from any system •Based on stack monitoring, operation of the target facility would be curtailed before annual release limits exceeded	Target facility shut down for repair
9.A—Loss of cryogenic moderator integrity: both the helium and the vacuum barriers fail inside core vessel (EU—multiple failures required for any release)	•Cryogenic moderator pressure and temperature indications, alarms. Vacuum indications and alarms; helium barrier space indications and alarms	TBD	•No damage expected: release of H_2 to core vessel does not result in a flammable mixture because the core vessel is He purged •Total release of the H_2 inventory to the core vessel actuates the core vessel pressure relief path to safe venting of the He/H_2 gas mixture	•Core vessel He atmosphere prevents flammable mixtures inside •If only the primary hydrogen (H_2) barrier fails, the vacuum system is designed to vent the H leakage safely. Sub-sequent failure of outer vacuum boundary contained by helium barrier	Target facility shut down for assessment of damage to cryogenic system, and reestablishment of the core vessel helium atmosphere prior to further operation

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
9.B—Same but between core vessel and safe room (EU)	Same as above	TBD	Leak	The cryogenic lines are enclosed in a protected trench that communicates with the safe room. An H_2 leak in the line would flow to the safe room	Same as above
Other miscellaneous target facility events					
9.C—Same but inside safe room (U to EU—maintenance activities occur in safe room, so this may increase frequency of a hydrogen leak to the U range)	Same as above, plus •Safe room atmosphere H_2 alarm (if all boundaries fail)	Initiation of enhanced ventilation mode	•Ventilation flow rate increases before H_2 increases to the flammable point •Operators take action to transfer the H_2 inventory to the storage tank before it is all lost out the leak	•The H_2 storage tank (located outdoors) can hold the entire H_2 inventory •The safe room has blow-out panel(s) to minimize the formation of projectiles should deflagration or detonation occur inside	Same as above
10—Loss of core vessel integrity (U)	Core vessel pressure alarm; atmosphere gas analyzer alarm	NA	He or air drawn into core vessel •Spallation; activation of air	Operators would shut down the target operation due to inability to maintain desired pressure and/or indication of air in the core vessel helium purge exhaust	Proton beam cut off and target shut down for repair
11—Loss of core vessel He atmosphere control (A)	•Core vessel pressure; helium purge flow indication and alarm		Little or no immediate effect. Long-term loss of He purge would eventually allow air ingress, which would be undesirable	It would take an extended loss of He purge flow to permit inleakage of air into core vessel	Proton beam cut off and target shut down for needed repair of He purge system; reestablish core vessel atmosphere control

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
12.A—Target cell ventilation system failures: loss of blower power or ventilation flow (A)	Control room instruments and alarms—cell negative pressure, ventilation system flow	None	Cell exhaust flow stops, hot cell air pressure increases toward atmospheric pressure	Operators would work to reestablish the flow by starting standby blower(s), utilizing standby power, etc. Airborne contamination from inside the target cell could eventually diffuse into adjacent operating spaces	Facility restored to normal operation with the ventilation system returned to service
12.B—Target cell ventilation system failures: HEPA filter failure (U)	Exhaust duct radiation level or concentration	None	Decrease in removal of particulate matter. Gross filter failure could result in some increase in air flow	Operators would take the failed HEPA filter out of service after diagnosis of the condition	Facility restored to normal operation with the faulty filter out of service
Facility-wide, external events, natural phenomena					
13—Loss of off-site power (A)	Loss of normal (A/C) lighting, other services	None	Loss of off-site power cuts off the proton beam. No damage	The proton beam cannot be maintained without magnet and other power. Forced circulation not required for mercury or other decay heat removal. Diesel generators started to maintain hot cell negative pressure until off-site power regained	Facility restored to normal operation after recovery of off-site power
14—Fire (U)	Visual/auditory alarms on fire detector panel	Automatic fire sprinklers provided where needed	Fire could possibly initiate one of the failures that initiate events 1 through 12	See CDR Sect. 9.2.1	Facility shut down for damage assessment

Table 3.2 (continued)

Sequence (frequency range)	How detected	Automatic protective actions	System response or damage	Mitigating actions or features	End state
15—Natural phenomena-tornado and seismic (U)	Primary senses. Information updates from laboratory shift supervisor	None	No "significant" damage since safety significant component required to function after design basis earthquake or high wind event	Target facility is classed PC-2 for natural phenomena resistance (CDR Table 8.4-2, Sect. 9.2.1)	Facility shut down for damage assessment
Events involving target hot off-gas system and waste systems—see Chap. 4.					
Beyond-design-basis accidents—see Sect. 3.17.					

In recognition of the economic and safety significance of proton beam cutoff to the target, a highly reliable system has been provided: the target protection system (TPS). This system was discussed in the SNS CDR as part of the personnel protection system (PPS). The new name was chosen to designate formally that the target protection function should be separated from the PPS function in order to ensure the appropriate design and operation of each. The TPS will be documented in the SNS Design Manual (to be published later in FY 1998).

The TPS consists of the instrumentation necessary to measure target cooling and integrity parameters, and the wiring and logic necessary to prevent the initiation of proton beam pulses when parameters are not within specified ranges. The basic design objective is to cutoff the beam for any event that could result in loss of mercury system integrity or upon any indication that loss of mercury system integrity has occurred. The actual mechanism for beam cut off is to prevent formation of pulses at the ion source in the very low energy end of the accelerator instead of trying to interrupt the high-energy proton beam itself. The parameters being considered for inclusion in the TPS include target mercury temperature, flow, pump outlet pressure, pump power status, and mercury presence outside the mercury system. In general, a design objective is that more than one operational parameter should be available to trigger the TPS beam cutoff for any given event. For example, mercury flow as well as pump status could signal a loss-of-flow event.

The TPS is envisioned to be a two-channel system, with 1-out-of-2 logic and fail-safe design. Separation and independence between the two channels is provided in the design as needed to ensure very high reliability for the beam cut-off function.

The primary purpose of the PPS is to protect personnel, by cutting off the proton beam in the event of unusual radiation levels or if accelerator tunnel access is attempted during beam operation, but the PPS also provides a beam cutoff of last resort for accident sequences involving the total failure of both the TPS and the run permit/beam pulse (BP) enable systems. The PPS is able to do this because any accident sequence that leads to voiding in the target plug or loss of mercury from the target plug will, in effect, put the beam about 3 m closer to the outside of the shielding, resulting in higher than normal radiation levels in and near the target hot cell wall. With respect to the target integrity, the PPS is considered to be a cutoff of "last resort" because it is not predictive—it does not occur until some leakage of mercury has occurred (or boiling

causes voiding in the mercury). Under full beam power, the voiding in the target vessel is consistent with loss or impairment of mercury vessel integrity. By contrast, the TPS and BP systems are predictive because they sense conditions that could cause loss of integrity and could actuate beam cutoff before the barrier damage happens.

The BP automatic beam cutoff function is credited in the analysis of some target accidents because it is implemented in a manner that is separate and independent from the TPS and PPS. If BP and TPS do share instrument outputs, it is through circuits that provide electrical/electronic isolation. The fast protect (FP) system is provided for equipment protection and to provide a means of very rapid detection of abnormal beam conditions in the accelerator, storage ring, or transfer tunnels. The purpose of the FP system is to prevent the initiation of more than 1 pulse under conditions of poor beam focus or directional control. Besides providing rapid equipment protection, the FP system minimizes activation of components surrounding the proton beam tube by very rapid cutoff when beam losses exceed a preset value. The FP system is directed at the proton beam upstream from the target facility. The FP system is not credited in the analysis of target facility accidents.

One additional proton beam cutoff mechanism is available and is credited or considered in some accident sequences. This is a manual beam cutoff by the control room operator. For the purposes of these analyses, it is assumed that after a period of 1 min with multiple alarms in the control room, the operator would initiate a manual beam cutoff using the switch provided in the control room for that purpose. This is a realistic, and conservative, assumption because it will be required that the SNS control room be occupied by a qualified operator during beam operation at power and because the operators will be trained to initiate the manual cutoff immediately upon the occurrence of multiple target system alarm annunciations.

3.1.3 Radionuclide Transport for Source Term Determinations

The unique nature of using a low-temperature liquid metal as a target and the physical properties of the spallation products have been recognized in the derivation of source terms. The target Hg is expected to last the entire life of the facility (40 years) because, even considering the eventual upgrade to a 4-MW proton beam power, only about 0.2% of the mercury is transformed by spallation into nonmercury spallation and/or activation products over the facility's life. Most of the spallation products are well below their solubility limits in Hg at the end of the 40-year facility design life. The need or desirability for cleanup of the Hg during facility life has not been determined, although allowance has been made in the conceptual design for cleanup. As a minimum, it is expected that filtration will be provided for the removal of insoluble spallation products.

The SNS accidents are relatively low temperature and are low-pressure events for several reasons. The boiling point of Hg is 357°C at 1 atm of pressure. The SNS Hg system operates at low pressure (a maximum of about 3 atm in the Hg vessel, for example) because the target vessel is not designed to withstand a high internal pressure. The normal hot leg temperature of the circulating Hg is only 110°C, and automatic, highly reliable systems interrupt the proton beam when conditions deviate significantly from normal. If the automatic beam trips fail and boiling of the Hg occurs, failure of the vessel could result, allowing the Hg to leak from the Hg vessel, and bringing other automatic beam trips into play.

In contrast to the low temperatures achievable in accidents of the SNS, the boiling points of all of the spallation products, excepting I and Xe, are well above the boiling point of Hg. At the

boiling point of Hg, all but Xe and I have very low to negligible vapor pressures. Therefore, in an accident in which Hg is heated above the normal range, or in which Hg is spilled and can evaporate, the Hg vaporizes selectively, separating from and leaving the spallation products behind. Distillation is a recognized method of purifying Hg. The five most risk-significant nongaseous spallation or activation products that are generated in the target Hg are shown in Table 3.3 (see Table 2.1 for radioactivity quantities involved).

As can be seen from Table 3.3, the dissolved solids have negligible vapor pressure in the temperature range for Hg accidents. Exhibit C discusses the vapor pressures of spallation products and their potential for release.

Table 3.3. The five most risk significant nongaseous radioactive elements found in target mercury

Element[a]	Melting point (°C)	Boiling point (°C)	Fraction released in SNS accidents
Hg	–39	357	<1%, as limited by evaporation or Hg carrying capacity of air
I	114	184	Assumed release of 100% of I in Hg heated to boiling point or exposed to air for >24 h[b]
Gd	1314	3264	Negligible
Hf	2233	4603	Negligible
Au	1064	2856	Negligible

[a]Essentially all of the gaseous spallation products (e.g., H and Xe) are removed from the target Hg by the normal He purge flow, and are, therefore, not present in significant quantities for release in an accident of the target mercury. Their possible release in off-gas system accidents is covered in Chap. 4 of this report.

[b]The elemental melting and boiling points are given above for discussion purposes. In the target Hg, the I is held in the form Hg2I2, which decomposes upon heating or oxidation, releasing HgI2 that can be released and transported in vapor form.

Although it is evident that the solid spallation products are not susceptible to vaporization-based transport at the relatively low temperature range for SNS accidents, other methods of transport need to be examined. This would include the postulated entrainment of small Hg droplets in the air from the interior of the hot cell during the leakage phase of a loss-of-integrity accident. By this essentially mechanical transport method, each droplet carried along with the flowing air would take all of its spallation products with it. There are several reasons why such transport is not a practical reality in accidents examined for the SNS:

- Hg has a high surface tension, which makes it difficult for small droplets to form; and, if droplets of Hg are formed, Hg's high density requires relatively high air velocity to remain suspended.
- For accidents involving boiling of Hg, the possible two-phase mixture (i.e., liquid plus gaseous Hg) is first discharged to an interior space where velocity is very low, allowing droplets to settle out.
- The ventilation flow in the interior of the hot cell has a residence time on the order of 10 min and, therefore, cannot stir up any kind of a breeze of air that could sweep up particulate or help mist particles remain aloft.
- Mist eliminator stages are provided as necessary to prevent the downstream HEPA filters from becoming clogged or wetted by any feasible mist component.

- The HEPA filters would be effective in stopping airborne particulate matter of any kind. Small Hg droplets stopped on a HEPA filter would continue to evaporate, eventually leaving behind a concentrated mercury–spallation product amalgam mixture.

These factors combine to justify the conclusion that the release fractions of Hg solid/ nonvolatile fission products are negligibly small.

3.1.4 Core Vessel Atmosphere Control and Venting

The core vessel is the ~3.5-m diam vessel (continuing design work has resulted in an increase in diameter from ~2 m to ~3.5 m) in the target station that holds the target's moderators, reflectors, and the shielding that requires active water cooling. The normal atmosphere inside the core vessel is helium gas. The helium purge flow is supplied at such a rate that the vessel's atmosphere is exchanged about once per 100 h (see CDR Table 5.3-6). The purge exhaust is routed to the contaminated off-gas system.

The normal pressure inside the core vessel is slightly less than 1 atm, but should the pressure inside the vessel exceed 2 atm, a relief line opens to prevent overpressurization. The vessel could withstand more than 2 atm, but the neutron beam windows are made thin to minimize neutron losses, so they can be expected to fail first. The reason that this venting capability is provided is that a 2-atm internal pressure could be exceeded (without venting) if a worst-case, multiple-barrier failure of the cryogenic moderator system released the cryogenic hydrogen into the core vessel. Special design requirements on the venting path design will be required in order to control flammability of the helium/hydrogen effluent should venting occur after a cryogenic moderator failure. The design of the venting path is ongoing, but, because of the possible flammability of its effluent, it is expected that the vent line will not vent into the normal ventilation system, or through a blower (unless it is hydrogen-qualified), and that parts or all of the vent path may be normally inerted. Potential hydrogen flammability accidents are examined in Sect. 3.10.

Since significant amounts of contamination may exist inside the core vessel during normal operation and more could be released in the event of an accident, it is required that the normal and relief venting paths discharge to the environment through HEPA filters. The relief venting path will have the appropriate features to protect the HEPA filters and ensure their operation including, for example, a diffuser section to allow velocity to decrease and a demister stage to remove any entrained mist.

3.1.5 Target Building and Beam Stop Ventilation

Target building ventilation is discussed in Sect. 8.6.3.7 of the CDR, and illustrated schematically on CDR drawing NSNS-18-012. Target building areas with potential for airborne radioactive material are included in the target confinement systems (primary and/or secondary confinement systems). The conceptual design follows accepted practices, such as ensuring that air flows from areas with lower potential for airborne contamination to areas of higher potential for contamination. Exhaust air is routed through HEPA filter banks. Each HEPA filter bank is designed to include prefilters and/or mist eliminators, as appropriate, and the exhaust point is the target building stack. The HEPA filters are credited with being able to remove nonvolatile particulate matter, but not with being able to remove iodine or mercury (i.e., since these two

elements can become airborne in vapor form). Filtration units specifically for mercury vapor removal from air inside the target hot cell are under consideration, but any such additional mercury vapor removal capability is not credited in any of the accident source terms.

Ventilation for beam stop buildings is exhausted to the environment through HEPA filters (as discussed in CDR Sect. 8.6.3.10). Each beam stop is designed for 200-kW continuous duty, although it is expected that only the ring injection beam stop will be operated continuously during normal operation. Activation levels of the coolant in the ring injection beam stops are expected to be significantly greater than in the other beam stops. Therefore, it has been decided that the HEPA exhaust for the ring injection beam stop should be routed such that it joins the target confinement exhaust and is discharged to the environment through the target building exhaust stack (see CDR Sect. 8.6.3.7).

3.2 LOSS OF CONTROL OF PROTON BEAM FOCUS OR DIRECTIONAL CONTROL (ACCIDENT SEQUENCE 1)

3.2.1 Sequence of Events

The proton beam could, hypothetically, be misdirected in such a manner as to cause overheating and release of radioactive material. To prevent such a possibility, the accelerator is equipped with the highly reliable, automatic systems discussed above that cut off the beam when abnormal conditions apply. In addition, the close-fitting collimator in the transfer tunnel immediately upstream from the proton beam window (in the ~3.5-m diam core vessel) is a passive device that prevents the beam from being misdirected onto target components other than the Hg vessel (i.e., the Hg-filled vessel that is the actual target of the proton beam). For any anticipated failures of beam control, inherent design features and automatic cutoff circuits preclude system damage.

The only beam control event that has any potential for causing release of Hg would be a focusing fault in which the beam is concentrated into a smaller than normal area as it impinges upon the Hg vessel. Preliminary conceptual design information shows that it may be possible for the beam under these abnormal circumstances to be focused onto a smaller, but not yet quantified, fraction of its normal area. Analysis has not been done to determine how much beam concentration the Hg vessel can withstand. Therefore, in addition to focusing magnet status signals, the conceptual design includes a provision for a beam focus sensor (comb-like device that detects the spatial energy distribution of the beam) that will be keyed in to one of the automatic beam cutoff systems. Thus, the excess beam focus base case anticipated event has no damage or release of radioactive material because the beam is cut off before damage can occur.

3.2.2 Estimated Frequency Range

It is anticipated that beam control faults will occur during the 40-year nominal life of the facility (i.e., frequency $> 2.5 \cdot 10^{-2}$/year), but it is highly certain that the beam will be automatically cut off after a small number of pulses when the abnormal conditions occur. The conditional probability for failure of the automatic beam cutoff system is estimated at less than 10^{-4} per demand because there are typically two independent signals for achieving automatic beam cutoff (e.g., focus magnet status signal and beam focus sensor signal). It is concluded that a

potentially damaging beam control fault compounded by failure of prompt automatic proton beam cutoff would be an unlikely [10^{-4}/year < frequency < $2.5(10)^{-2}$/year] or extremely unlikely event (frequency 10^{-4}/year to 10^{-6}/year). If the focus fault were severe enough to cause boundary failure after failure at prompt automatic beam cutoff, the subsequent Hg leakage would result in proton beam trip by the TPS.

3.2.3 Source Term

There is no source term for any of the beam control events in the anticipated range. The source term for extremely unlikely beam control events is bounded by the worst-case source term developed in Sect. 3.3 for extremely unlikely loss of Hg system integrity events.

3.3 LOSS OF HG VESSEL OR PIPE INTEGRITY: MAJOR FAULT (ACCIDENT SEQUENCE 2)

3.3.1 Sequence of Events for the Hg Spill

This event would be initiated by a major failure in the primary Hg boundary. The failure could be in the Hg vessel itself (the actual target of the proton beam), piping between components, the Hg reservoir, the Hg pump, or the Hg/H_2O heat exchanger. The fault is assumed to occur suddenly and to have a flow area consistent with rapid spillage of Hg (e.g., over a 10-min or shorter period).

The most likely places for boundary failures are thought to be the Hg vessel itself, which is directly in the proton beam, and the two bellows sections provided to allow for thermal expansion of the long pipe that runs through the target plug. The nominal conceptual design value for total Hg inventory is 1000 L, including the target vessel, the target plug, piping, heat exchanger, and pump. The rate of pumping is on the order of about 1000-L per min, giving a very approximate loop time of about 1 min for the circulating Hg. (None of the analyses of this report are sensitive to this loop time, including the mercury radionuclide inventories given in Chap. 2). The maximum static pressure inside the Hg vessel during operation is about 0.3 Mpa (static pressure does not include the pressure pulsations that are always present during normal operation because the proton beam is actually a train of discrete pulses).

The Hg system has features designed to work together to confine any Hg that might be inadvertently spilled or spilled because of an accident (see CDR Figs. 5.3-1 and 5.3-2). These features include a collection tank to which spilled Hg drains, engineered drainage paths to ensure that any spilled Hg is directed to the collection tank, and an enclosure that surrounds much of the "rear end" part of the Hg system that protrudes into the target cell (e.g., the Hg reservoir, heat exchanger, and related piping). In addition, the water-cooled shroud separates the Hg vessel from the interior of the core vessel that houses the reflectors, moderators, and associated shielding. The water-cooled shroud would prevent Hg from flowing into the core vessel in the event of a failure of the Hg vessel.

The floor of the mercury enclosure is sloped appropriately and otherwise engineered to ensure complete drainage of the Hg to the collection tank. This enclosure is entirely inside the target hot cell. If the Hg leak were spraying outward, it would strike a surface on the inside of the enclosure, drop to the floor, and drain to the collection tank. It is not intended to be a sealed

containment vessel; the target cell ventilation system will be designed to pull a slight negative pressure on the mercury enclosure to maintain inward flow of air from the target cell into the enclosure. The vent connection for this will be engineered so that Hg from a boundary failure in any component cannot stream directly into the exhaust duct. Special air treatment for the air exhausted from the mercury enclosure is currently under consideration by the project. Specifically, the need for Hg removal stage(s) is being determined, but has not been credited in any of the present accident source term estimates. As a minimum, the enclosure exhaust will include a mist elimination stage or robust prefilter that will accomplish the same purpose (i.e., the removal of entrained Hg and/or Hg-contaminated gross particulate). Downstream equipment, including HEPA filters, will accomplish the final air treatment for hot cell exhaust.

For completeness, it can be noted that the mercury enclosure serves another purpose unrelated to this discussion: it shields instrument components mounted near the Hg system from gamma irradiation. The degree of shielding provided is only that needed to ensure a reasonable lifetime for these electronic components.

Immediately upon initiation of the Hg leak, the system would continue to circulate Hg as normal, etc., but sensors (e.g., conductivity sensors) at the bottom of the stainless steel catch pan that forms the floor of the mercury enclosure and/or at other points in the system would detect rapidly the existence of the leaked Hg. The signals from these sensors, indicating spilled Hg, would initiate an automatic proton beam cutoff. After some delay, other signals would confirm the spill sensors (e.g., low reservoir tank level or eventually perhaps low Hg pressure and/or flow). These other sensors can also actuate automatic alarms and/or proton beam cutoffs.

Upon detection of the leak and following verification of proton beam cutoff, the prescribed operator action would be to turn off the Hg circulation pump, and open valves that allow any Hg not spilled from the Hg system to drain to the Hg collection tank. The reason for this action is to minimize the amount of Hg leaked from the Hg system and thus minimize the subsequent cleanup efforts.

The only source of heat to the Hg after beam cutoff is the approximately 9.6 kW of decay heat distributed throughout the Hg inventory (at end of a 4-MW operating cycle). Active cooling is not required to remove decay heat from the Hg. The Hg circulation pump would, however, continue to run without operator intervention. Since the pump is at the low point in the Hg circuit, its continued running would tend to maintain circulation and force more Hg through the leak. Eventually most of the Hg inventory would have leaked from the Hg system. However, essentially all of the leaked Hg will be collected and confined by gravity drainage to the Hg collection tank.

The multiplicity of ways in which the proton beam would be cut off in this event make it incredible that the beam would not be cut off in this event. Major Hg spill with failure of multiple automatic beam cutoffs is considered in Sect. 3.17, Beyond-Design-Basis Accidents.

3.3.2 Estimated Frequency Range for the Hg Spill

The basic initiating event, a major failure in the Hg system pressure boundary, is an unlikely event (10^{-4}/year < frequency < 2.5×10^{-2}/year). Generic data on bellows,[1] the most vulnerable part of the system with the possible exception of the Hg vessel itself, indicate a failure frequency of somewhat less than 2.5×10^{-2}/year. Failure likelihood for bellows is minimized by designing the bellows for an adequate number of cycles (the bellows are provided to allow the target plug to expand without stress buildup when it is heated from ambient temperature to operating

temperature, and vice versa for the cooldown that occurs after the beam is cut off). Piping flexibility analysis and other design work will be done with the objective of eliminating as many of the bellows as possible.

Potential proton and neutron irradiation effects, normal pressure pulsations, and other cyclic stresses are of concern for the Hg vessel. However, the research and development (R&D) program for the Hg vessel and evaluation of experience during initial facility operation will allow the staff to develop design and maintenance parameters, including replacement frequency, that minimize the probability of its failure.

The worst case (extremely unlikely) Hg spill source term calculated below assumes, in addition to a major Hg spill, the failure of the mercury enclosure and/or its engineered drainage paths and/or pipes that would allow any spilled Hg to drain to a collection tank in a vault below the target hot cell floor. These failures combine to put this postulated event in the extremely unlikely category.

3.3.3 Source Term for the Hg Spill

3.3.3.1 Base case unlikely event (no additional failures)

The source term for this event consists of the Hg and I isotopes. The other spallation products dissolved in the Hg are not released because they have very low vapor pressures in the temperature range of interest (i.e., below the boiling point of Hg). There may be some creation of spray droplets if Hg is sprayed from the boundary failure, but the high surface tension and density of Hg work against that tendency, and a mist elimination step will be included in the design of the cell exhaust to remove droplets carried out of the mercury enclosure by the ventilation flow. The mercury enclosure is ventilated at a low rate such that there is not a significant amount of turbulence in the air flowing through the enclosure. If the ventilation system failed during this event, the source term with no ventilation would be lower than derived here under the assumption of continuing flow.

The Hg spill drainage features are required to ensure that all the spilled Hg drains to the collection tank or other closed location. To provide a conservative source term for analysis purposes, it is assumed that 1 L of Hg fails to drain and is in a configuration with a large surface area exposed to air, such that it can evaporate and be released. The source term for this event is calculated as follows:

1. The release of Hg vapor during the first 10 min is bounded by assuming that the leakage flow and surface area presented by the leaking Hg (e.g., as it strikes a wall and flows across the catch pan floor to the drain) are sufficient to elevate the air temperature flowing inside the mercury enclosure to 95°C (the average of 80°C and 110°C inlet and outlet temperatures of the circulating Hg). Furthermore, it is assumed that the air becomes and remains saturated with mercury vapor for the entire period. This is very conservative because it is equivalent to assuming that the evaporation rate is, in effect, instantaneous during this stage of the accident.

   The equilibrium concentration of air saturated in Hg vapor is obtained as shown at bottom of page 2 and top of page 3 of Exhibit D, but utilizing the desired 95°C temperature. This concentration is then multiplied by the air bulk flow rate to give the bounding release rate. At the mercury enclosure air flow rate of 400 cfm, the bounding

initial release is therefore 200 g of Hg over the 10 min (see discussion below for the accompanying iodine release).

2. After the first 10 min, all the Hg inventory has leaked from the system, or the operator takes action to stop the leak. The mercury enclosure air temperature thus returns to its normal value of less than 60°C. The release after this point is bounded by assuming that the spilled Hg occupies the whole enclosure floor and that its temperature would be 60°C (floor should actually be cooler than this). Exhibit D calculates an evaporation rate at 110°C of 87.1 g Hg/m^2/day under assumed turbulent air flow conditions. The equivalent rate at 60°C is calculated by multiplying the 110°C rate by the ratio of vapor pressures: VP(60°)/VP(110°C). Exhibit D (second page) gives a correlation for mercury vapor pressure as a function of temperature. Thus, the evaporation rate at 60°C is calculated to be 5 g/m^2/day. A somewhat lower rate would be obtained if the reduction in diffusion coefficient as a function of temperature (see last page of Exhibit D) were credited. To bound the possible geometry and mass transfer correlation uncertainties, a factor of 10 is applied to the 5 g/m^2/d estimate. To further bound the surface area for evaporation, we assume that the entire floor area of the enclosure is covered by a thin layer of Hg. The resulting bounding total Hg release rate is 1.6 kg of Hg per day. At this rate it would take more than 8 d to evaporate the entire liter. Even though the enclosure would cool significantly over this period, reducing the evaporation rate significantly, it is conservatively assumed that the release takes place over an 8-d period. With the great bulk (i.e., ~99.9%) of the Hg having drained via gravity to the collection tank, and all the undrained Hg having been evaporated, there would be essentially no releases after the 8-d period. A small fraction of the postulated 1 L of undrained Hg would, in reality, not be released because the evaporation process would tend to concentrate the normally very dilute dissolved spallation products in the Hg, leaving behind small amounts of concentrated mercury-spallation product amalgam, which would not be easily volatilized or entrained by the low air flow in the mercury enclosure.

   If such a mercury leak occurred, only a small fraction of the 1 L could be vaporized because facility operators would take actions to curtail the release rate. For example, they would ensure or enhance cell cooling, would clean up the spilled Hg (using remote manipulators to activate and control cleanup equipment inside the hot cell), and/or would utilize a chemical agent (e.g., amalgamating compounds) to bind the Hg chemically.

The SNS target system designers are considering an Hg removal step for the cell ventilation system, but Hg removal is not credited in the present analysis. The entire 1 L of Hg and its contained iodine (as discussed below) are assumed to be released to the environment.

Since a helium purge regularly transports the gaseous spallation products from the Hg to the hot off-gas (HOG) system during operation, they are not available for release in a mercury spill event. For example, the helium purge sweeps any tritium gas into a hydride bed in the HOG system instead of allowing it to accumulate in the target Hg (see Chap. 4 for HOG system events). Or, for another example, xenon spallation products are also swept to a hold-up stage in the HOG system to allow for decay before release.

Iodine readily combines chemically with Hg and is therefore not immediately available for release from the 1 L of spilled Hg. With sufficient time of exposure to air, the Hg_2I_2 can oxidize slowly and release iodine (see Exhibit C). To bound the release, it is assumed that this conversion can occur over the same time scale as the Hg evaporation, and that 100% reaction

occurs, releasing all the radioiodine in the 1 L of nondraining Hg. The balance of the Hg drains to, or remains within, a tank where it is not effectively exposed to oxygen, so its contained Hg_2I_2 remains unoxidized and therefore releases negligible iodine.

In conclusion, the base case loss of target Hg system integrity (unlikely event) source term consists of 1 L of Hg and its initially contained radioiodine (i.e., the entire volatile and semi-volatile content of the Hg that fails to drain to the collection tank). Since the designers are trying to improve the target system design to minimize mercury inventory, it will be assumed that the mercury inventory will be reduced from the nominal 1000 L (13,600 kg of Hg) to a value of 10,000 kg (~735 L) of Hg. Thus, the fractional release of both Hg and I nuclides is adjusted upward from 0.1% to 0.14% of the total inventory, with all but the initial (first 10 min) release occurring over the abovementioned 8-d period. The radionuclide release source term (see Table 3.4) is estimated on the basis of 40-year end-of-life radionuclide inventory. See Table 3.4 for a summary of the release fractions and the initial mercury and iodine radionuclide-specific activities present immediately before the accident.

3.3.3.2 Bounding source term for the extremely unlikely (EU) event Hg spill

If a mercury spill occurs with failures in the mercury confinement and drainage system, the bounding source term would be worse than determined above for the base case (unlikely event). The bounding EU Hg spill is a failure(s) of the mercury enclosure that allows the Hg leak to escape from the Hg enclosure into the target hot cell. A compounding failure of the cooling water system that maintains normal Hg temperature is assumed with coincident failure of the first automatic proton beam cutoff (e.g., the beam cutoff based on cooling water pump status), such that the bulk temperature of the Hg has increased by 20°C over normal values at the time of the spill (i.e., to a value consistent with the beam cutoff based on Hg temperature). The discussions in the subsection above, pertaining generally to radionuclide release and transport, etc., are all applicable to the EU spill. The assumptions regarding Hg transport are analogous but must be scaled up to the entire mercury hot cell, and to Hg temperatures consistent with this EU event. Releases tend to be larger because the entire cell air flow specified in the conceptual design is 4800 cfm (136 m^3/min). The mercury releases are calculated as follows:

1. The release of Hg vapor during the first 10 min is bounded by assuming that the leakage flow and the surface area presented by the leaking Hg (e.g., as it strikes a wall and flows down the wall and across the floor) are adequate to ensure complete thermodynamic mixing between the cell air (40°C) and the leaking mercury (with the Hg at 215°C due to the assumed heat-up before the spill). Thus, the air temperature during the initial 10-min period is elevated from 40°C to 86°C. The further bounding assumption is made that the air is saturated with mercury vapor during this entire phase of the spill. This is a very conservative assumption (probably unrealistically conservative) because it neglects the limitations on heat transfer rate due to low temperature differences and the tendency for Hg to drain to or gather at any low point or drain opening, thus reducing exposed surface area. At the hot cell air flow rate of 4800 cfm, the bounding release during this initial 10-min period is, per the stated conservative assumptions, 1.5 kg of Hg.

Table 3.4. Source terms for the unlikely event and extremely unlikely event mercury spills

a. Radionuclide specific activities

Note 1: After 40 years of operation at 1 MW, with specific activity values given for the instant before the spill.

Note 2: Except as noted, multiply by 4 to get corresponding 4-MW values.

Radionuclide	Specific activity		Radionuclide	Specific activity (Ci per gram of Hg)
	(Ci/g Hg)[a]	(Ci/g I)[b]		
I-119	6.76E–7	5.59	Hg-180	8.45E–7
I-120	1.01E–6	8.34	Hg-181	2.37E–6
I-121	2.03E–6	16.8	Hg-182	3.55E–6
I-122	2.87E–6	23.7	Hg-183	6.42E–6
I-123	3.72E–6	30.7	Hg-184	1.2E–5
I-124	1.69E–6	14	Hg-185	1.96E–5
I-125	7.43E–6	61.4	Hg-186	5.12E–5
I-126	3.38E–7	2.79	Hg-187	1.05E–4
I-128	3.38E–7	2.79	Hg-188	2.4E–4
I-129	8.85E–13	7.31E–6	Hg-189	3.7E–4
I-130	1.69E–7	1.4	Hg-190	5.36E–4
			Hg-191	6.75E–4
			Hg-192	9.01E–4
			Hg-193	1.05E–3
			Hg-194	1.14E–4
			Hg-195	1.75E–3
			Hg-197	1.17E–2
			Hg-203	8.32E–3
			Hg-205	3.6E–4

[a]Specific activity in Ci/g Hg = nuclide inventory (Ci) divided by mercury mass (10^7 g Hg, constant throughout facility life)

[b]Specific activity in Ci/g I = nuclide inventory (Ci) divided by iodine mass (1.21 g I at end of facility 40-year design life). The Ci/g I specific activity after 40-year of 4-MW operations would be the same as above because not only the mass of iodine but also the radionuclide inventories would be four times as large. The total mass of iodine, dominated by stable I-127 and long-lived I-129, decreases by ~0.1% during a 30-d accident period due primarily to decay of I-125 (the shorter lived ones also decay, but their contribution to mass is negligible).

b. Accident release fractions (applicable to either 1-MW or 4-MW cases)—bulk mass fractions released[c]

Accident	Time period	Hg release fraction	Iodine release fraction
Hg Spill (U = unlikely)	0–10 min	2.0E–5	2.0E–5
Hg Spill (U)	10 min–8 d	1.4E–3	1.4E–3
Hg Spill (U)	>8 d	0	0
Hg Spill (EU) = extremely unlikely)	0–10 min	1.5E–4	1.5E–4
Hg Spill (EU)	10 min – 10 d	1.9E–3	3.3E–1
Hg Spill (EU)	10 days – 30 d	3.8E–4	6.7E–1
Hg Spill (EU)	>30 d	0	0

[c]Note: Release fractions for shorter-lived radionuclides would be smaller than the bulk mass release fractions provided that the release period is long in comparison to the half-life of the radionuclide.

2. After the first 10 min, all the Hg inventory has leaked from the system, or the operator takes action to stop the leak. The hot cell air temperature thus returns to its normal value of less than 40°C. The release after this point is bounded by assuming that the spilled Hg occupies the whole hot cell floor, and that its temperature would be 40°C (floor should actually be considerably colder). Based on the derivation in Exhibit D, the maximum evaporation rate of this spilled Hg is estimated to be 1.2 g $Hg/m^2/d$ at a 40°C temperature. To bound the possible geometry and mass transfer correlation uncertainties, a factor of 10 is applied to this estimate. To further bound the surface area for evaporation, we assume that the entire floor area of the hot cell is covered by a thin layer of Hg. The resulting estimated total Hg release rate is 1.9 kg of Hg per day. The release is assumed to continue at 1.9 kg of Hg/d for a 10-d prerecovery period. After this 10-d period, it is assumed that the several available accident recovery strategies would reduce the rate to 10% of the rate of the first 10 d (i.e., to 0.19 kg Hg/d). After 30 d, the release rate would be essentially terminated because of continuing cleanup efforts. As discussed in the previous section, it is expected that the facility operators should be able to greatly curtail or stop the releases much sooner than either 10 or 30 d because of the several actions they would be able to take.

The bounding assumptions (discussion above, plus Table 3.5) are thought to be sufficiently conservative that the resulting source term bounds the entire spectrum of events in the EU category (10^{-6}/year < frequency < 10^{-4}/year). The only way to have greater release would be to postulate events that are beyond credible (see Sect. 3.17).

The nuclides released in this event include only the mercury and iodine radionuclides. As previously mentioned, other potentially significant volatiles (e.g., tritium gas) are swept from the reservoir tank during normal operations by the helium purge flow. Release of tritium is considered under target off-gas accidents (Chap. 4). As with the unlikely event Hg spill, the assumption is made that all the iodine contained in nondrained Hg is volatilized. Thus, since the assumed failures include nondrainage of the whole Hg inventory (i.e., the engineered drainage paths and the mercury enclosure are failed somehow), the release fraction for the iodine is 100% for the 30-d accident period.

In summary, 0.015% of the Hg and I inventories is released over the first 10 min, and 0.228% of the Hg and 99.985% of the I is released to the environment over the balance of the 30-d accident period. Source terms and initial mercury and iodine radionuclide specific activities are summarized in Table 3.4.

Table 3.5. Worst case input parameter assumptions used to derive bounding source term for extremely unlikely events (10^{-6}/year < frequency < 10^{-4}/year); based on mercury spill event with multiple additional failures

Parameter	Nominal value (or nominal accident value)	Bounding value	Basis
Hg surface area exposed to air, early part of spill event	Estimated at <1 m^2 surface area of Hg as it drains across the catch pan to the collection tank	Sufficient Hg exposed to air to saturate air in mercury enclosure with Hg vapor during early part of spill	Conservative assumption that the leak is sprayed vigorously enough to result in a large surface of area for Hg/air contact
Target cell mercury enclosure air flow; hot cell air flow	Hg enclosure: 11.3 m^3/min Hot cell: 136 m^3/min	11.3 m^3/min Hot cell: 136 m^3/min	Assuming the ventilation flow continues at the nominal value, will maximize Hg vapor transport during the accident (there would be little-to-no air flow and, hence, little-to-no Hg vapor transport if the ventilation system fails or is turned off)
Hg decay heat	Depends on operating time in the proton beam; after 1 year in a 4-MW proton beam, decay heat is <10 kW immediately after beam cutoff	Hold at 10 kW throughout the accident	Decay heat decreases continuously after proton beam cutoff (e.g., is at ~70% of the initial value 1-h after cut off)
Hg decay heat dissipation paths	Decay heat would be dissipated to structures and to air	Assume 100% of decay heat is transferred to air	Higher air temperature increases Hg carrying capacity of the air
Cell air inlet temperature	14°C is the annual average outdoor air temperature for Oak Ridge, Tennessee. Building air is typically heated or cooled to ~22°C by the building HVAC system	30°C	Assuming 30°C is equivalent to assuming an A/C failure during summer months. Note: 24.8°C is the daily average temperature for hottest month of the year (July)
Duration of significant accident release	~0 days (if various systems work as designed, there is essentially no environmental release)	Bounding releases specified for short, intermediate, and long term releases, as applicable	Various factors would minimize or end the release after several days, including lower decay heat, oxide films on any exposed Hg, and possible operator actions

HVAC–heating, ventilating, and air conditioning.
A/C–air conditioning.

3.4 LOSS OF HG PUMPING DURING PROTON BEAM OPERATION (ACCIDENT SEQUENCE 3)

3.4.1 Sequence of Events for Loss of Hg Pumping

Forced circulation of the Hg is required to transport the heat deposited by the beam as it impinges upon the Hg target. If power is lost to the circulation pump or the pump fails for any other reason, the Hg flow decreases while temperature of the Hg increases. The circulation pump status and the Hg flow and/or pressure signals are utilized to initiate automatic cutoff of the proton beam whenever an abnormality is detected. If either the run permit/pulse enable [or beam

permit (BP), for short] systems or the TPS discontinues the proton beam during the first few seconds, then no damage occurs in any part of the mercury system. The BP and the TPS are independent. The likelihood that both the BP and the TPS might fail is thought to be beyond extremely unlikely, but is considered in Sect. 3.17, Beyond-Design-Basis Accidents.

If ac power were lost to the facility as a whole, then the beam would inherently and rapidly be discontinued as the Hg pump coasted down.

3.4.2 Estimated Frequency of the Loss of Hg Pumping

It is anticipated that failure of the Hg pump or its power supply will occur during the life of the facility. Failure of the BP (but not TPS) automatic beam cutoff after Hg pump failure would be an unlikely event, but simultaneous, total failure of both of these independent systems (BP and TPS) would be extremely unlikely or beyond design basis.

3.4.3 Source Term

The source term for loss of Hg circulation flow events is zero because of the multitude and independence of ways in which the proton beam can be cut off before damage can occur to the mercury boundary. The source term for loss of Hg flow with failure of both BP and TPS automatic proton beam cutoffs is developed in Sect. 3.17.

3.5 LOSS OF H_2O FLOW IN HG*H_2O HEAT EXCHANGER DURING PROTON BEAM OPERATION (ACCIDENT SEQUENCE 4)

3.5.1 Sequence of Events for Loss of H_2O Flow to Hg Heat Exchanger

A loss of cooling water flow to the Hg heat exchanger would result in increasing Hg temperature as the heat deposited by the proton beam is distributed throughout the Hg loop instead of being removed by the cooling water. Automatic beam cutoffs would detect the condition and discontinue the proton beam. If the automatic proton beam cutoff is assumed to fail, it is probable there would be sufficient time for the operators to react to alarms and cut off the beam before any damage occurred. The heat-up rate with no water in the Hg heat exchanger would be about 25°C/min for the 1-MW configuration or about 100°C/min for the 4-MW target configuration. In the worst case, without intervention, local boiling would eventually occur in the Hg vessel and the insufficiently cooled Hg vessel walls would fail (i.e., probably after >1 min even for the 4-MW configuration), causing a Hg spill event that would be similar to the sequences considered in Sect. 3.3.

3.5.2 Estimated Frequency Range for Loss of H_2O Flow to Hg Heat Exchanger

The base case loss of cooling water flow is an anticipated event. Failure of both the BP and TPS automatic beam cutoffs and operator initiated manual cutoffs is estimated to have an annual probability of occurrence below 10^{-6}/year because the TPS and BP automatic cutoffs are independent, and because there is sufficient time to make operator-initiated cutoff very likely. An appropriate EU loss of Hg H_2O cooling water would be to have a delayed automatic proton

beam cutoff following loss of the cooling water. For example, the trips based on H_2O flow and/or pump status will cut the beam off before the Hg has a chance to heat up, whereas the trip based on Hg temperature occurs only after some heat-up has occurred. To avoid spurious beam cutoffs, the high temperature–based trip will be adjusted to allow perhaps about 15°C of heat-up before preventing further beam pulsing (20°C was assumed for analysis of the EU Hg spill that bounds this event). Consistent with the EU probability level, this amount of heat-up might be the last straw for some incipient Hg boundary failure, in effect allowing this event sequence to develop into a Hg spill accident.

3.5.3 Source Term for Loss of H_2O Flow to Hg Heat Exchanger

There is no damage and therefore no release or source term for the base case anticipated event. The source term for the EU event with failure of the more promptly occurring automatic beam cutoff(s) is bounded by the worst case EU Hg spill event source term developed in Sect. 3.3.

3.6 LOSS OF H_2O FLOW: WATER-COOLED SHROUD (ACCIDENT SEQUENCE 5)

3.6.1 Sequence of Events for Loss of H_2O Flow to the Water-Cooled Shroud

The water-cooled shroud is provided to minimize the probability for mercury contamination to enter the core vessel. It is cooled because the proton beam passes through it before striking the Hg vessel. The base case loss of cooling water flow to the water-cooled shroud is an anticipated event. Automatic beam cutoffs based on status of the cooling water system would cut off the beam before any damage. There is a possibility that the operators could react to an alarm and discontinue the proton beam manually.

In the EU event of full beam power and no water flow, the shroud would not be adequately cooled, boiling of water would occur inside the shroud, and the shroud would fail soon thereafter. Some water might be spilled inside the core vessel, but the <60°C temperature of components inside the core vessel would not be sufficient to boil enough water to actuate the core vessel relief valve (that actuates for core vessel internal pressures exceeding 2 atm). The part of the uncooled shroud remaining in the beam might overheat, possibly melting and dropping down out of the path of the beam. This would cause an increase in the energy deposition rate into the Hg vessel but not enough to be likely to fail the Hg vessel. There should also be an increase in the neutron production rate. Melting of the water-cooled shroud could cause Hg vessel failure if the molten stainless steel drips onto the core vessel.

3.6.2 Estimated Frequency Range for Loss of H_2O Flow to the Water-Cooled Shroud

Loss of cooling water flow to the water-cooled shroud is an anticipated event. The shroud fills a contamination barrier function, and its replacement would require lengthy facility shutdown; therefore, sufficiently redundant and diverse shutdown mechanisms will ensure highly reliable prompt proton beam cutoff in the event of loss of its cooling water flow. Compounding the loss of cooling water with failure of automatic beam cutoff mechanisms would make this an extremely unlikely event.

3.6.3 Source Term for Loss of H_2O Flow to the Water-Cooled Shroud

There is no source term associated with the base case anticipated event. The extremely unlikely case with failure of automatic beam cutoff and possible spillage of cooling water is bounded by the unlikely event source term developed in Sect. 3.9, Loss of D_2O or H_2O Integrity in Target Cooling Loop.

3.7 LOSS OF H_2O FLOW: PROTON BEAM WINDOW (ACCIDENT SEQUENCE 6)

3.7.1 Sequence of Events for Loss of Water Cooling Flow to Proton Beam Window

The proton beam window forms the boundary between the proton beam tube and the core vessel. Its main purpose is to protect the high vacuum that is maintained in the beam tube against the helium atmosphere maintained inside the core vessel. The sequence of events upon loss of cooling water flow would be very similar to the sequence outlined in Sect. 3.6 for loss of water flow to the water-cooled shroud. There would, however, be an additional beam cutoff mechanism that would actuate should the undercooled window fail. Loss of beam tube vacuum automatically triggers closure of an isolation valve (to protect vacuum in the beam tube farther upstream), which simultaneously and automatically initiates beam cutoff.

3.7.2 Estimated Frequency Range for Loss of Water Cooling Flow to Proton Beam Window

The base case loss-of-coolant flow is an anticipated event. Loss of coolant flow without beam cutoff would be an extremely unlikely event. Large amounts of radioactivity are not present in the proton beam window's cooling water, and failure of the proton beam window would not threaten a mercury spill event, but the window fills a contamination barrier and also a facility segmentation function. Therefore, sufficiently redundant and diverse shutdown mechanisms will ensure highly reliable prompt proton beam cutoff in the event of loss of its cooling water flow.

3.7.3 Source Term for Loss of Water Cooling Flow to Proton Beam Window

There is no source term associated with the base case anticipated event. The extremely unlikely case with failure of automatic beam cutoff and possible spillage of cooling water is bounded by the unlikely event source term developed in Sect. 3.9, Loss of D_2O or H_2O Integrity in Target Cooling Loop.

3.8 LOSS OF WATER FLOW TO TARGET COMPONENT COOLING LOOP (ACCIDENT SEQUENCE 7)

3.8.1 Sequence of Events for Loss of Water Flow to Target Component Cooling Loop

This event can refer to any one of the following components:

- The moderator/proton beam window H_2O cooling loop
  - proton beam window
  - ambient moderator
  - cryogenic moderator
- The D_2O cooling loop
  - Ni and Be reflectors
- The shroud H_2O cooling system
  - target water-cooled shroud
- The shield cooling H_2O cooling water loop
  - stainless steel shielding units

These components are held inside the core vessel. The conceptual design provides a separate cooling loop for each component. The loss of water flow could be caused by failure of a pump, a valve, or the electrical power supply to the pump. Sensors provide status monitor signals for each component cooling loop to ensure that proton beam cutoff would be initiated in the event of loss of cooling water flow. The amount of heat-up that can occur after the loss of flow and proton beam cutoff is small because of the relatively low power densities involved and because of the rapidity with which proton beam cutoff can be accomplished.

If automatic beam cutoff fails, the amount of time for operators to respond to abnormal indications depends on which component is under consideration. Components that are closer to the Hg vessel have higher power density and corresponding higher adiabatic heat-up rates. For example, the ambient (H_2O) moderator has the highest power density at about 12 kW/L for a beam power of 4 MW. Total loss of coolant flow to the ambient moderator at full beam power could, therefore, cause the temperature of the water inside to increase from the normal value (about 20°C) to 100°C in about 15 s. Longer times would apply for the other components because they, being further from the target Hg, have lower power densities. See Fig. 5.3-30 and Table 5.3-4 of the SNS CDR.

If the temperature in any component increased enough to cause boiling of the cooling water inside, the resulting pressure surge could cause failure of the component pressure boundary. This would release the component cooling water inside the core vessel. Loss of coolant system integrity is addressed in Sect. 3.9. If the proton beam were still not cut off after this point, the temperature of the component would continue to increase until a thermal equilibrium was reached. Extensive melting would not occur because the component would begin exchanging heat with the surrounding adjacent components and achieve thermal equilibrium before the melting point was reached. After the proton beam is cut off, active cooling is not needed by any component.

The failure modes discussed above are loss of cooling water flow in the primary cooling loop for each component. An event such as loss of deionized water system flow could affect several of the target components in the core vessel at the same time. Thus, the BP system will provide

automatic cutoff of the proton beam. Nevertheless, tens of minutes would be available for the operator to respond to alarm annunciations associated with this problem because of the large thermal inertia provided by the volume of primary coolant in each loop. In its extremely unlikely conclusion, a loss of deionized water without proton beam cutoff would lead to loss of one or more component cooling loops, with source term as described in this section or in Sect. 3.9.

3.8.2 Estimated Frequency Range for Loss of Water Flow to Target Component Cooling Loop

The base event, loss of component cooling flow, is an anticipated event (2.5×10^{-2}/year < frequency < 10°/year) expected to occur during facility life. Compounding the base event with a failure of the automatic beam cutoff system(s) reduces the net sequence frequency to the unlikely range (frequency < 2.5×10^{-2}/year), or lower. Automatic beam cutoff in the event of loss of component cooling water is highly desirable from an operational point of view, but, in some cases, it is not clear that the loss of cooling water flow would cause component failure in a short period of time. Consequently, reliable beam cutoff will be provided (>99% probability of beam cutoff given occurrence of the loss of cooling water), but the degree of diversity and/or redundancy may be lower than is provided for other, more damaging events [e.g., ones that could escalate into a mercury spill event without prompt beam cutoff (see Sect. 3.4 and/or 3.5)]. In conclusion, loss of component cooling flow compounded by a failure of automatic beam cutoff is assigned to the unlikely event category. This is a very conservative assumption because components with a defined segmentation function (e.g., the proton beam window or the water-cooled shroud) will receive both TPS and BP coverage for automatic proton beam cutoff.

3.8.3 Source Term for Loss of Water Flow to Target Component Cooling Loop

There is no source term for the base event with automatic beam cutoff because there is no damage or release of material of any kind. If the automatic beam cutoff does not function, the operators may have time to initiate beam cutoff before damage. The possible source term for the extremely unlikely event with failure of automatic and manual proton beam cutoff is bounded by the source terms developed in Sect. 3.9 for loss of cooling water integrity in target component cooling loop.

3.9 LOSS OF H_2O OR D_2O INTEGRITY IN TARGET COMPONENT COOLING LOOP (ACCIDENT SEQUENCE 8)

There are four target cooling loops that will become activated during proton beam operation:

1. The proton beam window and moderator H_2O cooling loop:
   - proton beam window
   - ambient moderator
   - cryogenic moderator

2. The D_2O cooling loop
   - Ni and Be reflectors
3. The shroud H_2O cooling system
   - target water-cooled shroud
4. The shield cooling H_2O cooling water loop
   - stainless steel shielding units

The pumps and heat exchangers for these systems are located in the utility vault, and the actual cooled components (listed above) are inside the core vessel.

3.9.1 Sequence of Events for Loss of Integrity of Component Cooling Loop

If there is a major loss of integrity in any component cooling water system, this would soon result in loss of cooling of the affected component. For possible thermal response, see the discussion in Sect. 3.8. If there is a minor loss of integrity, cooling of the component would continue to be effective as long as there is adequate inventory for circulation.

3.9.2 Estimated Frequency Range for Loss of Integrity of Component Cooling Loop

The base event, loss of component cooling integrity, is an anticipated event (2.5×10^{-2}/year <frequency < 10°/year) for the slow leak loss of integrity and would be an unlikely event (10^{-4}/year < frequency < 2.5×10^{-2}/year) for the major failure loss of integrity. The low likelihood of major failure stems from the fact that these are low-pressure systems, with connections and leaktightness verified during installation before operation. However, since there are four of these systems, the major loss of component cooling loop integrity is assigned to the anticipated category.

3.9.3 Source Term for Loss of Integrity of Component Cooling Loop

The source term for a loss of coolant system integrity depends on the mode of failure and the location of the breach. For example, water spilled by a major failure outside the core vessel would, in general, tend to drain to sump tanks (in the utility vault except for the shroud-cooling system sump tank, which is inside the target hot cell) or floor sumps and thus not be available for evaporation and release. Nevertheless, the source terms developed for the major failure include a significant evaporation component. If the failure occurred inside the core vessel, the source term due to evaporation of water inside the warm core vessel would be as discussed below.

3.9.3.1 For slow leaks

The source term might not be sensitive to location (inside vs outside the core vessel) because such a leak outside the core vessel would evaporate before the leaked water reached the sump. The bounding source term for a slow leak would be one that causes a stack discharge rate that is high enough to exceed the allowable yearly total release (based on tritium) in a small fraction of a year (e.g., a week or a month). Since discharges are monitored, it is very unlikely that facility management would allow continued operation such that the yearly release limit would be

exceeded. A source term is not specified because facility operations would be curtailed before the yearly release limit is exceeded.

3.9.3.2 For leak into core vessel

In the event of a cooling water leak or spill inside the core vessel, some fraction of the spilled water would evaporate and be carried off with the core vessel helium purge that is discharged to the target hot off-gas system (discharge point upstream from the demisters that are upstream from the HEPA filter banks). The evaporation rate would be limited by the rate of flow of the He purge that is supplied to the core vessel, (i.e., the ~10 m^3 free volume is replaced every ~100 h) (see Table 5.3-6 in the CDR. *Note*: post- CDR design work has resulted in an increase in core vessel diameter—from 2-m to 3.5-m, with a higher estimate of core vessel free volume—10 m^3 instead of 3 m^3). For the purposes of this analysis the nominal 10 m^3/100-h purge rate will be doubled to account for possible operational variation of the purge flow.

If the bounding assumption is made that the helium purge is saturated with water vapor at the temperature of the core vessel (which should average less than 55°C based on CDR information concerning cooling water temperatures; see Sect. 5.3.6), the release can be estimated conservatively, as follows:

- Helium discharge temperature: 60°C (based on the 55°C estimated maximum value)
- Helium discharge rate: 20 m^3/100-h (twice the current nominal design figure)
- Water vapor density: 0.143 kg of D_2O or 0.13 kg H_2O/m^3 @ 60°C (i.e., 100% humidity)
- Discharge rate (D_2O or H_2O, as applicable, based on the above three assumptions): 0.6 L/d

As a conservative assumption for environmental impact statement (EIS) studies, it is assumed that the discharge continues for a period of one month. This is very conservative because conditions inside the core vessel are monitored and water vapor is not an operationally desirable atmosphere for the core vessel, since radiolytic effects may lead to corrosion of components inside. The nuclides of interest for this source term are tritium (H-3) and gaseous nuclides such as N-13, N-16, and O-15. As a practical matter, the release of the N and O nuclides would be nil because they are dissolved in the cooling water and would decay before being released. Any radioactive ions in the coolant would not be transported with the evaporated water, and insufficient other agitation or energy sources are present to create a vapor fog/aerosol that would be transported to the environment.

As developed above, the bounding release is 0.6 L/d for 30 d, for a total of 18 L of water evaporated and released to the environment. The nuclide of primary interest is tritium, and it will be in the form of HTO and T_2O. The coolant loop with highest tritium content determines the maximum tritium release. That most tritiated loop is the D_2O coolant loop that circulates through the reflectors. The tritium content is estimated at less than 5 Ci/L after equilibrium 4-MW operation is achieved. The maximum tritium source term is, therefore, 90 Ci of tritiated water vapor released over a 30-d period.

The light water component cooling loops will also have tritium contamination, but at much lower concentrations than the end-of-life concentrations in the heavy water coolant loop—because they are light water and thus have much less deuterium (which becomes tritium upon absorption of a neutron), and because the light water systems are replenished with new coolant several times per year. The tritium concentration for activated light water cooling systems is

estimated not to exceed 0.5 Ci/L, based on the lower production rate of tritium and periodic replenishment of the H_2O, resulting in a 9-Ci source term for evaporation of the same (18-L) volume of water.

3.9.3.3 For rapid, worst case leak into target hot cell or utility vault

The other type of leak would unfold rapidly because the leak rate would be too large for operation to continue for more than a few minutes, at most, forcing a shutdown for repair of the leak. For a bounding analysis it is assumed that the leak occurs near the pump outlet where the pressure is highest, so that the water is propelled out over a wide area of the enclosure in which it occurs [e.g., the target hot cell, the pipe chase, the target shielding enclosure, or the utility vault (inside the core vessel covered above)]. This is a very conservative assumption because the piping is typically located inside a pipe chase or trench or is behind shielding (provided to allow limited entry to the utility vault during operation). The source term for the bounding analysis would include two contributors: the water vapor that evaporates from the puddle over the floor and the small random droplets of water (e.g., formed if the leak hits an obstruction) that could be entrained in the ventilation system flow. The balance of the spilled water would gravity drain to a sump tank.

For bounding analysis, the puddle area is taken as the maximum floor area that could be wetted by any one pipe breaking in either the target hot cell or the utility vault, estimated at 50 m^2, and the puddle depth is assumed to be 3 mm, a value consistent with water lying on a flat floor. The puddle depth is limited by the surface tension of water; large floor areas cannot be flooded to greater depths because of gravity drainage to trenches and/or sump tanks. The mist contribution is assumed to be 1% of the spilled water—about 15 L (note: the total spill volume is taken to be 1500 L, but the puddle volume is limited to 150 L because of the limited floor area). The 1% mist fraction assumed here is greater than assumed for pressurized water/solution spills in the *Final EIS for the Safe Interim Storage of Hanford Tank Wastes* (DOE/EIS-0212, October 1995), and is thought to be conservative because the water pressure in these loops is relatively low (only a few atmospheres) and because the air velocities are not high in either the target hot cell or the utility vault. The amount of water becoming airborne is thus

Puddle evaporation: 150 L of H_2O or D_2O
Mist entrainment: 15 L of H_2O or D_2O

The tritium source term associated with these losses is calculated based on a concentration of 5.0 Ci/L for the D_2O cooling system and 0.5 Ci/L for the H_2O cooling systems. The source term associated with the mist entrainment depends (except for the tritium releases) primarily on how much credit is taken for the HEPA filters. If no credit is taken for the HEPA filters, then any radioactive solids or ions present in the entrained mist would be released. For conservatism, it is assumed here that the HEPAs do not function, so that the whole 15 L of H_2O or D_2O is released to the environment. The nontritium radionuclide content is estimated by modeling this as low-level liquid waste (LLLW, which is composed of used coolant); thus, the release is found by multiplying the nuclide inventories specified in List 8 of Exhibit E for 1-MW operation and a total volume of 800 gal of LLLW by the factor 15/(3.78*800) = 4.96E–3. The tritium content is determined from the same concentrations used to estimate the puddle evaporation source term. The mist release occurs over the time scale consistent with the residence time of ventilation air in

the room and ducts, greater than 5 min. The puddle evaporation can occur no faster than air can carry away the water from the puddle. Air at 90°F (summertime exhaust temperature) that is saturated at 100% humidity could hold about 38 g D_2O/m^3, so the 125 m^3/min (4400 cfm) of utility exhaust flow could, theoretically, transport 4.25 kg/min of D_2O. Thus, it would take at least 35 min for the 150 L of D_2O to evaporate.

In addition to the tritium released by this event, some fraction of the gaseous radionuclides dissolved in the coolant could be released, with the bounding assumption being the immediate release of 100% of these gases to the interior space or cell in which the coolant pipe break or leak occurs. Since the residence time of air in the cells is greater than 5 min, it would take at least that long to sweep the released gaseous nuclides to the environment through the target facility ventilation exhaust stack. It is appropriate to take credit for this delay because the assumption of 100% immediate release into the indoor space is very conservative for release of dissolved gases from a low-pressure coolant system from which the immediate release would be less than 50%, with the balance requiring considerable time for the dissolved gases to diffuse out of the water. The shroud-cooling water system generates the greatest quantity of radioactive gases, and this source term (Table 3.6) can be applied conservatively to all the target cooling water release accidents.

Table 3.6. Target shroud cooling water system gaseous radionuclides inventory
[Given numbers are for 1-MW operation—multiply by 4 to get 4-MW numbers.]

Radionuclide	Half life	Inventory for 1-MW continuous proton beam operation for 1 year (Ci)	Stack release after 5 min delay (Ci)
N-13	598 s	155	109
N-16	7 s	124	0
O-14	70 s	56	6.4
O-15	122 s	786	143

s-seconds.

Source terms for the loss of cooling system integrity events can be summarized as below. The results are expressed in a manner to allow convenient bracketing of the estimated releases between that consistent with the initial 1-MW proton beam operation and the eventually planned 4-MW beam operation. The reason for listing the worst case water spill event as an anticipated event for the H_2O cooling systems is that there are three such systems (or more, considering the beam stop cooling systems—see discussion, below), which means that even though the estimated frequency of occurrence might be in the unlikely category for any one system, the aggregate frequency for three systems will probably exceed the 0.025 per year threshold for the anticipated category, considering that there are three such systems (specific design data not currently available will be required for quantitative estimates of the failure frequencies).

Anticipated event: D_2O cooling water system (line break in utility vault)

Tritium: 750 Ci as DTO or T_2O (0.5 h-release period; bounds 4-MW operation)
Gases: See Table 3.6 (5-min release period; multiply by 4 for 4-MW operation)
Mist: 75 Ci of tritium plus 0.005 times List 8, Exhibit E (5-min release period)
(multiply List 8 by 4 for 4-MW operation)

Anticipated event : D_2O cooling water system (leak in core vessel)

Tritium: 90 Ci as DTO or T_2O (30 d-release period; bounds 4-MW operation)
Gases: negligible (decay before release)
Mist: none

Anticipated event: any of three H_2O cooling water systems (line break in utility vault)

Tritium: 75 Ci as HTO or T_2O (0.5 h-release period; bounds 4-MW operation)
Gases: See Table 3.6 (5-min release period; multiply by 4 for 4-MW operation)
Mist: 7.5 Ci of tritium plus 0.005 times List 8, Exhibit E (5-min release period)
(multiply List 8 by 4 for 4-MW operation)

3.9.4 Beam Stop Cooling Water Line Breaks

Three beam stops are to be installed for the original construction, and two more (beam injection and beam extraction) will be installed when the second ring is built for the upgrade to 4-MW operation. The ring injection beam stop for each ring will operate continuously at maximum power of 200 kW (during normal beam operation, the estimated continuous dumped power is only 40 kW, so the 200 kW is a bounding number). The other beam stops operate at lower power and/or are used intermittently. The injection stops thus have the largest radioactivity inventories. The line break events for the beam stop H_2O coolant systems are very similar to those considered above for the target cooling systems. Since their HEPA-filtered ventilation exhaust is routed to the target station ventilation exhaust path for discharge to the environment by the target stack, and since the maximum beam dump source terms are bounded by the target facility cooling water spill accident source terms, there is no need to do a separate consequence analysis for beam stop coolant accidents.

3.10 LOSS OF INTEGRITY OF CRYOGENIC MODERATOR (ACCIDENT SEQUENCE 9)

The cryogenic moderator system circulates an ~1.5 kg inventory of ~20 K hydrogen through cryogenic moderator vessels located in the core vessel above the water-cooled shroud and back to helium-cooled heat exchangers and pumps located in the safe room, which is located on the floor level of the high bay above, and to the west of, the target hot cell. Under abnormal conditions, or for system shutdown, the cryogenic hydrogen is allowed to heat up and expand into a 4500-L expansion tank (which is located outdoors). As described in Sect. 5 of the CDR, the safe room houses the active components of the system—pump, valves, heat exchanger. The safe room is so called because of special safety features, including explosive-rated (nonsparking) electrical equipment, hydrogen detection, and special ventilation. The safe room is not normally occupied. When personnel are present, hydrogen safety protocols will be followed.

3.10.1 Sequence of Events for Loss of Cryogenic Moderator System Integrity

The cryogenic moderator is maintained under multiple barriers both for safety and for cryogenic insulation reasons. The innermost tubing is surrounded by vacuum for insulation, and the vacuum is surrounded by a helium barrier for safety. The vacuum and He barriers are continuously monitored for any loss of integrity. The sequence of events for a leak would depend

on where the loss of integrity occurred and how many of the barriers were compromised (see also events 9.A, 9.B, 9.C in Table 3.2). If only the primary boundary fails, the hydrogen escapes into the vacuum system, which is vented safely. If all boundaries fail, the hydrogen is released to the immediate surroundings of the failure.

Combustion is not likely in any potential release location. Release of hydrogen into the core vessel would not involve combustion because a helium atmosphere is maintained inside the vessel. Release of hydrogen in the safe room could possibly involve combustion in this relatively small space; however, the hydrogen concentration is continuously monitored, and the safe room ventilation rate increased upon detection of airborne hydrogen. This automatic detection and accompanying actuation of a ventilation flow increase is designed to prevent combustion upon any credible hydrogen leak inside the safe room. An accompanying alarm would cause personnel present in the safe room to evacuate immediately. Credible leakage from the 4500-L expansion tank would be unlikely to lead to combustion because of the tank's outdoor location.

3.10.2 Estimated Frequency Range for Loss of Cryogenic Moderator System Integrity

Since cryogenic line and system connections are tested before use with hydrogen, failure is not an anticipated event. Monitoring of the vacuum and helium barriers during normal operation should catch any developing leaks in the early stage, making sudden, gross failures that occur during operation of the cryogenic system extremely unlikely events.

The hydrogen moderator vessel is positioned close outside the Hg vessel, but the close-fitting collimator (in the transfer tunnel upstream of the proton beam window) and the proton beam passages in the reflector plugs prevent beam directional and/or focus control failures from allowing the beam to strike the hydrogen moderator vessel.

3.10.3 Source Term for Loss of Cryogenic Moderator System Integrity

There is no source term of interest because calculations show that there is essentially no activation of the hydrogen. Combustion is a potential consequence, as discussed above, but this combustion would not initiate the release of radioactive material because the air-atmosphere locations that could receive such a leak (e.g., the safe room, the outdoor expansion tank) are not close to any other radioactive material. The accident sequence discussion provided above is for the purpose of pointing out how the accident potential for combustion of hydrogen has been considered in system and facility design. The design features and administrative controls that will be followed should make the risk of personnel injury due to combustion very small.

3.11 LOSS OF INTEGRITY: CORE VESSEL, 3.5-M DIAM TARGET CONTAINMENT VESSEL (ACCIDENT SEQUENCE 10)

3.11.1 Sequence of Events for Loss of Core Vessel Integrity

The core vessel helium atmosphere is maintained at or below atmospheric pressure. There is essentially no pressure stress, making failure probability low. The low pressure tends also to make the loss of vessel integrity a benign event. The helium atmosphere is monitored because it is desired to exclude air for two reasons: to maintain an inert atmosphere as a safety precaution

against hydrogen leakage inside the vessel and to maintain an atmosphere that will have much lower activation/spallation because of the passage of the proton beam through it than would other atmospheres (e.g., air).

3.11.2 Estimated Frequency Range for Loss of Core Vessel Integrity

Loss of integrity of a vessel that is not highly stressed would be an unlikely event.

3.11.3 Source Term for Loss of Core Vessel Integrity

Considering that this is an unlikely event, leakage of the vessel's slightly radioactive atmosphere would be of minimal interest for consequence analysis.

3.12 LOSS OF HE FLOW TO CORE VESSEL (ACCIDENT SEQUENCE 11)

3.12.1 Sequence of Events for Loss of He Flow

Loss of the helium purge flow would be unlikely to result in a significant source term because the He inlet flow and core vessel atmosphere are both monitored, allowing detection of the loss of He flow before air has time to diffuse into the vessel.

3.12.2 Estimated Frequency Range for Loss of He Flow

Anticipated.

3.12.3 Source Term for Loss of He Flow

Considering the unlikelihood of such an event developing into a significant release and the resistance of helium to activation, no source term is specified for this event.

3.13 TARGET CELL VENTILATION SYSTEM FAILURES (ACCIDENT SEQUENCE 12)

3.13.1 Sequence of Events for Target Cell Ventilation System Failures

Various target cell ventilation system failures could be postulated. For example, the power supply to the cell ventilation system blowers could fail or the blowers could fail. Without blower operation, the target cell pressure, normally maintained lower than atmospheric pressure, would equilibrate with the ambient pressure outside the cell. Contamination could then begin to diffuse out of the cell through any imperfections in the cell boundary. Reestablishment of power to the blowers or repair of the blowers would restore the cell's normally negative pressure.

It could be postulated that a target cell ventilation system HEPA filter might fail, initiating a period of higher than normal radioactivity in the target system ventilation exhaust. The higher

than normal stack discharges would be detected, and actions would be initiated as needed to correct the situation.

3.13.1.1 Frequency of occurrence for target cell ventilation system failures

Mishaps such as a loss of blower power are anticipated to occur during the facility lifetime. A HEPA filter could be improperly seated during installation, but post-installation testing conducted to confirm proper seating would make this unlikely. Spontaneous failure of a HEPA filter would be unlikely. The installed instrumentation and preventive and periodic maintenance make prolonged or undetected ventilation system failures unlikely.

3.13.1.2 Source terms for target cell ventilation system failures

There are no source terms of particular interest beyond the immediate confines of the facility. This is because high levels of airborne radioactivity inside the target hot cell are not necessary nor are they expected during normal operation of the hot cell. The radiological health protection and contamination control measures employed at the facility are adequate to protect the workers within the confines of the facility. These measures include ventilation system monitoring, air sampling, and routine surveys, as well as administrative controls.

3.14 LOSS OF OFF-SITE POWER (ACCIDENT SEQUENCE 13)

Loss of off-site power would immediately cut off the beam because the linac and ring magnets must be powered in order to maintain a beam on the target. Since the mercury decay heat level (~9.6 kW after continuous 4-MW operation) is only about 0.25% of the full beam power, the decay heat removal requirements of the target facility are not demanding. For example, the mass of the target mercury combined with the relatively low decay heat means that forced circulation is not required for decay heat removal. Therefore, the loss of off-site power puts the target into a safe state in which any decay heat present is removed by passive means.

Loss of off-site power would cause a loss of target hot cell ventilation, which is discussed above in Sect. 3.13. Diesel-backed power is provided. In the event of a prolonged power outage, the diesel generator would be started to power loads like the ventilation system blowers.

There is no accident-related source term of particular interest for loss of off-site power.

3.15 FIRE (ACCIDENT SEQUENCE 14)

Fire safety is discussed in Sect. 9.2.4.1 of the SNS CDR. As stated there, the SNS facility does not involve large accumulations of particularly hazardous flammable materials. Furthermore, smoke detector systems, sprinklers, and ventilation system features that can be controlled by fire fighters for smoke control purposes are provided. It is planned to do a fire-hazards analysis under the guidance of DOE Order 420.1 during Title 1 Design. For this reason, detailed analyses of fire hazard scenarios have not been conducted at this stage of the project.

3.16 NATURAL PHENOMENA—TORNADO AND SEISMIC (ACCIDENT SEQUENCE 15)

As outlined by Table 8.4-2 of the SNS CDR, the SNS facilities have been categorized in accordance with the DOE natural phenomena performance categories for the application of the appropriate levels of seismic and wind conditions. The target building is considered to be PC-2, which is consistent with a once per 1000 years seismic event. Safety-related systems would be expected to survive or at least perform their designated safety function(s) before failing during and after a PC-2 level seismic or wind event. Thus, a significant release of radioactive material would not be expected for an unlikely natural phenomena event.

A seismic event more severe than the design level could act as an initiator for any of the events considered in Sects. 3.2 through 3.14. The resulting source term would not be different because it was initiated by a natural phenomenon; thus, the source term would also be bounded by those evaluated in Sects. 3.2 through 3.14. The frequency of such failure initiation would be low because the system is basically designed for a 10^{-3}/year level of event without significant source term. It is concluded that natural phenomena will not significantly increase either the frequency or magnitude of SNS source terms. Therefore, special natural phenomena source terms are not recommended for detailed calculation and study in the EIS.

3.17 BEYOND-DESIGN-BASIS ACCIDENTS (ACCIDENT SEQUENCE 16)

The purpose of postulating these events is to determine if any risk significant source terms are present in the probability range somewhat below the 10^{-6} /year cutoff frequency used for design-basis events. The criterion selected for a BDB event selection is that the estimated frequency should be greater than 10^{-8}/year but less than 10^{-6}/year.

Table 3.7 lists the target facility accidents considered in this chapter and considers additional failures that could result in increased source terms. The results show that the Hg spill event (Sect. 3.3) and the loss of Hg circulation pump events (Sect. 3.4) provide the most significant additional source terms for residual risk evaluation. One source term that bounds both the 3.3 and the 3.4 BDB accident sequences (and also the other BDB events screened) is derived in Exhibit F. The source term is summarized below in Table 3.8.

Table 3.7. Screening for selection of limiting beyond-design-basis accident

Initiating event and section of report where considered as design basis event	Additional failures	Approx. annual probability level	Consequence assessment
Note: no sequences are postulated involving the failure of all automatic proton beam cutoffs. There are three separate automatic cutoff systems: the target protection system (TPS), the beam permit/pulse enable (BP) system(s), and the personnel protection system (PPS) that can initiate cutoff of the beam. Accident sequences with the assumption that all these fail simultaneously have annual probability below the 10^{-8}/year cutoff.			
3.2 Proton beam excessive focus density	In the worst case , this event leads to a Hg spill event. Thus, considerations under 3.3 (below, in this table) cover this event		
3.3 Hg spill	BP + TPS + mercury enclosure Hg drainage path + water-cooled shroud	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Short period of boiling of Hg may occur before PPS beam cutoff, depending on Hg spill rate. Short and long term Hg, I releases (see Exhibit E)
3.4 Loss of Hg pumping	BP + TPS + mercury enclosure Hg drainage path + water-cooled shroud	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Short period of bulk boiling of Hg may occur before PPS beam cutoff. Short and long term Hg, I releases (see Exhibit E)
3.5 Loss of Hg cooling water flow	BP + TPS + operator (>2 min available for manual beam cutoff)	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Bounded by the source term derived for 3.3 and 3.4. Additional failures (e.g., of the mercury enclosure Hg drainage path and/or water-cooled shroud would bring this event below the 10^{-8}/year screening criterion)
3.6–3.9 Loss of component cooling water, various combinations	BP + TPS + operator	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Overheating of the uncooled component. Worst case could lead to failure of water-cooled shroud and Hg spill. Bounded by 3.3/3.4 BDB event
3.10 Loss of integrity of cryogenic moderator	Core vessel relief valve and/or burst disc	$<10^{-6}$/year	Overpressurization of core vessel, release of He/H_2 mixture to shielding cavity. Negligible He/H_2 transport to hot cell. Combustion possible in shielding cavity or inside core vessel after long times (to allow air to diffuse in). No enhanced Hg source term. Consequences bounded by 3.3/3.4
3.11 Loss of core vessel integrity [seal(s) bad] + 3.12 loss of core vessel He purge flow (extended)	Loss of cryogenic moderator integrity postulated to occur at same time when core vessel atmosphere is mostly air, and the proton beam is on	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Combustion of H_2 inside the core vessel, failure of core vessel at weak points (e.g., the neutron beam windows). Conceivably could cause failure of the water-cooled shroud and the Hg vessel, with Hg spill, but not excessive Hg temperature. Source term bounded by BDB event for 3.3/3.4

Table 3.7 (continued)

Initiating event and section of report where considered as design basis event	Additional failures	Approx. annual probability level	Consequence assessment
3.13 Target cell ventilation system failures	As noted in Exhibit F and other sections of this chapter, for an Hg spill accident that occurs in conjunction with ventilation system failure, the release source term would be lower because there would be much weaker mechanism(s) for transporting mercury vapor to an atmospheric release point		
3.14 Loss of off-site power	There are no significant source terms in this category because a loss of off-site power results in essentially immediate, inherent termination of the proton beam, and because the post-operation decay heat level does not require active cooling to prevent damage		
3.15 Fire	Fire could result in destruction of wiring, resulting in the long-term outage of cooling pumps and/or other active equipment. However, the TPS is designed to be fail-safe, so that loss of TPS wiring insulation integrity resulting from a fire would be expected to cause automatic shutdown of the proton beam. The SNS decay heat level (10 kW immediately after beam cutoff from 4-MW operation) is such that active cooling is not required for decay heat removal		
3.16 Natural phenomena—beyond-design-basis wind event	Roof level ventilation equipment + facility stack(s) + cooling towers	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Damage to Hg system equipment inside the heavily shielded hot cell or the core vessel would be very unlikely. The damage to outside systems could lead to higher than normal releases due to loss of a filtration stage, etc., but not a source term of interest in the BDB context
3.16 Natural phenomena—beyond-design-basis earthquake	Any active system could be failed	$>10^{-8}$/year (but $\leq 10^{-6}$/year)	Could cause loss of cryogenic H_2 moderator integrity, and subsequent combustion could cause Hg spill, but the combustion would not be in the hot cell. The Hg releases from the Hg spill would not be greater than presented for U or EU events because automatic beam cutoff would be highly likely for two reasons: (1) the TPS has fail-safe design so that loss of signal causes beam trip and (2) extreme earthquakes tend to cause loss of off-site power that would terminate the proton beam

Table 3.8. Beyond-design-basis accident source term summary-bulk mass fractions released

Radionuclide category	Fractional release of total inventory		
	Short term (~10 min)	First 7 d	7 d to 30 d
	1-MW target configuration—fractional releases		
Mercury	6.6E–5	0.8E–2	3.0E–3
Iodine	1.40E–1	2.0E–1	6.6E–1
Nonvolatile solids	Negligible	Negligible	Negligible
	4-MW target configuration—fractional releases		
Mercury	1.83E–3	0.8E–2	3.0E–3
Iodine	1.4E–1	2.0E–1	6.6E–1
Nonvolatile solids	Negligible	Negligible	Negligible

Note: For initial Hg and I radionuclide specific activities, see Table 3.4.a. Release fractions for shorter-lived radionuclides would be smaller than the bulk mass fractions indicated above provided that the release period is long in comparison to the half-life of the radionuclide.

3.18 REFERENCES

1. Computationally-Compatible Component Database Release 0.0, New Production Reactors Program, Reliability, Availability, Maintainability and Inspectability, Engineering Technology Division, Department of Nuclear Energy, Brookhaven National Laboratory, Upton, New York, April 1990.

4. SNS WASTE SYSTEMS ACCIDENT SCENARIOS AND SOURCE TERMS

SNS Waste Systems Description

SNS wastes consist of gaseous, liquid, and solid components. Wastes are collected in the appropriate system within the facility and transferred to ORNL for processing or are packaged for off-site disposal. Accidents were analyzed only for the gaseous and liquid waste systems because these systems offer the greatest potential for radionuclide release to the environment.

Gaseous Wastes

The HVAC system will collect off-gases from systems that generate radioactive or potentially radioactive gases and discharge them to two central stacks after final filtration and radiation monitoring. The gaseous waste system is located between the mercury target off-gas (i.e., primarily the helium purge flow that maintains the helium atmosphere in the mercury reservoir) and the HVAC system and serves to remove mercury, noble gases, iodine, and tritium from this off-gas stream. The system consists of a chilled condenser to return mercury to the target system, a liquid nitrogen cooled charcoal bed to remove xenon and iodine, and a circulating hydride bed system for the removal of tritium. The charcoal adsorbs the xenon and iodine spallation products and holds them for decay. It also removes any mercury that is not removed by the mercury condenser. The tritium removal system consists of a uranium metal bed and a circulation pump. The helium exiting the charcoal absorber system is passed through this system, and is discharged to the HVAC system.

Another system to process gaseous wastes is a set of decay tanks and a compressor for off-gas from the target, moderator, reflector, and beam stop cooling systems. During shutdown for maintenance, these cooling systems are vented. The compressors compress the vented gases into the decay tanks, where they are held for the decay of the short-lived isotopes.

Liquid Wastes

Liquid wastes from the SNS are characterized in four broad categories: low-level liquid, process liquid, hazardous, and conventional. Accidents concerning the hazardous and conventional wastes were not analyzed because they were thought to present significantly lower hazards than the other two categories.

The low level liquid wastes are collected from the linac, transfer line, ring, target, and beam stop cooling water systems; from the target and other cells; and from the radioactive target ventilation systems. The LLLW system in the tunnels consists of a series of piping headers and a central collection tank. The waste in this tank is pumped to another set of storage tanks located in the target building, where it is combined with target building LLLW. The waste will be pre-treated as necessary before it is transferred to a load-out station and to a 1000-gal DOT-certified tank truck, which will transport it to the ORNL LLLW evaporator for further processing.

Process wastes are collected from clean and buffer area building floor drains, cooling water system leakage, building HVAC condensate, central services building ion exchange regeneration solutions, and groundwater in-leakage from tunnel french drains. The process waste system consists of a series of sumps, sump pumps, and collection headers leading to a diversion tank

system where the waste is monitored for radioactivity. Waste that exceeds a preset limit will be diverted to the LLLW collection system; otherwise, the waste drains by gravity to a set of storage tanks, from where it is transported to the ORNL treatment facilities in a 3000-gal truck tanker.

Listed below are accident scenarios for the SNS waste systems. This suite of accidents is based in nuclide inventories calculated with a beam power of 1 MW. These inventories are given by the ORIHET-calculated activity inventory at 30 years continuous irradiation, which is equivalent to 40 years of facility operation. To obtain source terms for higher power levels, these activities should be multiplied by the appropriate factor (e.g., 2 or 4) depending on the power level desired. The calculations of the source terms for these accident sequences are contained in the Excel 97 spreadsheet "SNS Waste Accident Source Terms 5 Rev 4." The resulting source terms are presented in Exhibit E.

4.1 FAILURE TO REMOVE MERCURY FROM OFF-GAS

4.1.1 Hg Condenser Failure (Event Sequence 17)

4.1.1.1 Sequence of events for Hg condenser failure

The Hg condenser serves to remove Hg from the helium purge applied to the Hg loop through the pump seal. The condenser is served by a refrigerated cooling system, which is operated at a temperature of –20°C. Operating at this temperature reduces the vapor pressure of Hg in the stream outlet to the maximum extent possible, without freezing. The charcoal absorber downstream of the condenser functions as a polishing filter for the removal of all traces of Hg before entering the rest of the off-gas treatment system and also serves as a backup to the condenser. This event is initiated by a failure of the cooling system to the Hg condenser.

4.1.1.2 Frequency range for Hg condenser failure

The frequency range for Hg condenser failure is an anticipated event, since no additional reliability enhancement requirements will be placed on the refrigeration system.

4.1.1.3 Source term for Hg condenser failure

The source term is calculated as the quantity of mercury that would exit the condenser under a 1 L/min flow, at the maximum temperature of the mercury loop (110°C). See Exhibit E, list 6 for the accident source term. Since the helium is added to the pump seal, it is a good assumption that the He is saturated with Hg. Therefore, the vapor pressure of Hg at this temperature is 0.56 torr (relationship between temperature and vapor pressure from the CRC handbook, p. D-212), and the resulting Hg flow is 0.0047 g/min (calculated with the ideal gas law). The Hg specific activity is given by the ORIHET-calculated activity inventory of the mercury at 30 years continuous irradiation at 1-MW beam power (equivalent to 40 years of operation), assumed to be uniformly distributed in the 1-m^3 Hg volume. This, when multiplied times the calculated flow, gives the activity release past the condenser. No plate-out or removal of Hg in the off-gas or ventilation system is conservatively assumed, since the charcoal absorber is also assumed to be

ineffective, in order to bound the source term. The duration is estimated to be 48 h, or the time required for repair of the refrigeration system.

4.1.2 Hg Charcoal Absorber Failure (Event Sequence 18)

4.1.2.1 Sequence of events for Hg charcoal absorber failure

A design study is presently underway to determine if charcoal filtration is required for the cell ventilation system. These sulfur-impregnated charcoal absorbers would be for final removal of Hg from the target cell ventilation air. This accident sequence assumes that the absorbers are improperly installed or are not changed on a timely basis, and the Hg detector in the ventilation stream fails, causing Hg to exit the ventilation system.

4.1.2.2 Frequency range for Hg charcoal absorber failure

The frequency range for Hg charcoal absorber failure is that of an unlikely event. The principal failure mode for this component is saturation, and downstream Hg detectors would detect breakthrough of the absorber and permit shutdown of the system for absorber replacement before any significant loss of Hg could occur. This detector is assumed to fail. Detection is assumed to occur with the SNS stack detectors, and 10 d is estimated to be required to change the Hg absorbers.

4.1.2.3 Source term for Hg charcoal absorber failure

The source term is calculated based on a mercury release to the target cell, which is anticipated to occur every time the target end is changed. The total quantity of mercury estimated to be spilled is 10 cc, and it is assumed to be transformed into droplets of 1-mm diam. This is assumed to evaporate at a rate of 2.5 g/m^2 surface area per day. If the absorbers were not functioning, the entire spill quantity could be ventilated out of the cell in 900 d. This means that there is a net accumulation of Hg in the target cell, equal to $900/365 \times 4$ target changes/year $\times$ 10 cc/change = 98.6 cc of Hg present in the cell at any one time. Cleanup of the released mercury is ignored. See Exhibit E, list 7 for the accident source term.

Note: This source term is the same as the routine release would be if the charcoal absorbers were not present in an untreated cell air scenario.

4.2 FAILURE TO REMOVE TRITIUM FROM OFF-GAS

4.2.1 Helium Circulator Failure (Event Sequence 19)

4.2.1.1 Sequence of events for helium circulator failure

The tritium removal system consists of a getter bed with a helium circulator. Because the tritium concentration in the helium is expected to be low, the circulation rate must be large relative to the helium flow of 1 L/min. In order to provide positive off-gas relief, the system has fail-open and fail-closed valves which bypass the tritium removal system upon detection of loss

of helium flow from the circulator. This event is initiated by circulator failure, causing the loss of flow and the bypassing of the tritium removal system. This would result in the loss of tritium removal capability until the circulator could be repaired.

4.2.1.2 Frequency range for helium circulator failure

The frequency range for helium circulator failure is an anticipated event, since the helium circulator is not intended to be redundant.

4.2.1.3 Source term for helium circulator failure

The only isotope affected is tritium, and the loss of tritium removal results in the discharge of 0.46 Ci/h of tritium as triated hydrogen (HT) (the annual Hg target production of 4012 Ci/year expressed on a per hour basis). This release rate is conservative since hydrogen removal by hydriding with impurities within the mercury loop is ignored. Spallation product impurity hydriding could remove a significant fraction of the hydrogen isotopes produced. The duration of the outage is one day because the helium circulator would be designed for a direct change-out and should be relatively easy to replace.

4.2.2 Oxidation of Getter Bed (Event Sequence 20)

4.2.2.1 Sequence of events for oxidation of getter bed

The getter bed consists of a container filled with uranium metal. Hydrogen isotopes flowing over the uranium react with it to produce uranium hydride, effectively removing them from the gas stream. Oxidation of the uranium could occur over a period of time, such that the uranium surface was coated with uranium oxides, and tritium absorption rates would be greatly reduced. This effect is assumed to affect the getter bed such that it ceases to absorb tritium.

4.2.2.2 Frequency range for oxidation of getter bed

The frequency range for getter bed oxidation is considered unlikely, because of the general lack of oxygen in the helium atmosphere of the mercury off-gas system.

4.2.2.3 Source term for oxidation of getter bed

The source term is the same as in Sect. 4.2.1 above, and results in the discharge of 0.46 Ci/h or 4012 Ci/year of tritium as HT. The duration of the event is assumed to be 24 h, because the bed is designed to be easily replaceable.

4.3 RELEASE OF STORED RADIOACTIVITY

4.3.1 Failure of Getter Bed (Event Sequence 21)

4.3.1.1 Sequence of events for failure of getter bed

The getter bed is heated to remove the tritium from it for storage on an annual basis. Overheating of the getter bed is assumed to cause it to rupture, resulting in combustion of the pyrophoric metal in the bed and a release of the tritium contained in it as tritiated water (HTO). The bed would be designed for a pressure greater than its operating pressure and would have a redundant temperature control system.

Frequency range for failure of getter bed. The frequency range of failure for getter bed failure is extremely unlikely, since a catastrophic boundary failure would be required to allow free contact of oxygen to the getter bed.

Source term for failure of getter bed. Since the bed can contain up to one year's production of tritium before the tritium is removed, a source term of 4,000 Ci is expected. The duration of the event is considered to be one hour because of the required diffusion of tritium from the ruptured bed to the cell atmosphere. In addition to tritium, the oxidized uranium is a source of particulates. It is assumed that 10% of the 2 kg of uranium contained in the bed is fine particulate and is exhausted to the cell ventilation.

4.4 FAILURE TO TREAT OFF-GAS

4.4.1 Cryogenic Charcoal Absorber (Event Sequence 22)

4.4.1.1 Sequence of events for cryogenic charcoal absorber failure

Because the mass of xenon and iodine isotopes is small, an alternative method of hold-up for decay other than storage in compressed gas form is being considered. These short-lived isotopes can be absorbed on charcoal at liquid nitrogen temperatures. Since the mass is so small, replacement of the charcoal should be infrequent, and retention of the isotopes should be essentially 100% allowing for 100% decay. Such a method could have significantly reduced emissions while at the same time could be more reliable and less expensive. This system consists of a charcoal absorber column cooled with liquid nitrogen. This option is currently under study.

Loss of liquid nitrogen cooling would reduce significantly the effect of charcoal for the absorption of short-lived xenon and iodine. This would result in the release of a significant portion of the off-gas undecayed. An option exists for holding the off-gas in the compressed gas storage for later release, but is assumed to be unavailable.

Frequency range for cryogenic charcoal absorber failure. The frequency range for failure for cryogenic charcoal absorber failure is in the unlikely range, since reliability enhancements to the cryogenic cooling system are anticipated. In addition, charcoal has an affinity for both xenon and iodine at room temperature, although at a reduced capacity.

Source term for cryogenic charcoal absorber failure. The source term is calculated based on ORIHET calculations of the production of volatile isotopes from the Hg target. Very short time steps (10 s) were used in the ORIHET calculations for the mercury and activated air to

estimate the production rate instead. In calculating the off-gas from the mercury, consideration was also given to decay of the xenon isotopes to iodine using the Bateman equation to calculate the equilibrium daughter distributions. The xenon produced is assumed to be removed as soon as it is produced, and the off-gas produced was assumed to be vented with short period decay. See Exhibit E, list 1 for the source term. The duration is 24 h because of the ease of repairing the liquid nitrogen cooling.

4.5 OPERATOR ERROR

4.5.1 Tritium Release from Removal System (Event Sequence 23)

4.5.1.1 Sequence of events for tritium release from removal system

An operator is assumed to commit a valve sequence error when transferring one year's accumulation of tritium for recovery. It is assumed that the material is discharged through a vacuum system to ventilation and then to the stack on a short-term basis.

Frequency range for tritium release from removal system. The frequency range for a general operator error is anticipated, but the frequency range for this particular accident sequence is unlikely. This is because the control system will contain interlocks to prevent this accident, which would have to fail before this accident could happen.

Source term for tritium release from removal system. The source term is the same as in 4.3.1 above, or 4,000 Ci tritium as HT. No absorption in the vacuum pump is anticipated. The duration of the event is 20 min because the evacuation of this volume is estimated to be approximately this long.

4.5.2 Release of Off-Gas from Decay Tank (Event Sequence 24)

4.5.2.1 Sequence of events for release of off-gas from decay tank

An operator is assumed to commit a valve sequence error, resulting in sudden loss of the contents of one off-gas tank to cell ventilation system. Although this is a routine discharge, the operator is assumed to release the wrong tank. The tank released is assumed to have recently been filled.

Frequency range for release of off-gas from decay tank. The frequency range for a general operator error is anticipated, but the frequency range for this particular accident sequence is unlikely. This is because the control system will contain interlocks to prevent this accident, which would have to fail before this accident could happen.

Source term for release of off-gas from decay tank. The source term is the contents of one off-gas decay tank at initial fill-up. To bound the release, the total quantity of gas in the tank calculated to be an equilibrium mixture of the xenon and daughter isotopes that would exist after the 7-d fill time. The duration of the event is 1 h, because of the anticipated pumping rate. See Exhibit E, list 2 for the source term.

4.5.3 Spill of LLLW from Storage Tanks (Event Sequence 25)

4.5.3.1 Sequence of events for spill of LLLW from storage tanks

An operator is filling the LR-56 transport tank and fails to connect the hose properly, releasing the contents of 1 tank to the floor drain in the loading area. This floor drain is routed to the LLLW tank cell instead of process waste.

Frequency range for spill of LLLW from storage tanks. The frequency range for this operator error is anticipated, because no special equipment is provided to prevent this other than operator training and procedures.

Source term for spill of LLLW from storage tanks. The source term is a zero liquid release because tank vault provides secondary containment of the leak. Sumps are provided for pumping the liquid back into the LLLW system. A gaseous release source term is provided in list 11 in Exhibit E.

4.5.4 Airborne Release of LLLW from Storage Tanks (Event Sequence 26)

4.5.4.1 Sequence of events for airborne release of LLLW from storage tanks

The LLLW tanks are located inside a shielded cell, capable of containing the contents. This accident sequence is assumed to be an operator pumping a tanker load of LLLW into the LR-56 tanker during a loading operation, but having a crack in the fill line caused either by a defective line or poor connection. The operator is assumed to notice the spray after 20 min pumping and to shut off the pump.

Frequency range for airborne release of process waste from storage tanks. The frequency range for this operator error is anticipated, because no special equipment is provided to prevent this other than operator training and procedures.

Source term for airborne release of process waste from storage tanks. The tanker is assumed to be filled in 1.6 h at a pumping rate of 50 gpm. Curbing is assumed to contain the spray (assumed to be 5% of 50 gpm × 20 m = 50 gal), but 10% (5 gal) is assumed to become airborne as a mist. The HEPA filters are assumed to remove 99.95% of the material. See Exhibit E, list 10 for the source term. Nuclides and nuclide concentrations of representative LLLW, which are assumed to consist of a mixture of target water coolants, were obtained from the Excel-97 spreadsheets "Cooling Water Waste Volume & Activation 5 rev-2" and "SNS Waste Accident Source Terms 5 rev-4." This is based on the total volume of the target coolants, which are assumed to represent the maximum of LLLW radionuclide concentrations.

4.5.5 Spill of Process Waste from Storage Tanks (Event Sequence 27)

4.5.5.1 Sequence of events for spill of process waste from storage tanks

The process waste tanks are located inside a diked area capable of containing the contents. This accident sequence is assumed to be an operator error spilling a tanker load of process waste into the tanker curbing during a tanker loading operation. This area is not designed to retain the entire tanker load of liquid.

Frequency range for spill of process waste from storage tanks. The frequency range for this operator error is anticipated, because no special equipment is provided to prevent this other than operator training and procedures.

Source term for spill of process waste from storage tanks. The tanker curbing is assumed to contain 10% of the spill, but 90% (13,500 gal) is assumed to overflow to the retention basin and then to the White Oak Creek headwaters. The duration of this accident is 3-1/3 h, because of the anticipated pumping rate of the process waste pumps (75 gpm). See Exhibit E, list 4 for the liquid source term. The gaseous release source term is in list 12. Nuclides and nuclide concentrations of representative process wastewater, which are assumed to consist of magnet coolant, were obtained from the Excel-97 spreadsheets "Cooling Water Waste Volume & Activation 5 rev-2" and "SNS Waste Accident Source Terms 5 rev-4." This is based on the total volume of the linac and ring magnet coolant, which is assumed to represent the maximum of process waste radionuclide concentration.

4.5.6 Airborne Release of Process Waste from Storage Tanks (Event Sequence 28)

4.5.6.1 Sequence of events for airborne release of process waste from storage tanks

The process waste tanks are located inside a diked area capable of containing the contents. This accident sequence is assumed to be an operator pumping a tanker load of process waste into the tanker during a loading operation, but having a crack in the fill line caused either by a defective line or poor connection. The operator is assumed to notice the spray after 20 min pumping and to shut off the pump.

Frequency range for airborne release of process waste from storage tanks. The frequency range for this operator error is anticipated, because no special equipment is provided to prevent this other than operator training and procedures.

Source term for airborne release of process waste from storage tanks. The tanker is assumed to be filled in 3-1/3 h at a pumping rate of 75 gpm. Curbing is assumed to contain the spray (assumed to be 5% of 75 gpm × 20 m = 75 gal), but 10% (7.5 gal) is assumed to become airborne as a mist. See Exhibit E, list 9 for the source term. Nuclides and nuclide concentrations of representative process wastewater, which are assumed to consist of magnet coolant, were obtained from the Excel-97 spreadsheets "Cooling Water Waste Volume & Activation 5 rev-2" and "SNS Waste Accident Source Terms 5 rev-4." This is based on the total volume of the linac and ring magnet coolant, which is assumed to represent the maximum of process waste radionuclide concentration.

4.6 EQUIPMENT FAILURE

4.6.1 Off-Gas Treatment Pipe Leak/Break (Event Sequence 29)

4.6.1.1 Sequence of events for off-gas treatment pipe leak/break

This event is a pipe leak or break resulting in the release of off-gas to cell ventilation.

Frequency range for off-gas treatment pipe leak/break. The frequency range for this is unlikely, since a boundary failure (weld crack or valve leak) would be required. The location of

the off-gas piping should reduce the chance of mechanical damage during material moving operations in the target cell.

Source term for off-gas treatment pipe leak/break. Since there is no hold-up for decay, all of the isotopes released to cell ventilation would be released from the stack. See Exhibit E, list 1 for the source term. The duration is 24 h because the continuous purging of the mercury would continue past the beam-off condition, until the inventory could be expected to be exhausted. The off-gas stream is conservatively estimated to be at the production concentrations. The duration of this sequence is 24 h, because the mercury would be purged of gases during this time after beam cutoff.

4.6.2 Off-Gas Compressor Failure (Event Sequence 30)

4.6.2.1 Sequence of events for off-gas compressor failure

This sequence is the general failure of the off-gas compressor. This compressor may not be required except during cooling water system venting (cooling water systems are assumed to be operated pressurized and unvented during normal operation). This is because of the presence of the cryogenic charcoal absorber. In the event this is not the design, then the compressor would be needed for all operations.

Frequency range for off-gas compressor failure. The frequency range for this is unlikely, since reliability enhancements to the off-gas compressor, adding additional compressors, accelerator power reduction, or operations curtailment is anticipated.

Source term for off-gas compressor failure. In order to bound it, the source term is conservatively assumed to be the mercury off-gas, assuming there is no cryogenic charcoal absorber. Since there is no hold-up for decay, all of the isotopes released to cell ventilation would be released from the stack. See Exhibit E, list 1 for the source term. The duration is 1 h before operator response to the release would begin. Continuous purging of the mercury would continue, until the compressor was repaired.

4.6.3 Off-Gas Decay Tank Failure (Event Sequence 31)

4.6.3.1 Sequence of events for off-gas decay tank failure

The off-gas decay tank is assumed to fail, resulting in sudden loss of contents of one off-gas tank to the cell ventilation system.

Frequency range for off-gas decay tank failure. The frequency range for this is extremely unlikely, since a catastrophic boundary failure would be required.

Source term for off-gas decay tank failure. See Exhibit E, list 2 for the source term. The duration is 1 min because of the anticipated sudden release.

4.6.4 Iodine Filter Failure (Event Sequence 32)

4.6.4.1 Sequence of events for iodine filter failure

The iodine filter is a charcoal filter located in the off-gas filter train to provide iodine containment for decay of the longer-lived iodine isotopes. This filter could become saturated or

could be improperly installed, resulting in iodine discharge to the cell ventilation. The iodine filter may not be required if there is a cryogenic charcoal absorber. This is presently under study.

Frequency range for iodine filter failure. The frequency range for this is unlikely, because similar installations have a great degree of experience with this filter type.

Source term for iodine filter failure. See Exhibit E, list 1 for the source term, but assume only the iodine is present. The duration is 24 h before the filter could be replaced.

4.6.5 LLLW Piping System Failure (Event Sequence 33)

4.6.5.1 Sequence of events for LLLW piping system failure

LLLW piping is routed through the linac tunnels to avoid the requirement for double-contained piping. In this accident sequence, the LLLW piping is assumed to break during heavy component handling, releasing LLLW to the floor of the linac or ring tunnel.

Frequency range for LLLW piping system failure. The frequency range for this is unlikely, since a boundary failure (weld crack or valve leak) would be required. The location of the piping relative to the components moved (magnets and beamline components) should preclude damage from potential falling objects that would be the principal hazard.

Source term for LLLW piping system failure. The source term is zero release because the linac tunnel provides secondary containment of the leak. Sumps are provided with pumping through a diversion tank system to the LLLW system. A gaseous release source term is provided in list 11 in Exhibit E.

4.6.6 LLLW Storage Tank Failure (Event Sequence 34)

4.6.6.1 Sequence of events for LLLW storage tank failure

An LLLW tank is assumed to leak or rupture releasing contents of one tank to the cell floor.

Frequency range for LLLW storage tank failure. The frequency range is in the extremely unlikely range, since a catastrophic boundary failure would be required.

Source term for LLLW storage tank failure. The source term is zero release to environment because tank vault provides secondary containment of the leak. Sumps are provided with pumping back to the LLLW system. A gaseous release source term is provided in list 11 in Exhibit E.

4.6.7 LLLW Pumping System Failure (Event Sequence 35)

4.6.7.1 Sequence of events for LLLW pumping system failure

This sequence is the loss of the ability to pump LLLW because of pump failure.

Frequency range for LLLW pumping system failure. The frequency range is anticipated.

Source term for LLLW pumping system failure. The source term is zero release to environment because of backup pumps and pump containment.

4.6.8 Process Waste System Piping Failure (Event Sequence 36)

4.6.8.1 Sequence of events for process waste system piping failure

This accident sequence is an underground piping leak/break resulting from damage to piping during excavation, improper installation, or corrosion over a period of time.

Frequency range for process waste system piping failure. The frequency range is anticipated, because process waste piping of this design is known to develop leaks over the design life of the piping.

Source term for process waste system piping failure. The source term is release of process waste underground to soil, assumed to be 10% of annual system flow (1.04E6 gal/year). See Exhibit E, list 3 for the source term. The duration is 1 year, assumed to be the time for detection and repair of the leak.

4.6.9 Process Waste Storage Tank Failure (Event Sequence 37)

4.6.9.1 Sequence of events for process waste storage tank failure

In this accident sequence, a process waste tank is assumed to leak or rupture, releasing the contents of one tank to the diked containment area.

Frequency range for process waste storage tank failure. The frequency range is unlikely, since a boundary failure (weld crack or valve leak) would be required.

Source term for process waste storage tank failure. The source term is zero release to the environment because the tank dike provides secondary containment of the leak. Sumps are provided with pumping back to the process waste system. A gaseous release source term is provided in list 12 in Exhibit E.

4.6.10 Process Waste Pumping System Failure (Event Sequence 38)

4.6.10.1 Sequence of events for process waste pumping system failure

This accident sequence is the loss of the ability to pump process waste because of pump failure.

Frequency range for process waste pumping system failure. The frequency range is anticipated.

Source term for process waste pumping system failure. The source term is zero release to the environment because of backup pumps and pump containment.

4.7 TRANSPORTATION

4.7.1 LLLW Transportation Accident (Event Sequence 39)

4.7.1.1 Sequence of events for LLLW transportation accident

This sequence of events is a transportation accident involving the LR-56 LLLW tanker, which releases the contents of the tanker to the environment.

Frequency range for LLLW transportation accident. The frequency range of release of radionuclides during type B shipping casks like the LR-56 is estimated to be 5×10^{-9}/mi × 3.5 mi = 1.75×10^{-8} (estimated from data given in ref.1). The frequency for this accident is therefore BDB.

Source term for LLLW transportation accident. The source term is 800 gal of LLLW released to environment. See Exhibit E, list 8 for the source term. The duration of the accident is 24 h. Nuclides and nuclide concentrations of representative LLLW wastewater, which are assumed to consist of a mixture of coolant, were obtained from the Excel-97 spreadsheets "Cooling Water Waste Volume & Activation 5 rev-2" and "SNS Waste Accident Source Terms 5 rev-4." This is based on the total volumes from the various target, linac, and beam-stop coolant systems, which are assumed to be changed with each target end change (ion exchange effectiveness is ignored).

4.7.2 Process Waste Transportation Accident (Event Sequence 40)

4.7.2.1 Sequence of events for process waste transportation accident

This sequence of events is a transportation accident involving the process waste tanker.

Frequency range for process waste transportation accident. The frequency range of truck accidents is estimated to be 5×10^{-7}/mi × 3.5 mi = 1.75×10^{-6} (estimated from data given in ref.1). The frequency for this accident is therefore extremely unlikely, since a catastrophic boundary failure would be required, and the tanker is designed to withstand the transportation environment in which it will be used.

Source term for process waste transportation accident. The source term is 15,000 gal of process waste released to environment. See Exhibit E, list 5 for the source term. The duration of the accident is 1 h.

Information source terms are summarized in Table 4.1. Other information about the individual accidents, including method of detection, system response, and mitigating actions or features, are summarized in Table 4.2.

4.8 REFERENCES

1. *Final Environmental Impact Statement*, Safe Interim Storage of Hanford Tank Wastes, Hanford Site, Richland, Washington, DOE/EIS-0212, Vol. 1, F47–48.

Table 4.1. Source term summary—waste systems
(Frequency ranges: $2.5 * 10^{-2}$/year < A < 10^{0}/year; 10^{-4}/year < U < $2.5 * 10^{-2}$/year; 10^{-6}/year < EU < 10^{-4}/year)

Frequency category	Event(s) [sequence number(s) from Table 4-2]	Recommended source term		
		Material released	Time span	Nuclides released to environment[a]
A	35, 38	None	NA	None
A	25	LLLW	1 h	List 11
A	19	Tritium	24 h	0.46 Ci/h
A	17	Mercury	48 h	4.7 mg/min (list 6)
A	27, 36, 28	Process waste	3-1/3 h (27), 1 year (36), 20 min (28)	Lists 4 and 12 (27), list 3 (36), list 9 (28)
A	26	LLLW	20 min	List 10
U	24	Off-gas	1 h	List 2
U	22, 30	Off-gas	24 h (22), 72 h (30)	List 1 (22, 30)
U	33	LLLW	1 h	List 11
U	20, 23	Tritium	24 h (20), 20 min (23)	0.46 Ci/h (4), 4000 Ci (7)
U	18	Mercury	10 d	List 7
U	29, 32	Off-gas	24 h	List 1 (29), list 1 (32, iodine only)
EU	34	LLLW	1 h	List 11
EU	37	Process waste	1 h	List 12
EU	40	Process waste	1 h	15,000 gal (list 5)
EU	21	Tritium, uranium	1 h	4000 Ci tritium, 0.2 kg depleted U as oxide
EU	31	Off-gas	1 min	List 2
BDB	39	LLLW	24 h	800 gal (list 8)

[a]See Exhibit E for source term lists.

Table 4.2. Waste system accidents

Sequence	How detected	System response or damage	Mitigating actions or features
17. Failure to remove Hg from off-gas–Hg condenser failure	Increase in temperature in condenser	Condenser ceases to condense Hg	Charcoal absorber downstream
18. Failure to remove Hg from ventilation; Hg charcoal absorber failure	Increase in Hg in air concentration measured by Hg detector	Hg is released from cell ventilation until absorber is replaced	Detection of absorber breakthrough by Hg detector prior to last absorber saturation
19. Failure to remove tritium from off-gas–He circulator failure	Operator observation of process instrumentation	Tritium is released from off-gas until circulator is repaired or replaced	NA
20. Failure to remove tritium from off-gas–getter bed oxidation	Operator observation of tritium in off-gas	Tritium is released from off-gas until circulator is repaired or replaced	NA
21. Release of stored activity–failure of getter bed	Operator observation of conditions in cell after failure	Combustion of pyrophoric uranium and release of tritium	NA
22. Failure to treat off-gas–cryogenic charcoal absorber failure	Detection of activity in off-gas	Radioactive off-gas is released from cell ventilation until off-gas can be shut off	Off-gas contains short-lived isotopes only
23. Operator error–tritium release from removal system	Operator observation of tritium in off-gas	Tritium is released from cell ventilation	NA
24. Operator error–off-gas release from decay tank	Operator observation of activity in off-gas	Undecayed off-gas is released from cell ventilation	NA
25. Operator error–spill from LLLW storage tanks	Operator observation of liquid in sumps	LLLW drains to sump, is pumped back to LLLW system	NA
27. Operator error–spill from process waste storage tanks	Operator observation of liquid in dikes	Process waste drains to curb; 10% is pumped back to process waste system; 90% is released to environment	Process waste contains low levels of short-lived isotopes only
29. Off-gas pipe leak/break	Detection of activity in cell ventilation	Off-gas leaks to cell ventilation and is released	Off-gas contains short-lived isotopes only
30. Off-gas compressor failure	Operator observation of failure to compress off-gas	Undecayed off-gas is released from cell ventilation	Off-gas contains short-lived isotopes only

Table 4.2 (continued)

Sequence	How detected	System response or damage	Mitigating actions or features
31. Off-gas decay tank failure	Detection of activity in cell ventilation	Radioactive off-gas is released from cell ventilation	Off-gas contains short-lived isotopes only
32. Iodine filter failure	Detection of activity in off-gas	Radioactive iodine is released from cell ventilation	Iodine has been decayed partially
33. LLLW piping system failure	Detection of activity in process waste	LLLW leaking into linac tunnel is returned to LLLW system	NA
34. LLLW storage tank failure	Detection of liquid In LLLW cell sump	LLLW leaking into sump is returned to LLLW system	NA
35. LLLW pumping system failure	Operator observation of pump not operating	LLLW leaking into sump is returned to LLLW system	NA
36. Process waste piping system failure	Detection of activity In groundwater monitoring well	Process waste leaks into soil	Process waste contains low levels of short-lived isotopes only
37. Process waste storage tank failure	Operator observation of water in dike	Process waste leaking into dike is returned to process waste system	NA
38. Process waste pumping system failure	Operator observation of pump not operating	Process waste leaking into dike is returned to process waste system	NA
39. LLLW transportation accident	Driver observation of accident	LLLW leaking from LR-56 tanker spills to environment	NA
40. Process waste transportation accident	Driver observation of accident	Process waste leaking from tanker spills to environment	NA
28. Process waste airborne release	Operator observation of water spray	Airborne release of process waste	Process waste contains low levels of short-lived isotopes only
26. LLLW airborne release	Operator observation of water spray	Airborne release of LLLW	HEPA filters on ventilation air

EXHIBIT A

A COMPARISON OF THE AIRBORNE CONCENTRATIONS OF METALLIC MERCURY ALLOWED FROM CHEMICAL TOXICITY vs RADIOLOGICAL HEALTH POINTS OF VIEW

EXHIBIT A. A COMPARISON OF THE AIRBORNE CONCENTRATIONS OF METALLIC MERCURY ALLOWED FROM CHEMICAL TOXICITY vs RADIOLOGICAL HEALTH POINTS OF VIEW

The current OSHA Standard for occupational exposure to nonradioactive metallic mercury is a ceiling limit of 0.1 mg/m^3 (29 CFR 1910.20, OSHA Regulations). The National Institute of Occupational Safety and Health (NIOSH) has recommended an alternative limit of 0.05 mg/m^3 averaged over an 8-h period. The American Congress of Government Industrial Hygienists (ACGIH) recommends a threshold limit value (TLV) of 0.025 mg/m^3 [time-weighted average (TWA)]. Adherence to these limits prevents mercury sickness in workers exposed to airborne, nonradioactive mercury.

This exhibit considers the following question: If an airspace in contact with Spallation Neutron Source irradiated mercury were at the ACGIH-recommended TLV-TWA of 0.025 mg Hg/m^3, would the concentration of radioactive mercury isotopes exceed the occupational limit for radiation exposure?

It will be assumed that the SNS mercury has been irradiated by a 1-MW proton beam for a period of 1 year, allowing all the Hg radionuclides, except Hg-194, to come to equilibrium. The irradiation time of only 1 year is chosen intentionally to show that the radioactivity content becomes controlling early in the life of the facility. Similarly, the proton beam (preupgrade) power of 1 MW is chosen because the intent is to demonstrate that the radioactivity content of this mercury is, in effect, more controlling than the toxic material content under the least radioactive scenario. As the radioactivity content of this mercury increases with each year of operation and is further increased by the planned upgrades to 2 MW and eventually to 4 MW, the conclusion will only be strengthened. The total amount of each Hg radionuclide present in the target mercury is provided by SNS HECT96/MCNP/ORIHET95 calculations (See CDR, Sect. 5.4):

Hg-193 = $1.05(10)^4$	Ci	(half life = 3.8 h)
Hg-194 = 39	Ci	(half life = 529 year)
Hg-195 = $1.75(10)^4$	Ci	(half life = 9.9 h)
Hg-197 = $1.17(10)^5$	Ci	(half life = 2.67 d)
Hg-203 = $8.28(10)^4$	Ci	(half life = 46.6 d)

The total volume of Hg in the SNS target is ~1 m^3. The concentration of each radionuclide in air with 0.025 mg/m^3 of irradiated SNS mercury is determined by simple ratios. The resulting concentrations are then multiplied by the breathing rate, and by the effective dose conversion factor given for each nuclide by ICRP-68. The hourly and yearly effective dose accumulation rates due to inhalation of each nuclide then summed in Table A.1 to give an integral comparison to the 5 rem yearly radiation dose limit specified by 10CFR835.202.

From Table A.1, we see that, if the mercury were present in air at the 0.025 mg/m^3 ACGIH recommended TLV-TWA concentration, the radioactivity of the airborne mercury would be too high to allow normal occupancy since the 19.4 rem yearly effective dose commitment would exceed the 10CFR835.202 limit by a factor of four. Considering the lower administrative limits that are routinely applied to radiation exposures would make the radioactivity content more limiting than the ACGIH TLV by a factor of approximately ten. Increasing integrated target

proton beam exposure time above the 1 year assumed in the calculations above would increase the factor even further by increasing the amount of Hg-194 present. Considering volatile spallation or activation products other than the Hg isotopes included in the calculation would only further reinforce the conclusion. Since the facility features to control airborne Hg concentrations inside the facility, to separate the workers from the Hg, and to prevent airborne emissions of Hg will have to be built into the facility from the very first day of operation, it can be concluded that strong protection against the chemical toxicity of the mercury will be provided by those installed systems and radiological control procedures.

The above analysis is not intended to imply that the chemical toxicity of mercury can be ignored during operation of the SNS. The laboratory industrial hygiene department will maintain cognizance of planned SNS target facility operations and will prescribe additional controls for special situations in which chemical toxicity may be more important. Such special situations might arise infrequently, either before initial facility operation when the mercury is not irradiated at all, or after a long shutdown when the dominant nuclides have decayed (Hg-203, for example, has a 47-d half life). If the installed facility ventilation, compartmentation, and surveillance features are not totally adequate for those special situations that may arise, the hygienist will be able to prescribe additional surveillance, training, and/or ventilation as needed to control exposure to the hazard.

Table A.1. Radiation dose commitment rate due to inhalation of SNS-activated mercury, assuming that the total mercury concentration of the air is 0.025 mg/m^3 of irradiated (1 MW for 1 year) SNS mercury
[0.025 mg/m^3 is the ACGIH recommended occupational limit (TLV)[a] for nonradioactive Hg]

Hg radionuclide	Concentration Ci/m^3	DCF[b] (Rem/Ci)	Radiation dose rate (Rem/h)	(Rem/y)
Hg-193	1.93E-08	4.07E+03	9.90E-05	1.98E-01
Hg-194	7.17E-11	1.48E+05	1.34E-05	2.67E-02
Hg-195	3.22E-08	5.18E+03	2.10E-04	4.20E-01
Hg-197	2.15E-07	1.63E+04	4.41E-03	8.82E+00
Hg-203	1.52E-07	2.59E+04	4.97E-03	9.93E+00
		TOTAL	9.70E-03	1.94E+01

[a]The 0.025 mg/m^3 TLV-TWA is the limit set by the ACGIH for the maximum allowable TWA mercury vapor concentration for a normal 8-h work day or 40-h work week.
[b]DCF means dose conversion factor, with values taken from ICRP-68 publication (July 1994) titled "Dose Coefficients for Intakes of Radionuclides by Workers." [Annals of the ICRP, 24(4), 1994].

EXHIBIT B

TARGET MERCURY SPALLATION/ACTIVATION PRODUCT RADIONUCLUDE INVENTORY

EXHIBIT B. TARGET MERCURY SPALLATION/ACTIVATION PRODUCT RADIONUCLUDE INVENTORY

(1-MW beam power—multiply by 4 to get 4-MW beam end-of-life inventory)

SNS target mercury decay activity after 30 years continuous irradiation (equivalent to 40 years of actual operation); 1 GeV proton energy; 1 MW beam power (decay); nuclide radioactivity during decay (curies); time units = seconds, except as otherwise noted.

Note: the column labeled "TS" gives the source of the hazard category threshold:

- A = threshold taken from DOE-STD-6003-96, "Safety of Magnetic Fusion Facilities: Guidance"
- B = threshold calculated from published dose conversion factors (DOE/EH-0071, July 1988) using the DOE-STD-1027-92 threshold definition formula
- C = threshold calculated using recently calculated dose conversion factors (K. Eckerman, ORNL, letters dated 6/18/98 and 8/24/98) and the threshold definition formula in DOE-STD-1027-92
- C* = threshold bounded by comparison to available bounding similar isotope of same element
- D = threshold taken as the generic 4.3E5 Ci value for beta-gamma emitters specified by DOE-STD-1027-92 (9/97 Change Notice No. 1)

Fraction of Cat. 2 calculated by dividing 10-min inventory by the Cat. 2 threshold (10 min is transport time between target hot cell and receptor at 300 m).

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
H3	4.50E+03	5.90E+04	5.90E+04	5.90E+04	5.90E+04	5.90E+04	3.03E+05	A	1.95E-01	5.90E+04	5.90E+04	5.90E+04	5.90E+04	5.90E+04
RH101	1.20E+03	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	4.30E+05	A	3.92E-06	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00
AG109M	4.58E-04	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.41E+10	A	1.20E-10	1.69E+00	1.69E+00	1.67E+00	1.61E+00	1.28E+00
CD109	4.64E+02	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	6.81E+05	A	2.48E-06	1.69E+00	1.69E+00	1.67E+00	1.61E+00	1.28E+00
CD115	2.23E+00	1.69E+00	1.69E+00	1.69E+00	1.68E+00	1.67E+00	7.35E+06	A	2.30E-07	1.45E+00	1.24E+00	1.92E-01	1.31E-04	3.41E-25
IN110	2.04E-01	1.69E+00	1.69E+00	1.65E+00	1.57E+00	1.47E+00	9.50E+07	B	1.74E-08	3.09E-01	5.67E-02	8.01E-11	0.00E+00	0.00E+00
IN111	2.83E+00	3.38E+00	3.38E+00	3.37E+00	3.36E+00	3.35E+00	3.05E+07	A	1.10E-07	2.99E+00	2.65E+00	6.08E-01	1.95E-03	1.19E-19
IN112	1.43E-02	1.69E+00	1.61E+00	1.04E+00	3.99E-01	9.41E-02	3.60E+09	B	2.89E-10	1.50E-15	1.34E-30	0.00E+00	0.00E+00	0.00E+00
IN114	8.33E-04	3.38E+00	1.90E+00	1.04E-02	9.83E-08	2.86E-15	1.57E+09	A	6.62E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IN115M	1.87E-01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.66E+08	A	1.02E-08	1.55E+00	1.35E+00	2.09E-01	1.43E-04	3.72E-25
IN116M	3.92E-03	3.38E+00	1.81E-01	6.44E-13	0.00E+00	0.00E+00	4.30E+05	A	1.50E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IN117	3.04E-02	1.69E+00	1.66E+00	1.44E+00	1.05E+00	6.57E-01	8.20E+07	A	1.76E-08	2.00E-05	2.38E-10	0.00E+00	0.00E+00	0.00E+00
SN113	1.15E+02	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.20E+06	A	1.06E-06	3.37E+00	3.36E+00	3.24E+00	2.81E+00	1.12E+00
SB113	4.63E-03	3.38E+00	3.05E+00	1.21E+00	1.55E-01	7.07E-03	4.30E+05	D	2.81E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SB115	2.23E-02	8.45E+00	8.27E+00	6.79E+00	4.39E+00	2.28E+00	5.30E+07	B	1.28E-07	1.29E-06	1.98E-13	0.00E+00	0.00E+00	0.00E+00
SB116	1.10E-02	5.07E+00	4.85E+00	3.24E+00	1.33E+00	3.46E-01	2.20E+07	B	1.47E-07	5.27E-14	5.49E-28	0.00E+00	0.00E+00	0.00E+00
SB117	1.17E-01	2.37E+01	2.36E+01	2.32E+01	2.21E+01	2.03E+01	2.97E+08	A	7.81E-08	1.56E+00	7.99E-02	2.60E-17	0.00E+00	0.00E+00
SB118	2.50E-03	2.20E+01	2.04E+01	1.47E+01	1.35E+01	1.35E+01	4.30E+05	D	3.42E-05	1.28E+01	1.20E+01	6.02E+00	4.02E-01	9.04E-09
SB119	1.59E+00	2.20E+01	2.20E+01	2.20E+01	2.19E+01	2.19E+01	2.10E+08	C	1.05E-07	2.02E+01	1.78E+01	1.60E+00	5.62E-05	0.00E+00
SB120	1.10E-02	1.52E+01	1.46E+01	9.83E+00	4.11E+00	1.11E+00	7.60E+06	B	1.29E-06	3.49E-13	8.00E-27	0.00E+00	0.00E+00	0.00E+00
SB122	2.70E+00	3.38E+00	3.38E+00	3.37E+00	3.36E+00	3.34E+00	5.84E+06	A	5.77E-07	2.98E+00	2.62E+00	5.67E-01	1.44E-03	1.95E-20
SB124	6.02E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.31E+06	A	1.29E-06	1.68E+00	1.67E+00	1.56E+00	1.19E+00	2.06E-01
SB125	9.96E+02	5.02E+00	5.02E+00	5.02E+00	5.02E+00	5.02E+00	2.86E+06	A	1.76E-06	5.02E+00	5.02E+00	5.02E+00	5.02E+00	5.02E+00
TE117	4.29E-02	1.18E+01	1.17E+01	1.06E+01	8.41E+00	5.98E+00	4.30E+05	D	2.47E-05	3.31E-03	9.27E-07	0.00E+00	0.00E+00	0.00E+00
TE118	6.00E+00	1.35E+01	1.35E+01	1.35E+01	1.35E+01	1.35E+01	4.30E+05	D	3.14E-05	1.28E+01	1.20E+01	6.02E+00	4.01E-01	9.03E-09
TE119	6.69E-01	1.69E+01	1.69E+01	1.68E+01	1.66E+01	1.63E+01	4.20E+06	C	4.00E-06	1.02E+01	6.05E+00	1.20E-02	3.39E-13	0.00E+00
TE121	1.68E+01	2.70E+01	2.70E+01	2.70E+01	2.70E+01	2.70E+01	1.54E+06	A	1.75E-05	2.66E+01	2.60E+01	2.03E+01	7.72E+00	1.42E-02

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
TE125M	5.80E+01	7.76E-01	7.76E-01	7.76E-01	7.76E-01	7.76E-01	4.27E+05	A	1.82E-06	7.76E-01	7.76E-01	7.75E-01	7.72E-01	7.17E-01
TE127	3.90E-01	1.69E+00	1.69E+00	1.67E+00	1.63E+00	1.57E+00	9.78E+06	A	1.71E-07	6.94E-01	2.85E-01	6.56E-06	5.09E-24	0.00E+00
I119	1.33E-02	6.76E+00	6.63E+00	5.30E+00	2.77E+00	9.59E-01	8.50E+04	C	6.24E-05	4.88E-11	2.88E-22	0.00E+00	0.00E+00	0.00E+00
I120	5.63E-02	1.01E+01	1.01E+01	9.56E+00	8.44E+00	6.88E+00	2.00E+04	C	4.78E-04	2.84E-02	6.00E-05	0.00E+00	0.00E+00	0.00E+00
I121	8.83E-02	2.03E+01	2.02E+01	1.93E+01	1.74E+01	1.49E+01	1.00E+05	C	1.93E-04	4.16E-01	8.22E-03	2.88E-23	0.00E+00	0.00E+00
I122	2.52E-03	2.87E+01	2.58E+01	1.43E+01	1.17E+01	1.15E+01	1.10E+05	C	1.30E-04	7.84E+00	5.19E+00	3.61E-02	1.36E-10	0.00E+00
I123	5.50E-01	3.72E+01	3.72E+01	3.70E+01	3.67E+01	3.62E+01	6.60E+04	C	5.61E-04	2.16E+01	1.15E+01	5.35E-03	5.29E-16	0.00E+00
I124	4.18E+00	1.69E+01	1.69E+01	1.69E+01	1.68E+01	1.68E+01	1.30E+03	C	1.30E-02	1.55E+01	1.43E+01	5.25E+00	1.05E-01	9.18E-13
I125	6.01E+01	7.43E+01	7.43E+01	7.43E+01	7.43E+01	7.43E+01	1.10E+03	C	6.75E-02	7.42E+01	7.39E+01	6.92E+01	5.29E+01	9.16E+00
I126	1.30E+01	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.37E+00	5.80E+02	C	5.83E-03	3.29E+00	3.20E+00	2.33E+00	6.68E-01	2.00E-04
I128	1.74E-02	3.38E+00	3.29E+00	2.56E+00	1.47E+00	6.40E-01	2.10E+05	C	1.22E-05	7.23E-09	1.55E-17	0.00E+00	0.00E+00	0.00E+00
I129	5.73E+09	8.85E-06	8.85E-06	8.85E-06	8.85E-06	8.85E-06	1.60E+02	C	5.53E-08	8.85E-06	8.85E-06	8.85E-06	8.85E-06	8.85E-06
I130	5.15E-01	1.69E+00	1.69E+00	1.67E+00	1.64E+00	1.60E+00	7.20E+03	C	2.32E-04	8.64E-01	4.42E-01	1.41E-04	3.11E-18	0.00E+00
XE119	4.03E-03	3.38E+00	3.01E+00	1.06E+00	1.06E-01	3.30E-03	4.30E+05	D	2.47E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
XE120	2.78E-02	3.38E+00	3.34E+00	2.88E+00	2.04E+00	1.21E+00	4.30E+05	D	6.70E-06	1.31E-05	4.99E-11	0.00E+00	0.00E+00	0.00E+00
XE121	2.78E-02	1.69E+00	1.66E+00	1.41E+00	9.89E-01	5.79E-01	4.30E+05	D	3.28E-06	4.38E-06	1.14E-11	0.00E+00	0.00E+00	0.00E+00
XE122	8.38E-01	1.18E+01	1.18E+01	1.18E+01	1.16E+01	1.14E+01	1.05E+06	A	1.12E-05	7.82E+00	5.17E+00	3.60E-02	1.35E-10	0.00E+00
XE123	8.67E-02	2.03E+01	2.02E+01	1.95E+01	1.76E+01	1.49E+01	9.92E+04	A	1.97E-04	3.81E-01	6.98E-03	9.89E-24	0.00E+00	0.00E+00
XE125	7.08E-01	5.74E+01	5.74E+01	5.72E+01	5.66E+01	5.57E+01	2.52E+05	A	2.27E-04	3.61E+01	2.23E+01	6.95E-02	1.13E-11	0.00E+00
XE127	3.64E+01	1.45E+02	1.45E+02	1.45E+02	1.45E+02	1.45E+02	2.39E+05	A	6.07E-04	1.45E+02	1.43E+02	1.28E+02	8.19E+01	4.50E+00
CS120	7.01E-04	1.69E+00	8.57E-01	1.91E-03	2.45E-09	3.54E-18	4.30E+05	D	4.44E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS123	4.08E-03	8.45E+00	7.67E+00	2.93E+00	2.86E-01	8.28E-03	4.30E+05	D	6.81E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS124	3.56E-04	1.86E+01	8.42E+00	2.75E+00	7.36E-01	1.02E-01	4.30E+05	D	6.40E-06	1.22E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CS125	3.13E-02	2.03E+01	2.00E+01	1.75E+01	1.29E+01	8.10E+00	6.20E+06	B	2.82E-06	3.12E-04	4.76E-09	0.00E+00	0.00E+00	0.00E+00
CS126	1.14E-03	5.41E+01	4.70E+01	3.24E+01	2.79E+01	2.27E+01	5.59E+06	A	5.80E-06	2.34E-01	1.59E-03	0.00E+00	0.00E+00	0.00E+00
CS127	2.60E-01	1.20E+02	1.20E+02	1.19E+02	1.15E+02	1.09E+02	1.00E+07	B	1.19E-05	3.23E+01	8.54E+00	9.85E-07	0.00E+00	0.00E+00
CS128	2.51E-03	1.88E+02	1.76E+02	1.31E+02	1.21E+02	1.20E+02	4.30E+05	D	3.05E-04	1.06E+02	9.16E+01	1.65E+01	2.07E-02	2.71E-21
CS129	1.34E+00	2.04E+02	2.04E+02	2.04E+02	2.04E+02	2.03E+02	1.07E+07	A	1.91E-05	1.67E+02	1.30E+02	5.91E+00	3.45E-05	0.00E+00
CS130	2.08E-02	3.89E+01	3.80E+01	3.08E+01	1.94E+01	9.67E+00	8.80E+06	B	3.50E-06	2.19E-06	1.24E-13	0.00E+00	0.00E+00	0.00E+00
CS131	9.69E+00	2.59E+02	2.59E+02	2.59E+02	2.58E+02	2.58E+02	1.75E+07	A	1.48E-05	2.58E+02	2.57E+02	2.33E+02	1.03E+02	3.02E-02
CS132	6.47E+00	6.76E+00	6.76E+00	6.75E+00	6.74E+00	6.73E+00	1.87E+06	A	3.61E-06	6.41E+00	6.07E+00	3.19E+00	2.60E-01	2.12E-08
CS136	1.32E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	3.35E+05	A	5.04E-06	1.65E+00	1.60E+00	1.16E+00	3.33E-01	9.83E-05
BA123	1.88E-03	1.69E+00	1.31E+00	1.30E-01	7.64E-04	3.46E-07	4.30E+05	D	3.02E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA124	8.22E-03	5.07E+00	4.75E+00	2.62E+00	7.00E-01	9.66E-02	4.30E+05	D	6.09E-06	1.16E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA125	2.43E-03	1.69E+00	1.39E+00	2.33E-01	4.44E-03	1.17E-05	4.30E+05	D	5.42E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BA126	6.96E-02	3.38E+01	3.36E+01	3.15E+01	2.75E+01	2.23E+01	4.50E+07	B	7.00E-07	2.30E-01	1.56E-03	0.00E+00	0.00E+00	0.00E+00
BA127	8.82E-03	6.25E+01	6.00E+01	3.92E+01	1.35E+01	2.64E+00	4.30E+05	D	9.12E-05	6.00E-16	5.15E-33	0.00E+00	0.00E+00	0.00E+00
BA128	2.43E+00	1.22E+02	1.22E+02	1.21E+02	1.21E+02	1.20E+02	9.70E+06	B	1.25E-05	1.06E+02	9.15E+01	1.65E+01	2.07E-02	2.71E-21
BA129	9.25E-02	1.61E+02	1.60E+02	1.55E+02	1.42E+02	1.22E+02	4.30E+05	D	3.60E-04	3.82E+00	8.70E-02	1.69E-21	0.00E+00	0.00E+00
BA131	1.18E+01	2.40E+02	2.40E+02	2.40E+02	2.40E+02	2.40E+02	3.27E+07	A	7.34E-06	2.34E+02	2.27E+02	1.61E+02	4.15E+01	6.22E-03
BA133	3.84E+03	8.11E+01	8.11E+01	8.11E+01	8.11E+01	8.11E+01	4.05E+06	A	2.00E-05	8.11E+01	8.11E+01	8.10E+01	8.07E+01	7.85E+01
BA136M	3.59E-06	2.70E-01	2.70E-01	2.70E-01	2.70E-01	2.70E-01	4.30E+05	D	6.28E-07	2.63E-01	2.56E-01	1.86E-01	5.33E-02	1.57E-05
LA126	6.94E-04	1.69E+00	8.45E-01	1.65E-03	1.57E-09	1.47E-18	4.30E+05	D	3.84E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA127	2.66E-03	1.69E+01	1.41E+01	2.73E+00	7.10E-02	2.99E-04	4.30E+05	D	6.35E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA128	3.47E-03	4.90E+01	4.26E+01	1.20E+01	7.28E-01	1.08E-02	4.30E+05	D	2.79E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA129	8.06E-03	8.28E+01	7.72E+01	4.14E+01	1.04E+01	1.29E+00	4.30E+05	D	9.63E-05	1.76E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA130	6.04E-03	1.22E+02	1.16E+02	7.55E+01	3.43E+01	1.32E+01	4.30E+05	D	1.76E-04	1.44E-07	3.09E-16	0.00E+00	0.00E+00	0.00E+00
LA131	4.10E-02	1.67E+02	1.66E+02	1.53E+02	1.23E+02	8.76E+01	6.60E+07	B	2.32E-06	4.85E-02	1.36E-05	0.00E+00	0.00E+00	0.00E+00
LA132	2.00E-01	1.61E+02	1.60E+02	1.59E+02	1.55E+02	1.50E+02	1.70E+07	B	9.35E-06	4.87E+01	1.05E+01	1.17E-08	0.00E+00	0.00E+00
LA133	1.63E-01	9.12E+01	9.12E+01	9.03E+01	8.82E+01	8.46E+01	4.30E+05	D	2.10E-04	1.59E+01	1.92E+00	1.58E-11	0.00E+00	0.00E+00
LA134	4.48E-03	1.17E+02	1.14E+02	1.01E+02	9.38E+01	9.24E+01	4.30E+05	D	2.35E-04	8.35E+01	7.49E+01	2.01E+01	1.18E-01	3.65E-16
LA135	8.13E-01	2.03E+02	2.03E+02	2.03E+02	2.03E+02	2.02E+02	3.90E+08	B	5.21E-07	1.85E+02	1.54E+02	2.71E+00	9.79E-09	0.00E+00
LA136	6.85E-03	2.20E+01	2.05E+01	1.09E+01	2.67E+00	3.25E-01	4.30E+05	D	2.53E-05	2.42E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LA137	2.19E+07	1.44E-01	1.44E-01	1.44E-01	1.44E-01	1.44E-01	1.50E+06	A	9.57E-08	1.44E-01	1.44E-01	1.44E-01	1.44E-01	1.44E-01
LA140	1.68E+00	1.69E+00	1.69E+00	1.68E+00	1.68E+00	1.66E+00	5.19E+06	A	3.24E-07	1.37E+00	1.12E+00	9.33E-02	5.76E-06	0.00E+00
CE130	9.99E-01	4.39E+01	4.27E+01	3.33E+01	1.91E+01	8.32E+00	4.30E+05	D	7.74E-05	9.41E-08	2.01E-16	0.00E+00	0.00E+00	0.00E+00
CE131	6.94E-03	6.76E+01	5.88E+01	1.69E+01	1.06E+00	1.65E-02	4.30E+05	D	3.93E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CE132	9.99E-01	8.96E+01	8.93E+01	8.68E+01	8.13E+01	7.36E+01	4.30E+05	D	2.02E-04	8.39E+00	7.84E-01	3.47E-13	0.00E+00	0.00E+00
CE133	2.04E-01	6.08E+01	6.05E+01	5.76E+01	5.03E+01	4.06E+01	4.30E+05	D	1.34E-04	3.64E-01	2.12E-03	0.00E+00	0.00E+00	0.00E+00
CE134	3.16E+00	9.29E+01	9.29E+01	9.28E+01	9.26E+01	9.22E+01	3.90E+06	B	2.38E-05	8.34E+01	7.47E+01	2.01E+01	1.18E-01	3.65E-16
CE135	7.37E-01	1.91E+02	1.91E+02	1.90E+02	1.89E+02	1.86E+02	1.50E+07	B	1.27E-05	1.22E+02	7.63E+01	2.76E-01	8.07E-11	0.00E+00
CE137	3.75E-01	4.14E+02	4.14E+02	4.14E+02	4.12E+02	4.09E+02	4.60E+08	B	9.00E-07	2.02E+02	8.02E+01	1.22E-03	1.87E-22	0.00E+00
CE139	1.38E+02	5.39E+02	5.39E+02	5.39E+02	5.39E+02	5.39E+02	3.78E+06	A	1.43E-04	5.38E+02	5.37E+02	5.21E+02	4.63E+02	2.14E+02
CE141	3.25E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	3.35E+06	A	5.04E-07	1.67E+00	1.65E+00	1.46E+00	8.83E-01	3.43E-02

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
CE142	1.83E+19	3.35E-10	3.35E-10	3.35E-10	3.35E-10	3.35E-10	4.30E+05	D	7.78E-16	3.35E-10	3.35E-10	3.35E-10	3.35E-10	3.35E-10
PR132	9.99E-01	2.20E+01	1.42E+01	2.89E-01	4.98E-05	1.13E-10	4.30E+05	D	6.72E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR133	4.51E-03	2.20E+01	1.97E+01	7.56E+00	8.96E-01	3.66E-02	4.30E+05	D	1.76E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PR134	1.18E-02	3.55E+01	3.41E+01	2.36E+01	1.04E+01	3.07E+00	1.20E+07	B	1.97E-06	6.32E-12	1.13E-24	0.00E+00	0.00E+00	0.00E+00
PR135	1.67E-02	1.37E+02	1.34E+02	1.11E+02	6.98E+01	3.25E+01	4.30E+05	D	2.58E-04	5.10E-07	1.50E-15	0.00E+00	0.00E+00	0.00E+00
PR136	9.10E-03	3.06E+02	2.97E+02	2.34E+02	1.50E+02	8.88E+01	2.30E+07	B	1.02E-05	1.00E-02	5.28E-07	0.00E+00	0.00E+00	0.00E+00
PR137	5.33E-02	3.85E+02	3.84E+02	3.73E+02	3.43E+02	2.90E+02	1.10E+08	B	3.39E-06	9.88E-01	1.49E-03	0.00E+00	0.00E+00	0.00E+00
PR138	1.01E-03	4.43E+02	4.01E+02	3.31E+02	3.16E+02	2.95E+02	4.30E+05	D	7.70E-04	6.50E+01	1.25E+01	3.10E-08	0.00E+00	0.00E+00
PR139	1.84E-01	5.34E+02	5.34E+02	5.32E+02	5.23E+02	4.99E+02	2.30E+08	B	2.31E-06	9.17E+01	1.39E+01	2.04E-09	0.00E+00	0.00E+00
PR140	2.35E-03	6.47E+02	6.42E+02	6.23E+02	6.18E+02	6.16E+02	4.30E+05	D	1.45E-03	5.61E+02	5.06E+02	1.47E+02	1.19E+00	2.87E-14
PR142	7.97E-01	3.38E+00	3.38E+00	3.36E+00	3.32E+00	3.26E+00	1.05E+07	A	3.20E-07	2.19E+00	1.42E+00	7.74E-03	1.13E-11	0.00E+00
PR143	1.36E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	3.92E+06	A	4.31E-07	1.65E+00	1.61E+00	1.18E+00	3.57E-01	1.49E-04
ND135	8.56E-03	3.89E+01	3.67E+01	2.22E+01	7.27E+00	1.36E+00	4.30E+05	D	5.16E-05	1.29E-16	4.25E-34	0.00E+00	0.00E+00	0.00E+00
ND136	3.52E-02	1.40E+02	1.39E+02	1.23E+02	9.39E+01	6.23E+01	1.10E+08	B	1.12E-06	7.45E-03	3.92E-07	0.00E+00	0.00E+00	0.00E+00
ND137	2.67E-02	2.62E+02	2.59E+02	2.24E+02	1.57E+02	9.13E+01	4.30E+05	D	5.21E-04	6.31E-04	1.48E-09	0.00E+00	0.00E+00	0.00E+00
ND138	2.10E-01	3.35E+02	3.34E+02	3.29E+02	3.14E+02	2.94E+02	2.60E+07	B	1.27E-05	6.47E+01	1.24E+01	3.09E-08	0.00E+00	0.00E+00
ND139	2.06E-02	4.90E+02	4.86E+02	4.27E+02	2.82E+02	1.40E+02	1.00E+08	B	4.27E-06	2.87E-05	1.45E-12	0.00E+00	0.00E+00	0.00E+00
ND140	3.37E+00	6.20E+02	6.20E+02	6.19E+02	6.18E+02	6.15E+02	4.30E+05	D	1.44E-03	5.60E+02	5.05E+02	1.47E+02	1.19E+00	2.87E-14
ND141	1.04E-01	7.72E+02	7.72E+02	7.66E+02	7.39E+02	6.73E+02	3.49E+09	A	2.19E-07	3.30E+01	1.18E+00	5.34E-18	0.00E+00	0.00E+00
ND147	1.10E+01	3.38E+00	3.38E+00	3.38E+00	3.37E+00	3.37E+00	4.57E+06	A	7.40E-07	3.27E+00	3.17E+00	2.17E+00	4.95E-01	3.31E-05
PM136	1.24E-03	3.72E+01	2.52E+01	7.62E-01	3.21E-04	2.77E-09	4.30E+05	D	1.77E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM137	1.67E-03	1.05E+02	7.85E+01	5.83E+00	1.81E-02	3.12E-06	4.30E+05	D	1.36E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM138	1.16E-04	1.88E+02	1.55E+02	2.71E+01	5.44E-01	1.48E-03	4.30E+05	D	6.30E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM139	2.88E-03	3.41E+02	3.04E+02	8.58E+01	3.38E+00	2.28E-02	4.30E+05	D	2.00E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM140	1.06E-04	5.10E+02	2.26E+02	1.46E+02	5.71E+01	1.40E+01	4.30E+05	D	3.40E-04	4.73E-13	9.58E-28	0.00E+00	0.00E+00	0.00E+00
PM141	1.45E-02	6.91E+02	6.82E+02	5.80E+02	3.51E+02	1.42E+02	6.20E+07	B	9.35E-06	4.64E-08	1.98E-18	0.00E+00	0.00E+00	0.00E+00
PM142	4.69E-04	8.43E+02	7.35E+02	6.22E+02	5.13E+02	3.85E+02	4.30E+05	D	1.45E-03	7.00E-01	7.19E-04	0.00E+00	0.00E+00	0.00E+00
PM143	2.65E+02	9.26E+02	9.26E+02	9.26E+02	9.26E+02	9.26E+02	3.95E+06	A	2.34E-04	9.25E+02	9.24E+02	9.09E+02	8.55E+02	5.74E+02
PM144	3.63E+02	7.27E+01	7.27E+01	7.27E+01	7.27E+01	7.27E+01	6.84E+05	A	1.06E-04	7.26E+01	7.26E+01	7.17E+01	6.84E+01	5.06E+01
PM145	6.46E+03	6.22E+02	6.22E+02	6.22E+02	6.22E+02	6.22E+02	1.06E+06	A	5.87E-04	6.22E+02	6.22E+02	6.22E+02	6.23E+02	6.27E+02
PM146	2.02E+03	7.76E+00	7.76E+00	7.76E+00	7.76E+00	7.76E+00	2.59E+05	A	3.00E-05	7.76E+00	7.76E+00	7.74E+00	7.68E+00	7.29E+00
PM147	9.56E+02	8.41E+00	8.41E+00	8.41E+00	8.41E+00	8.41E+00	8.41E+05	A	1.00E-05	8.41E+00	8.41E+00	8.38E+00	8.26E+00	7.40E+00
PM148	5.37E+00	6.76E+00	6.76E+00	6.75E+00	6.74E+00	6.72E+00	2.78E+06	A	2.43E-06	6.34E+00	5.94E+00	2.74E+00	1.33E-01	3.80E-10
PM150	1.12E-01	3.38E+00	3.36E+00	3.24E+00	2.97E+00	2.61E+00	9.86E+07	A	3.29E-08	1.52E-01	6.81E-03	4.49E-19	0.00E+00	0.00E+00
PM153	3.75E-03	1.69E+00	1.49E+00	4.68E-01	3.59E-02	7.64E-04	1.66E+07	A	2.82E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM138	2.08E-03	5.07E+00	4.02E+00	5.03E-01	4.94E-03	4.83E-06	4.30E+05	D	1.17E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM139	1.78E-03	1.13E+02	8.58E+01	7.08E+00	2.76E-02	6.75E-06	4.30E+05	D	1.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM140	1.03E-02	2.31E+02	2.21E+02	1.45E+02	5.65E+01	1.38E+01	4.30E+05	D	3.37E-04	4.69E-13	9.48E-28	0.00E+00	0.00E+00	0.00E+00
SM141	7.08E-03	4.11E+02	3.87E+02	2.11E+02	5.43E+01	7.07E+00	6.20E+07	B	3.40E-06	2.36E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM142	5.04E-02	6.78E+02	6.71E+02	6.16E+02	5.09E+02	3.82E+02	3.80E+07	B	1.62E-05	6.92E-01	7.12E-04	0.00E+00	0.00E+00	0.00E+00
SM143	6.13E-03	7.87E+02	7.56E+02	4.37E+02	9.44E+01	8.97E+00	4.30E+05	D	1.02E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SM145	3.40E+02	1.08E+03	1.08E+03	1.08E+03	1.08E+03	1.08E+03	2.80E+06	B	3.86E-04	1.08E+03	1.08E+03	1.07E+03	1.03E+03	7.53E+02
SM147	3.87E+13	1.85E-07	1.85E-07	1.85E-07	1.85E-07	1.85E-07	4.03E+02	A	4.58E-10	1.85E-07	1.85E-07	1.85E-07	1.85E-07	1.85E-07
SM151	3.24E+04	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	9.86E+05	A	1.03E-06	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00
SM153	1.95E+00	1.69E+00	1.69E+00	1.69E+00	1.68E+00	1.67E+00	1.66E+07	A	1.02E-07	1.42E+00	1.19E+00	1.40E-01	3.30E-05	0.00E+00
EU141	4.63E-04	9.46E+01	3.35E+01	2.89E-03	2.69E-12	7.64E-26	4.30E+05	D	6.72E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU142	2.78E-05	2.74E+02	8.16E-06	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU143	1.83E-03	4.12E+02	3.35E+02	3.96E+01	2.16E-01	7.57E-05	4.30E+05	D	9.21E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU144	1.18E-04	6.61E+02	2.02E+02	4.85E+01	2.23E+00	2.20E-02	4.30E+05	D	1.13E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EU145	5.93E+00	9.64E+02	9.64E+02	9.64E+02	9.63E+02	9.61E+02	8.50E+06	B	1.13E-04	9.13E+02	8.62E+02	4.27E+02	2.76E+01	5.05E-07
EU146	4.59E+00	1.05E+03	1.05E+03	1.05E+03	1.05E+03	1.05E+03	5.60E+06	B	1.88E-04	1.03E+03	1.01E+03	8.39E+02	5.54E+02	6.18E+01
EU147	2.40E+01	8.91E+02	8.91E+02	8.91E+02	8.90E+02	8.90E+02	8.70E+06	B	1.02E-04	8.87E+02	8.81E+02	7.54E+02	3.55E+02	2.61E+00
EU148	5.45E+01	1.01E+02	1.01E+02	1.01E+02	1.01E+02	1.01E+02	1.90E+06	B	5.32E-05	1.01E+02	1.00E+02	9.27E+01	6.86E+01	9.69E+00
EU149	9.31E+01	9.32E+02	9.32E+02	9.32E+02	9.32E+02	9.32E+02	1.70E+07	B	5.48E-05	9.32E+02	9.31E+02	9.18E+02	8.08E+02	2.63E+02
EU150	1.25E+04	1.93E+01	1.93E+01	1.93E+01	1.93E+01	1.93E+01	1.06E+05	A	1.82E-04	1.93E+01	1.93E+01	1.93E+01	1.93E+01	1.93E+01
EU152	4.86E+03	1.49E+01	1.49E+01	1.49E+01	1.49E+01	1.49E+01	1.29E+05	A	1.16E-04	1.49E+01	1.49E+01	1.49E+01	1.49E+01	1.49E+01
EU154	3.14E+03	3.08E+00	3.08E+00	3.08E+00	3.08E+00	3.08E+00	1.10E+05	A	2.80E-05	3.08E+00	3.08E+00	3.07E+00	3.06E+00	2.96E+00
EU155	1.81E+03	1.68E+00	1.68E+00	1.68E+00	1.68E+00	1.68E+00	7.32E+05	A	2.30E-06	1.68E+00	1.68E+00	1.67E+00	1.64E+00	1.56E+00
EU156	1.52E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	2.45E+06	A	6.90E-07	1.65E+00	1.61E+00	1.23E+00	4.22E-01	4.03E-04
GD143	4.51E-04	9.80E+01	6.67E+01	2.08E+00	9.42E-04	9.05E-09	4.30E+05	A	4.84E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GD144	3.13E-03	2.18E+02	1.87E+02	4.67E+01	2.15E+00	2.11E-02	4.30E+05	A	1.09E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GD145	1.60E-02	4.31E+02	4.17E+02	3.14E+02	1.66E+02	6.40E+01	2.00E+07	B	1.57E-05	4.93E-08	5.63E-18	0.00E+00	0.00E+00	0.00E+00
GD146	4.83E+01	7.73E+02	7.73E+02	7.73E+02	7.73E+02	7.73E+02	7.50E+05	B	1.03E-03	7.68E+02	7.62E+02	6.99E+02	4.99E+02	5.59E+01
GD147	1.59E+00	7.06E+02	7.06E+02	7.05E+02	7.03E+02	6.98E+02	1.30E+07	B	5.42E-05	5.78E+02	4.65E+02	3.37E+01	1.20E-03	0.00E+00

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
GD148	2.72E+04	1.89E+02	1.89E+02	1.89E+02	1.89E+02	1.89E+02	3.41E+02	A	5.55E-01	1.89E+02	1.89E+02	1.89E+02	1.89E+02	1.88E+02
GD149	9.38E+00	8.36E+02	8.36E+02	8.36E+02	8.35E+02	8.35E+02	1.10E+07	B	7.60E-05	8.14E+02	7.86E+02	5.01E+02	8.65E+01	9.47E-04
GD150	6.53E+08	1.16E-02	1.16E-02	1.16E-02	1.16E-02	1.16E-02	4.30E+05	D	2.70E-08	1.16E-02	1.16E-02	1.16E-02	1.16E-02	1.16E-02
GD151	1.24E+02	1.31E+03	1.31E+03	1.31E+03	1.31E+03	1.31E+03	3.60E+06	B	3.64E-04	1.31E+03	1.31E+03	1.27E+03	1.11E+03	4.60E+02
GD152	3.94E+16	2.14E-10	2.14E-10	2.14E-10	2.14E-10	2.14E-10	4.68E+02	A	4.57E-13	2.14E-10	2.14E-10	2.14E-10	2.14E-10	2.14E-10
GD153	2.42E+02	1.61E+03	1.61E+03	1.61E+03	1.61E+03	1.61E+03	3.38E+06	A	4.76E-04	1.61E+03	1.61E+03	1.59E+03	1.49E+03	9.59E+02
TB146	9.26E-05	1.13E+02	1.86E+01	1.59E-06	0.00E+00	0.00E+00	4.30E+05	D	3.70E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TB147	6.83E-02	2.85E+02	2.83E+02	2.66E+02	2.30E+02	1.86E+02	2.60E+07	B	1.02E-05	1.63E+00	9.29E-03	0.00E+00	0.00E+00	0.00E+00
TB148	4.17E-02	6.68E+02	5.79E+02	1.08E+02	1.55E+00	1.93E-03	4.30E+05	D	2.51E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TB149	1.72E-01	6.90E+02	6.89E+02	6.76E+02	6.40E+02	5.89E+02	3.80E+06	B	1.78E-04	9.38E+01	1.26E+01	4.49E-10	0.00E+00	0.00E+00
TB150	1.45E-01	7.87E+02	7.85E+02	7.69E+02	7.24E+02	6.56E+02	2.00E+07	B	3.85E-05	7.33E+01	6.72E+00	2.32E-12	0.00E+00	0.00E+00
TB151	7.34E-01	1.19E+03	1.19E+03	1.19E+03	1.18E+03	1.16E+03	2.60E+07	B	4.58E-05	7.53E+02	4.70E+02	1.61E+00	3.86E-10	0.00E+00
TB152	7.29E-01	1.59E+03	1.59E+03	1.59E+03	1.58E+03	1.57E+03	4.30E+05	D	3.70E-03	1.10E+03	6.90E+02	2.30E+00	4.84E-10	0.00E+00
TB153	2.34E+00	1.54E+03	1.54E+03	1.54E+03	1.54E+03	1.54E+03	3.30E+07	B	4.67E-05	1.42E+03	1.25E+03	2.06E+02	1.77E-01	1.98E-21
TB154	8.96E-01	2.35E+02	2.35E+02	2.34E+02	2.31E+02	2.27E+02	1.20E+07	B	1.95E-05	1.59E+02	1.08E+02	1.02E+00	1.24E-08	0.00E+00
TB155	5.32E+00	1.70E+03	1.70E+03	1.70E+03	1.70E+03	1.70E+03	3.70E+07	B	4.59E-05	1.67E+03	1.59E+03	7.40E+02	3.49E+01	8.28E-08
TB156	5.35E+00	6.08E+01	6.08E+01	6.08E+01	6.07E+01	6.05E+01	6.10E+06	B	9.97E-06	5.70E+01	5.34E+01	2.46E+01	1.18E+00	3.12E-09
TB157	3.59E+04	2.18E+02	2.18E+02	2.18E+02	2.18E+02	2.18E+02	3.16E+06	A	6.88E-05	2.18E+02	2.18E+02	2.18E+02	2.18E+02	2.18E+02
TB158	6.59E+04	1.79E+00	1.79E+00	1.79E+00	1.79E+00	1.79E+00	1.14E+05	A	1.57E-05	1.79E+00	1.79E+00	1.79E+00	1.79E+00	1.79E+00
DY148	2.15E-03	3.36E+02	2.79E+02	3.76E+01	4.30E-01	5.29E-04	4.30E+05	D	8.74E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DY149	2.94E-03	3.32E+02	2.93E+02	6.75E+01	2.33E+00	1.50E-02	4.30E+05	D	1.57E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DY150	4.98E-03	5.48E+02	5.06E+02	2.13E+02	3.05E+01	1.64E+00	6.16E+06	C	4.95E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DY151	1.24E-02	8.74E+02	8.51E+02	5.96E+02	2.63E+02	7.67E+01	2.10E+07	C	1.39E-03	1.35E-10	2.02E-23	0.00E+00	0.00E+00	0.00E+00
DY152	9.88E-02	1.24E+03	1.24E+03	1.19E+03	1.08E+03	9.32E+02	4.30E+05	D	2.77E-03	3.73E+01	1.12E+00	5.63E-19	0.00E+00	0.00E+00
DY153	2.66E-01	1.26E+03	1.26E+03	1.24E+03	1.20E+03	1.13E+03	4.30E+05	D	2.88E-03	3.37E+02	8.99E+01	1.15E-05	0.00E+00	0.00E+00
DY154	1.04E+09	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03	4.30E+05	D	7.78E-09	3.35E-03	3.35E-03	3.35E-03	3.35E-03	3.35E-03
DY155	4.17E-01	1.57E+03	1.57E+03	1.56E+03	1.55E+03	1.52E+03	5.00E+07	B	3.12E-05	7.30E+02	3.18E+02	1.46E-02	1.71E-19	0.00E+00
DY157	3.39E-01	1.62E+03	1.62E+03	1.61E+03	1.59E+03	1.55E+03	1.25E+08	A	1.29E-05	6.08E+02	2.16E+02	9.02E-04	8.84E-25	0.00E+00
DY159	1.44E+02	1.31E+03	1.31E+03	1.31E+03	1.31E+03	1.31E+03	1.36E+07	A	9.63E-05	1.31E+03	1.31E+03	1.27E+03	1.13E+03	5.45E+02
H0150	1.02E-03	1.40E+02	5.26E+01	4.54E-03	4.23E-12	1.20E-25	4.30E+05	D	1.06E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H0151	4.07E-04	4.16E+02	2.30E+02	1.41E-01	3.19E-09	9.46E-21	4.30E+05	D	3.28E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H0152	1.88E-03	6.20E+02	3.68E+02	3.58E+00	1.00E-04	1.69E-11	4.30E+05	D	8.33E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H0153	1.39E-03	7.01E+02	5.35E+02	2.62E+01	2.56E-02	7.82E-07	4.30E+05	D	6.09E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H0154	8.22E-03	1.02E+03	9.83E+02	6.41E+02	2.06E+02	3.56E+01	4.30E+05	D	1.49E-03	5.18E-16	2.23E-34	0.00E+00	0.00E+00	0.00E+00
H0155	3.33E-02	1.19E+03	1.18E+03	1.07E+03	8.20E+02	5.38E+02	7.90E+07	B	1.35E-05	4.74E-02	1.79E-06	0.00E+00	0.00E+00	0.00E+00
H0156	3.89E-02	1.34E+03	1.14E+03	5.40E+02	2.56E+02	8.82E+01	4.30E+05	D	1.26E-03	5.71E-09	4.39E-20	0.00E+00	0.00E+00	0.00E+00
H0157	8.75E-03	1.45E+03	1.42E+03	1.18E+03	7.35E+02	3.35E+02	1.00E+08	B	1.18E-05	1.88E-06	1.75E-15	0.00E+00	0.00E+00	0.00E+00
H0158	7.64E-03	1.62E+03	1.60E+03	1.46E+03	1.26E+03	1.07E+03	4.30E+05	D	3.40E-03	4.45E+01	1.39E+00	1.19E-18	0.00E+00	0.00E+00
H0159	2.30E-02	1.28E+03	1.27E+03	1.24E+03	1.12E+03	8.63E+02	1.10E+08	B	1.13E-05	1.19E-02	1.42E-08	0.00E+00	0.00E+00	0.00E+00
H0160	9.99E-01	1.15E+03	1.15E+03	1.13E+03	1.11E+03	1.09E+03	4.30E+05	D	2.63E-03	8.30E+02	6.20E+02	1.88E+01	2.24E-05	0.00E+00
H0161	1.03E-01	9.80E+02	9.80E+02	9.78E+02	9.74E+02	9.63E+02	1.40E+09	B	6.99E-07	2.31E+02	2.33E+01	1.15E-12	0.00E+00	0.00E+00
H0162	1.04E-02	5.07E+00	4.84E+00	3.19E+00	1.27E+00	3.17E-01	3.10E+08	B	1.03E-08	1.80E-14	6.41E-29	0.00E+00	0.00E+00	0.00E+00
H0163	1.67E+06	4.14E+02	4.14E+02	4.14E+02	4.14E+02	4.14E+02	4.30E+05	D	9.63E-04	4.14E+02	4.14E+02	4.14E+02	4.14E+02	4.11E+02
ER151	2.72E-04	7.27E+01	1.24E+01	1.06E-06	0.00E+00	0.00E+00	4.30E+05	D	2.47E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ER152	1.17E-04	1.88E+02	1.51E+01	2.38E-06	0.00E+00	0.00E+00	4.30E+05	D	5.53E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ER153	4.29E-04	3.13E+02	1.50E+02	1.73E-02	2.64E-12	2.62E-27	4.30E+05	D	4.02E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ER154	2.56E-03	4.02E+02	3.34E+02	6.33E+01	1.57E+00	6.14E-03	4.30E+05	D	1.47E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ER155	3.68E-03	5.20E+02	4.57E+02	1.41E+02	1.03E+01	2.04E-01	4.30E+05	D	3.28E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ER156	1.35E-02	6.67E+02	6.44E+02	4.68E+02	2.30E+02	7.91E+01	4.30E+05	D	1.09E-03	5.13E-09	3.94E-20	0.00E+00	0.00E+00	0.00E+00
ER157	1.30E-02	9.07E+02	8.89E+02	7.11E+02	4.03E+02	1.69E+02	4.30E+05	D	1.65E-03	8.93E-07	8.33E-16	0.00E+00	0.00E+00	0.00E+00
ER158	9.38E-02	1.29E+03	1.29E+03	1.24E+03	1.13E+03	9.81E+02	4.30E+05	D	2.88E-03	4.09E+01	1.28E+00	1.09E-18	0.00E+00	0.00E+00
ER159	2.50E-02	1.13E+03	1.12E+03	1.03E+03	7.60E+02	4.40E+02	4.30E+05	D	2.40E-03	1.34E-03	1.28E-09	0.00E+00	0.00E+00	0.00E+00
ER160	1.19E+00	1.09E+03	1.09E+03	1.09E+03	1.08E+03	1.07E+03	4.30E+05	D	2.53E-03	8.17E+02	6.11E+02	1.86E+01	2.21E-05	0.00E+00
ER161	1.34E-01	9.50E+02	9.49E+02	9.43E+02	9.16E+02	8.56E+02	4.80E+07	B	1.96E-05	8.52E+01	6.54E+00	2.70E-13	0.00E+00	0.00E+00
ER163	5.21E-02	8.01E+02	8.01E+02	7.97E+02	7.83E+02	7.44E+02	4.30E+05	D	1.85E-03	2.52E+01	2.83E-01	0.00E+00	0.00E+00	0.00E+00
ER165	4.32E-01	1.11E+03	1.11E+03	1.11E+03	1.11E+03	1.11E+03	5.80E+08	B	1.91E-06	1.02E+03	8.55E+02	3.51E+01	8.17E-05	0.00E+00
TM154	9.38E-05	5.91E+01	1.44E-02	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM155	3.94E-04	1.22E+02	4.19E+01	2.84E-03	1.55E-12	1.98E-26	4.30E+05	D	6.60E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM156	9.72E-04	2.06E+02	1.23E+02	1.14E+00	3.48E-05	5.86E-12	4.30E+05	D	2.65E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM157	2.43E-03	2.89E+02	2.38E+02	4.21E+01	8.96E-01	2.78E-03	4.30E+05	D	9.79E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM158	2.79E-03	6.13E+02	5.34E+02	1.19E+02	3.80E+00	2.16E-02	4.30E+05	D	2.77E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM159	6.35E-03	7.15E+02	6.75E+02	3.78E+02	8.81E+01	8.93E+00	4.30E+05	D	8.79E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM160	6.53E-03	7.67E+02	7.34E+02	4.49E+02	1.14E+02	1.23E+01	4.30E+05	D	1.04E-03	3.15E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TM161	2.64E-02	8.14E+02	8.05E+02	6.90E+02	4.43E+02	2.22E+02	4.30E+05	D	1.60E-03	5.29E-05	3.16E-12	0.00E+00	0.00E+00	0.00E+00

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
TM162	1.51E-02	1.34E+03	1.33E+03	1.21E+03	8.74E+02	4.55E+02	2.90E+07	B	4.17E-05	8.79E-07	9.98E-17	0.00E+00	0.00E+00	0.00E+00
TM163	7.54E-02	7.70E+02	7.69E+02	7.49E+02	6.80E+02	5.68E+02	4.30E+05	D	1.74E-03	8.63E+00	8.94E-02	0.00E+00	0.00E+00	0.00E+00
TM164	1.39E-03	1.38E+03	1.35E+03	1.22E+03	1.02E+03	7.74E+02	4.30E+05	D	2.84E-03	1.85E+00	2.56E-03	0.00E+00	0.00E+00	0.00E+00
TM165	1.25E+00	1.10E+03	1.10E+03	1.10E+03	1.09E+03	1.08E+03	4.30E+05	D	2.56E-03	8.41E+02	6.38E+02	2.30E+01	5.36E-05	0.00E+00
TM166	3.24E-01	2.18E+03	2.18E+03	2.18E+03	2.18E+03	2.17E+03	1.90E+07	B	1.15E-04	2.04E+03	1.82E+03	3.19E+02	3.29E-01	1.24E-20
TM167	9.24E+00	1.98E+03	1.98E+03	1.98E+03	1.98E+03	1.98E+03	1.10E+07	B	1.80E-04	1.92E+03	1.85E+03	1.18E+03	2.04E+02	2.23E-03
TM168	9.31E+01	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	4.30E+05	D	7.86E-06	3.37E+00	3.35E+00	3.21E+00	2.69E+00	8.66E-01
YB155	1.98E-05	2.03E+01	2.85E-03	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB156	3.02E-04	4.06E+01	8.15E+00	1.41E-06	0.00E+00	0.00E+00	4.30E+05	D	3.28E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB157	4.47E-04	1.20E+02	4.85E+01	8.95E-04	2.12E-14	2.46E-30	4.30E+05	D	2.08E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB158	1.15E-03	1.52E+02	8.10E+01	2.79E-01	9.39E-07	5.79E-15	4.30E+05	D	6.49E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB159	9.72E-04	1.86E+02	1.60E+02	4.12E+01	2.02E+00	2.20E-02	4.30E+05	D	9.58E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB160	3.33E-03	3.41E+02	2.95E+02	8.05E+01	4.49E+00	5.89E-02	4.30E+05	D	1.87E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB161	2.92E-03	4.46E+02	3.78E+02	8.56E+01	3.16E+00	2.23E-02	4.30E+05	D	1.99E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB162	1.31E-02	1.01E+03	9.86E+02	7.23E+02	3.47E+02	1.15E+02	1.90E+08	B	3.81E-06	3.41E-09	1.12E-20	0.00E+00	0.00E+00	0.00E+00
YB163	7.67E-03	5.66E+02	5.31E+02	3.01E+02	8.49E+01	1.27E+01	4.30E+05	D	7.00E-04	9.50E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00
YB164	5.25E-02	1.27E+03	1.26E+03	1.19E+03	9.91E+02	7.54E+02	4.30E+05	D	2.77E-03	1.80E+00	2.49E-03	0.00E+00	0.00E+00	0.00E+00
YB165	6.88E-03	1.04E+03	1.02E+03	7.94E+02	3.57E+02	8.29E+01	4.30E+05	D	1.85E-03	1.93E-15	8.34E-34	0.00E+00	0.00E+00	0.00E+00
YB166	2.36E+00	2.15E+03	2.15E+03	2.14E+03	2.14E+03	2.12E+03	1.00E+07	B	2.14E-04	1.86E+03	1.60E+03	2.76E+02	2.84E-01	1.07E-20
YB167	1.22E-02	1.97E+03	1.97E+03	1.92E+03	1.70E+03	1.26E+03	1.70E+08	B	1.13E-05	1.89E-01	1.17E-05	0.00E+00	0.00E+00	0.00E+00
YB169	3.20E+01	1.87E+03	1.87E+03	1.87E+03	1.87E+03	1.87E+03	4.00E+06	A	4.68E-04	1.86E+03	1.86E+03	1.67E+03	1.01E+03	3.72E+01
LU162	9.51E-04	4.26E+02	2.60E+02	3.01E+00	1.51E-04	5.35E-11	4.30E+05	D	7.00E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LU164	2.18E-03	8.09E+02	6.50E+02	9.09E+01	1.15E+00	1.62E-03	4.30E+05	D	2.11E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LU165	7.45E-03	7.62E+02	7.19E+02	4.24E+02	1.31E+02	2.25E+01	4.30E+05	D	9.86E-04	3.27E-16	1.34E-34	0.00E+00	0.00E+00	0.00E+00
LU166	5.31E-03	2.02E+03	1.85E+03	7.98E+02	1.06E+02	4.93E+00	4.30E+05	D	1.86E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LU167	3.58E-02	1.90E+03	1.89E+03	1.74E+03	1.34E+03	8.95E+02	4.30E+05	D	4.05E-03	1.24E-01	7.69E-06	0.00E+00	0.00E+00	0.00E+00
LU168	3.82E-03	2.14E+03	2.11E+03	1.80E+03	1.12E+03	5.08E+02	4.30E+05	D	4.19E-03	1.12E-05	4.99E-14	0.00E+00	0.00E+00	0.00E+00
LU169	1.42E+00	1.84E+03	1.84E+03	1.84E+03	1.83E+03	1.81E+03	1.50E+07	B	1.23E-04	1.45E+03	1.13E+03	6.05E+01	6.46E-04	0.00E+00
LU170	2.00E+00	3.24E+03	3.24E+03	3.24E+03	3.24E+03	3.24E+03	7.20E+06	B	4.50E-04	3.11E+03	2.85E+03	4.32E+02	1.39E-01	0.00E+00
LU171	8.24E+00	2.40E+03	2.40E+03	2.40E+03	2.40E+03	2.40E+03	9.60E+06	B	2.50E-04	2.37E+03	2.31E+03	1.42E+03	1.96E+02	5.13E-04
LU172	6.70E+00	3.95E+03	3.95E+03	3.95E+03	3.95E+03	3.95E+03	5.10E+06	B	7.75E-04	3.95E+03	3.95E+03	3.93E+03	3.85E+03	3.30E+03
LU173	5.00E+02	1.68E+03	1.68E+03	1.68E+03	1.68E+03	1.68E+03	1.50E+06	B	1.12E-03	1.68E+03	1.68E+03	1.67E+03	1.62E+03	1.31E+03
LU174	1.21E+03	8.30E+00	8.30E+00	8.30E+00	8.30E+00	8.30E+00	8.92E+05	A	9.30E-06	8.30E+00	8.30E+00	8.27E+00	8.16E+00	7.48E+00
LU176	1.32E+13	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09	4.50E+04	A	4.33E-14	1.95E-09	1.95E-09	1.95E-09	1.95E-09	1.95E-09
HF159	6.48E-05	3.38E+00	2.01E-03	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF160	1.39E-04	6.76E+00	2.11E-01	6.00E-15	0.00E+00	0.00E+00	4.30E+05	D	1.40E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF161	1.97E-04	4.73E+01	5.52E+00	1.52E-09	0.00E+00	0.00E+00	4.30E+05	D	3.53E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF166	4.70E-03	1.34E+03	1.24E+03	4.98E+02	6.42E+01	2.98E+00	4.30E+05	D	1.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF167	1.42E-03	1.51E+03	1.27E+03	2.02E+02	1.97E+00	1.55E-03	4.30E+05	D	4.70E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF168	9.99E-01	1.87E+03	1.84E+03	1.52E+03	8.93E+02	4.01E+02	4.30E+05	D	3.53E-03	8.85E-06	3.93E-14	0.00E+00	0.00E+00	0.00E+00
HF169	2.25E-03	1.69E+03	1.57E+03	6.34E+02	4.90E+01	8.04E-01	4.30E+05	D	1.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HF170	6.67E-01	3.14E+03	3.14E+03	3.13E+03	3.10E+03	3.03E+03	2.10E+07	B	1.49E-04	1.88E+03	1.11E+03	2.11E+00	4.87E-11	0.00E+00
HF171	5.05E-01	2.36E+03	2.36E+03	2.35E+03	2.33E+03	2.29E+03	4.30E+05	D	5.47E-03	1.23E+03	6.17E+02	1.60E-01	1.58E-15	0.00E+00
HF172	6.83E+02	3.93E+03	3.93E+03	3.93E+03	3.93E+03	3.93E+03	1.10E+05	B	3.57E-02	3.93E+03	3.93E+03	3.90E+03	3.81E+03	3.27E+03
HF173	1.00E+00	1.66E+03	1.66E+03	1.66E+03	1.66E+03	1.66E+03	4.50E+07	B	3.69E-05	1.36E+03	9.77E+02	1.53E+01	1.35E-06	0.00E+00
HF175	7.00E+01	3.81E+03	3.81E+03	3.81E+03	3.81E+03	3.81E+03	6.35E+06	A	6.00E-04	3.80E+03	3.79E+03	3.57E+03	2.83E+03	6.26E+02
TA166	3.98E-04	5.73E+02	1.56E+02	1.30E-03	6.68E-15	7.81E-32	4.30E+05	D	3.02E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TA167	9.99E-01	7.67E+02	6.04E+02	7.03E+01	5.90E-01	4.54E-04	4.30E+05	D	1.63E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TA168	9.99E-01	1.19E+03	8.98E+02	6.97E+01	2.37E-01	4.73E-05	4.30E+05	D	1.62E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TA169	3.40E-03	1.15E+03	1.00E+03	2.88E+02	1.80E+01	2.81E-01	4.30E+05	D	6.70E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TA170	4.70E-03	2.74E+03	2.61E+03	1.39E+03	2.18E+02	1.06E+01	4.30E+05	D	3.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TA171	1.62E-02	2.14E+03	2.11E+03	1.79E+03	1.10E+03	4.72E+02	4.30E+05	D	4.16E-03	1.43E-06	7.11E-16	0.00E+00	0.00E+00	0.00E+00
TA172	2.56E-02	3.79E+03	3.78E+03	3.48E+03	2.54E+03	1.46E+03	2.50E+07	B	1.39E-04	6.26E-03	8.69E-09	0.00E+00	0.00E+00	0.00E+00
TA173	1.31E-01	1.57E+03	1.57E+03	1.55E+03	1.49E+03	1.37E+03	4.80E+07	B	3.23E-05	1.70E+02	1.74E+01	2.30E-11	0.00E+00	0.00E+00
TA174	4.92E-02	3.97E+03	3.96E+03	3.90E+03	3.61E+03	2.97E+03	4.90E+07	B	7.96E-05	2.47E+00	8.30E-04	0.00E+00	0.00E+00	0.00E+00
TA175	4.38E-01	3.79E+03	3.79E+03	3.78E+03	3.76E+03	3.69E+03	3.40E+07	B	1.11E-04	1.82E+03	8.24E+02	6.11E-02	4.56E-18	0.00E+00
TA176	3.37E-01	3.78E+03	3.78E+03	3.78E+03	3.77E+03	3.73E+03	1.50E+07	B	2.52E-04	1.85E+03	6.74E+02	2.90E-03	3.20E-24	0.00E+00
TA177	2.36E+00	3.62E+03	3.62E+03	3.62E+03	3.62E+03	3.62E+03	9.00E+07	B	4.02E-05	3.26E+03	2.82E+03	4.82E+02	4.92E-01	1.66E-20
TA178	6.47E-03	4.87E+03	4.86E+03	4.83E+03	4.80E+03	4.79E+03	2.00E+08	B	2.42E-05	4.72E+03	4.65E+03	3.83E+03	1.80E+03	1.32E+01
TA179	6.46E+02	4.79E+03	4.79E+03	4.79E+03	4.79E+03	4.79E+03	4.90E+06	A	9.78E-04	4.79E+03	4.78E+03	4.75E+03	4.64E+03	3.96E+03
TA182	1.15E+02	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	7.59E+05	A	2.23E-06	1.68E+00	1.68E+00	1.62E+00	1.41E+00	5.61E-01
TA183	5.10E+00	1.69E+00	1.69E+00	1.69E+00	1.68E+00	1.68E+00	5.95E+06	A	2.84E-07	1.58E+00	1.47E+00	6.40E-01	2.48E-02	1.65E-11
W165	5.90E-05	3.21E+01	1.30E-02	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W166	1.85E-04	1.25E+02	1.12E+01	7.82E-10	0.00E+00	0.00E+00	4.30E+05	D	1.82E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
W170	9.99E-01	1.54E+03	1.32E+03	2.77E+02	8.66E+00	4.78E-02	4.30E+05	D	6.44E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W171	9.99E-01	1.15E+03	1.06E+03	5.30E+02	1.14E+02	1.13E+01	4.30E+05	D	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W172	4.63E-03	3.07E+03	2.89E+03	1.16E+03	1.46E+02	6.57E+00	4.30E+05	D	2.70E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W173	9.99E-01	1.09E+03	1.04E+03	7.16E+02	3.09E+02	8.76E+01	4.30E+05	D	1.67E-03	7.98E-11	5.84E-24	0.00E+00	0.00E+00	0.00E+00
W174	2.04E-02	3.62E+03	3.59E+03	3.05E+03	1.90E+03	9.27E+02	4.30E+05	D	7.09E-03	1.31E-04	4.39E-12	0.00E+00	0.00E+00	0.00E+00
W175	2.36E-02	3.57E+03	3.56E+03	3.21E+03	2.22E+03	1.21E+03	4.30E+05	D	7.47E-03	1.73E-03	7.31E-10	0.00E+00	0.00E+00	0.00E+00
W176	9.63E-02	3.63E+03	3.63E+03	3.56E+03	3.26E+03	2.81E+03	8.60E+07	C	4.14E-05	1.02E+02	2.74E+00	3.84E-19	0.00E+00	0.00E+00
W177	9.38E-02	3.54E+03	3.54E+03	3.50E+03	3.30E+03	2.89E+03	4.90E+07	B	7.14E-05	9.82E+01	2.44E+00	1.30E-19	0.00E+00	0.00E+00
W178	2.16E+01	4.80E+03	4.80E+03	4.80E+03	4.80E+03	4.79E+03	1.10E+08	B	4.36E-05	4.72E+03	4.65E+03	3.83E+03	1.80E+03	1.32E+01
W179	2.60E-02	4.77E+03	4.77E+03	4.72E+03	4.36E+03	3.28E+03	8.40E+08	B	5.62E-06	2.29E-02	3.81E-08	0.00E+00	0.00E+00	0.00E+00
W179M	4.44E-03	3.33E+03	3.33E+03	3.18E+03	2.21E+03	8.91E+02	2.20E+08	C*	1.45E-05	7.57E-08	7.54E-19	0.00E+00	0.00E+00	0.00E+00
W181	1.21E+02	5.39E+03	5.39E+03	5.39E+03	5.39E+03	5.39E+03	1.74E+08	A	3.10E-05	5.39E+03	5.38E+03	5.22E+03	4.56E+03	1.90E+03
W183M	6.02E-05	8.96E-01	8.96E-01	8.95E-01	8.93E-01	8.90E-01	4.30E+05	D	2.08E-06	8.36E-01	7.80E-01	3.39E-01	1.32E-02	8.75E-12
W185	7.51E+01	6.76E+00	6.76E+00	6.76E+00	6.76E+00	6.76E+00	3.81E+07	A	1.77E-07	6.73E+00	6.70E+00	6.34E+00	5.10E+00	1.25E+00
W188	6.94E+01	1.69E+00	1.69E+00	1.69E+00	1.69E+00	1.69E+00	6.97E+06	A	2.42E-07	1.68E+00	1.67E+00	1.58E+00	1.25E+00	2.72E-01
RE170	9.26E-05	6.10E+02	4.15E+00	1.99E-20	0.00E+00	0.00E+00	4.30E+05	D	4.63E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE172	1.74E-04	1.96E+03	6.16E+02	2.61E-03	2.37E-15	2.11E-33	4.30E+05	D	6.07E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE174	1.60E-03	2.74E+03	2.20E+03	1.75E+02	5.43E-01	9.38E-05	4.30E+05	D	4.07E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE175	9.99E-01	2.88E+03	2.61E+03	7.54E+02	3.72E+01	4.05E-01	4.30E+05	D	1.75E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE176	3.94E-03	3.18E+03	2.96E+03	1.25E+03	1.11E+02	2.20E+00	1.30E+08	C	9.62E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE177	9.72E-03	3.16E+03	3.08E+03	2.19E+03	8.42E+02	1.91E+02	4.90E+07	B	4.47E-05	1.23E-12	4.07E-28	0.00E+00	0.00E+00	0.00E+00
RE178	9.17E-03	4.53E+03	4.46E+03	3.37E+03	1.32E+03	2.80E+02	2.90E+07	B	1.16E-04	2.50E-13	9.51E-30	0.00E+00	0.00E+00	0.00E+00
RE179	1.35E-02	4.61E+03	4.57E+03	4.01E+03	2.34E+03	8.53E+02	4.20E+06	C*	9.55E-04	7.06E-08	7.04E-19	0.00E+00	0.00E+00	0.00E+00
RE180	1.69E-03	5.00E+03	4.81E+03	3.66E+03	1.94E+03	7.44E+02	4.20E+07	C	8.71E-05	5.20E-07	5.35E-17	0.00E+00	0.00E+00	0.00E+00
RE181	8.33E-01	5.33E+03	5.33E+03	5.33E+03	5.32E+03	5.29E+03	2.10E+07	C	2.54E-04	3.82E+03	2.52E+03	1.67E+01	5.17E-08	0.00E+00
RE182	2.67E+00	5.47E+03	5.47E+03	5.47E+03	5.46E+03	5.45E+03	9.19E+06	B	5.95E-04	4.88E+03	3.93E+03	6.42E+01	1.37E-06	0.00E+00
RE183	7.00E+01	5.60E+03	5.60E+03	5.60E+03	5.60E+03	5.60E+03	1.50E+07	B	3.73E-04	5.60E+03	5.58E+03	5.27E+03	4.19E+03	9.47E+02
RE184	3.80E+01	1.30E+02	1.30E+02	1.30E+02	1.30E+02	1.30E+02	7.11E+06	A	1.83E-05	1.29E+02	1.28E+02	1.15E+02	7.47E+01	4.63E+00
RE186	3.78E+00	6.59E+01	6.58E+01	6.58E+01	6.56E+01	6.54E+01	9.49E+06	A	6.93E-06	6.01E+01	5.48E+01	1.82E+01	2.47E-01	1.75E-13
RE188	7.08E-01	5.07E+00	5.07E+00	5.05E+00	5.00E+00	4.93E+00	1.56E+07	A	3.24E-07	3.76E+00	2.95E+00	1.60E+00	1.26E+00	2.75E-01
RE190	2.15E-03	1.69E+00	1.35E+00	1.81E-01	2.06E-03	2.51E-06	4.30E+05	D	4.21E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RE192	1.85E-04	1.69E+00	1.26E-01	8.69E-12	0.00E+00	0.00E+00	4.30E+05	D	2.02E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS169	4.05E-05	8.45E+00	8.86E-06	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS170	8.22E-05	3.38E+01	9.67E-02	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS171	9.26E-05	1.33E+02	8.87E-01	1.33E-20	0.00E+00	0.00E+00	4.30E+05	D	3.09E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS172	2.20E-04	3.19E+02	3.93E+01	1.09E-07	0.00E+00	0.00E+00	4.30E+05	D	2.53E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS173	1.85E-04	5.44E+02	4.11E+01	2.85E-09	0.00E+00	0.00E+00	4.30E+05	D	6.63E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS174	5.09E-04	8.82E+02	3.54E+02	8.68E-02	8.15E-10	7.41E-22	4.30E+05	D	2.02E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS175	9.99E-01	1.24E+03	7.57E+02	8.79E+00	4.40E-04	1.56E-10	4.30E+05	D	2.04E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS176	2.08E-03	1.54E+03	1.27E+03	2.24E+02	4.77E+00	1.48E-02	4.30E+05	D	5.21E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS177	2.43E-03	1.70E+03	1.40E+03	2.35E+02	4.48E+00	1.18E-02	4.30E+05	D	5.47E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS178	3.53E-03	3.24E+03	2.88E+03	8.29E+02	5.18E+01	8.09E-01	4.30E+05	D	1.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS179	4.51E-03	3.66E+03	3.45E+03	1.74E+03	2.51E+02	1.08E+01	4.30E+05	D	4.05E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
OS180	1.49E-02	4.28E+03	4.21E+03	3.27E+03	1.72E+03	6.61E+02	5.90E+08	C	5.54E-06	4.62E-07	4.75E-17	0.00E+00	0.00E+00	0.00E+00
OS181	1.88E-03	4.83E+03	4.82E+03	4.64E+03	4.10E+03	3.37E+03	1.30E+08	C	3.57E-05	4.31E+01	3.72E-01	0.00E+00	0.00E+00	0.00E+00
OS182	9.21E-01	5.14E+03	5.14E+03	5.13E+03	5.10E+03	5.03E+03	1.80E+07	B	2.85E-04	3.56E+03	2.45E+03	2.67E+01	5.81E-07	0.00E+00
OS183	5.42E-01	3.43E+03	3.43E+03	3.42E+03	3.40E+03	3.35E+03	2.10E+07	C	1.63E-04	1.98E+03	1.08E+03	5.66E-01	5.40E-14	0.00E+00
OS183M	4.12E-01	2.19E+03	2.19E+03	2.19E+03	2.18E+03	2.15E+03	4.30E+05	D	5.09E-03	1.05E+03	4.53E+02	1.89E-02	1.48E-19	0.00E+00
OS185	9.36E+01	5.31E+03	5.31E+03	5.31E+03	5.31E+03	5.31E+03	4.38E+06	A	1.21E-03	5.30E+03	5.29E+03	5.07E+03	4.26E+03	1.38E+03
OS189M	2.00E-01	8.03E+02	8.03E+02	8.03E+02	8.03E+02	8.03E+02	9.86E+08	A	8.14E-07	8.00E+02	7.90E+02	5.84E+02	1.69E+02	5.31E-02
OS191	1.54E+01	1.69E+01	1.69E+01	1.69E+01	1.69E+01	1.69E+01	7.65E+06	A	2.21E-06	1.65E+01	1.62E+01	1.23E+01	4.29E+00	4.49E-03
OS193	1.27E+00	3.38E+00	3.38E+00	3.37E+00	3.34E+00	3.30E+00	1.48E+07	A	2.28E-07	2.58E+00	1.96E+00	7.51E-02	2.20E-07	0.00E+00
OS196	2.42E-02	1.69E+00	1.66E+00	1.39E+00	9.33E-01	5.15E-01	4.30E+05	D	3.23E-06	1.08E-06	6.97E-13	0.00E+00	0.00E+00	0.00E+00
IR172	9.99E-01	8.45E+00	2.01E-10	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR173	3.47E-05	1.35E+01	1.29E-05	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR174	4.63E-05	1.30E+02	4.64E-03	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR175	5.21E-05	3.12E+02	3.87E-01	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR176	9.99E-01	5.14E+02	2.84E+00	1.36E-20	0.00E+00	0.00E+00	4.30E+05	D	3.16E-26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR177	2.43E-04	8.70E+02	1.29E+02	2.34E-06	0.00E+00	0.00E+00	4.30E+05	D	5.44E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR178	1.39E-04	1.33E+03	9.28E+01	1.42E-06	0.00E+00	0.00E+00	4.30E+05	D	3.30E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR179	9.99E-01	1.74E+03	1.49E+03	3.18E+02	9.93E+00	5.49E-02	4.30E+05	D	7.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR180	1.04E-03	2.47E+03	1.72E+03	3.22E+01	3.14E-03	3.00E-09	3.00E+07	C	1.07E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR181	3.40E-03	3.18E+03	2.87E+03	8.58E+02	5.36E+01	8.38E-01	3.40E+07	C	2.52E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR182	1.04E-02	3.90E+03	3.79E+03	2.67E+03	1.07E+03	2.68E+02	5.60E+07	B	4.77E-05	1.52E-11	5.42E-26	0.00E+00	0.00E+00	0.00E+00

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
IR183	3.82E-02	4.38E+03	4.35E+03	4.03E+03	3.21E+03	2.21E+03	1.60E+07	C	2.52E-04	5.39E-01	6.18E-05	0.00E+00	0.00E+00	0.00E+00
IR184	1.26E-01	4.97E+03	4.96E+03	4.88E+03	4.62E+03	4.17E+03	2.40E+07	B	2.03E-04	3.37E+02	2.14E+01	9.37E-14	0.00E+00	0.00E+00
IR185	5.79E-01	4.87E+03	4.87E+03	4.85E+03	4.82E+03	4.76E+03	2.50E+07	C	1.94E-04	2.86E+03	1.58E+03	1.26E+00	1.01E-12	0.00E+00
IR186	6.93E-01	5.79E+03	5.79E+03	5.78E+03	5.76E+03	5.72E+03	1.30E+07	C	4.45E-04	3.92E+03	2.40E+03	6.29E+00	5.24E-10	0.00E+00
IR187	4.38E-01	7.12E+03	7.12E+03	7.11E+03	7.08E+03	7.03E+03	5.30E+07	C	1.34E-04	4.03E+03	1.85E+03	1.37E-01	1.03E-17	0.00E+00
IR188	1.73E+00	9.56E+03	9.56E+03	9.56E+03	9.56E+03	9.55E+03	9.90E+06	C	9.66E-04	9.42E+03	9.25E+03	6.61E+03	1.36E+03	4.31E-02
IR189	1.32E+01	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.60E+07	C	6.69E-04	1.06E+04	1.04E+04	7.65E+03	2.21E+03	6.95E-01
IR190	1.18E+01	3.28E+02	3.28E+02	3.28E+02	3.27E+02	3.27E+02	4.30E+06	A	7.63E-05	3.18E+02	3.09E+02	2.17E+02	5.47E+01	6.96E-03
IR192	7.38E+01	1.69E+02	1.69E+02	1.69E+02	1.69E+02	1.69E+02	1.22E+06	A	1.39E-04	1.68E+02	1.67E+02	1.58E+02	1.27E+02	3.06E+01
IR194	7.98E-01	7.43E+01	7.43E+01	7.39E+01	7.30E+01	7.17E+01	1.04E+07	A	7.11E-06	4.82E+01	3.12E+01	1.70E-01	2.44E-10	0.00E+00
IR195	1.04E-01	7.26E+01	7.23E+01	6.91E+01	6.25E+01	5.37E+01	1.90E+08	B	3.64E-07	1.95E+00	5.25E-02	7.34E-21	0.00E+00	0.00E+00
IR196	6.02E-04	4.22E+01	1.99E+01	1.44E+00	9.56E-01	5.28E-01	4.30E+05	D	3.35E-06	1.11E-06	7.14E-13	0.00E+00	0.00E+00	0.00E+00
IR197	4.03E-03	2.03E+01	1.89E+01	1.00E+01	2.45E+00	2.97E-01	4.30E+05	D	2.33E-05	2.01E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IR198	9.26E-05	1.01E+01	5.58E-02	2.67E-22	0.00E+00	0.00E+00	4.30E+05	D	6.21E-28	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT175	2.92E-05	1.95E+01	1.37E-06	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT176	9.99E-01	5.58E+01	8.85E-02	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT177	1.27E-04	1.28E+02	3.53E-01	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT178	2.43E-04	2.16E+02	3.08E+01	6.64E-07	0.00E+00	0.00E+00	4.30E+05	D	1.54E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT179	4.98E-04	3.66E+02	1.05E+02	1.24E-03	1.40E-14	5.33E-31	4.30E+05	D	2.88E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT180	6.02E-04	6.61E+02	2.88E+02	1.62E-01	9.65E-09	1.40E-19	4.60E+09	C	3.52E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT181	5.90E-04	1.17E+03	5.45E+02	3.70E-01	3.19E-08	7.72E-19	1.10E+09	C	3.36E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT182	1.81E-03	1.77E+03	1.40E+03	1.28E+02	6.20E-01	2.08E-04	4.30E+05	D	2.98E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT183	4.51E-03	2.30E+03	2.10E+03	8.16E+02	9.67E+01	3.94E+00	4.30E+05	D	1.90E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PT184	1.20E-02	2.93E+03	2.85E+03	2.00E+03	8.98E+02	2.70E+02	2.60E+07	C	7.69E-05	8.86E-10	2.63E-22	0.00E+00	0.00E+00	0.00E+00
PT185	4.92E-02	3.20E+03	3.18E+03	2.96E+03	2.44E+03	1.82E+03	1.60E+07	C	1.85E-04	2.87E+00	2.52E-03	0.00E+00	0.00E+00	0.00E+00
PT185M	9.99E-01	1.87E+02	1.87E+02	1.76E+02	1.26E+02	6.83E+01	4.30E+05	D	4.09E-04	6.52E-05	1.77E-11	0.00E+00	0.00E+00	0.00E+00
PT186	8.33E-02	4.65E+03	4.64E+03	4.49E+03	4.08E+03	3.46E+03	5.00E+07	C	8.98E-05	7.65E+01	1.20E+00	2.48E-22	0.00E+00	0.00E+00
PT187	9.79E-02	6.36E+03	6.35E+03	6.20E+03	5.71E+03	4.95E+03	3.60E+07	C	1.72E-04	1.93E+02	5.60E+00	1.97E-18	0.00E+00	0.00E+00
PT188	1.02E+01	8.93E+03	8.93E+03	8.93E+03	8.92E+03	8.91E+03	4.30E+06	C	2.08E-03	8.64E+03	8.35E+03	5.55E+03	1.13E+03	3.58E-02
PT189	4.54E-01	1.02E+04	1.02E+04	1.02E+04	1.00E+04	9.78E+03	3.80E+07	C	2.68E-04	4.87E+03	2.27E+03	2.32E-01	6.14E-17	0.00E+00
PT191	2.91E+00	1.31E+04	1.31E+04	1.31E+04	1.31E+04	1.31E+04	3.92E+07	A	3.34E-04	1.22E+04	1.09E+04	2.72E+03	1.21E+01	6.13E-15
PT193	1.85E+04	5.68E+03	5.68E+03	5.68E+03	5.68E+03	5.68E+03	1.36E+08	A	4.18E-05	5.68E+03	5.68E+03	5.68E+03	5.68E+03	5.64E+03
PT197	7.63E-01	5.52E+02	5.51E+02	5.48E+02	5.42E+02	5.32E+02	5.38E+07	A	1.02E-05	3.51E+02	2.23E+02	9.51E-01	5.31E-10	0.00E+00
PT197M	6.54E-02	1.01E+01	1.01E+01	9.92E+00	8.93E+00	7.26E+00	1.85E+08	A	5.36E-08	5.72E-02	2.89E-04	0.00E+00	0.00E+00	0.00E+00
PT199	2.14E-02	2.72E+02	2.66E+02	2.18E+02	1.39E+02	7.06E+01	1.90E+08	B	1.15E-06	2.50E-05	2.30E-12	0.00E+00	0.00E+00	0.00E+00
PT200	5.21E-01	1.95E+02	1.95E+02	1.93E+02	1.90E+02	1.85E+02	1.90E+07	B	1.02E-05	1.01E+02	5.21E+01	1.88E-02	6.86E-16	0.00E+00
PT201	1.74E-03	6.36E+01	4.82E+01	3.98E+00	1.55E-02	3.79E-06	4.30E+05	D	9.26E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU178	3.01E-05	1.18E+01	1.34E-06	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU179	8.68E-05	4.30E+01	1.34E-01	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU181	1.32E-04	1.98E+02	5.21E+00	2.14E-14	0.00E+00	0.00E+00	4.30E+05	D	4.98E-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU182	2.43E-04	3.96E+02	6.45E+01	2.88E-06	0.00E+00	0.00E+00	4.30E+05	D	6.70E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU183	4.86E-04	5.74E+02	2.18E+02	2.95E-02	7.39E-11	9.27E-24	4.30E+05	D	6.86E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU184	6.13E-04	9.34E+02	4.59E+02	4.29E-01	6.56E-08	3.92E-18	5.80E+07	C	7.40E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU185	3.01E-03	1.14E+03	9.66E+02	2.27E+02	9.02E+00	7.16E-02	5.10E+07	C	4.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU185M	9.99E-01	1.87E+02	1.81E+02	7.63E+01	9.94E+00	4.67E-01	4.30E+05	D	1.77E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU186	7.41E-03	2.42E+03	2.30E+03	1.31E+03	3.58E+02	5.13E+01	5.00E+07	C	2.62E-05	1.39E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU187	5.83E-03	3.98E+03	3.74E+03	1.93E+03	3.83E+02	3.32E+01	5.30E+07	C	3.64E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU188	6.13E-03	6.24E+03	5.93E+03	3.33E+03	7.28E+02	6.95E+01	4.30E+05	D	7.74E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU189	1.99E-02	4.24E+03	4.14E+03	3.33E+03	2.06E+03	9.96E+02	2.20E+07	C	1.51E-04	1.19E-04	3.34E-12	0.00E+00	0.00E+00	0.00E+00
AU189M	3.19E-03	3.70E+03	3.68E+03	2.64E+03	6.80E+02	6.58E+01	5.00E+07	C*	5.28E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU190	2.97E-02	1.00E+04	9.97E+03	9.23E+03	7.43E+03	5.02E+03	2.30E+07	C	4.01E-04	1.28E-01	1.11E-06	0.00E+00	0.00E+00	0.00E+00
AU191	1.32E-01	1.17E+04	1.17E+04	1.15E+04	1.11E+04	1.03E+04	5.90E+07	C	1.95E-04	1.03E+03	7.52E+01	1.74E-12	0.00E+00	0.00E+00
AU191M	1.06E-05	6.75E+03	6.67E+03	5.92E+03	4.48E+03	2.93E+03	5.90E+07	C*	1.00E-04	2.59E-01	9.77E-06	0.00E+00	0.00E+00	0.00E+00
AU192	2.06E-01	1.38E+04	1.38E+04	1.37E+04	1.35E+04	1.31E+04	2.00E+07	C	6.85E-04	5.43E+03	1.54E+03	1.35E-05	0.00E+00	0.00E+00
AU193	7.35E-01	1.55E+04	1.55E+04	1.55E+04	1.54E+04	1.53E+04	6.50E+07	B	2.38E-04	1.11E+04	7.01E+03	2.34E+01	4.94E-09	0.00E+00
AU194	1.58E+00	5.64E+03	5.64E+03	5.63E+03	5.60E+03	5.56E+03	1.77E+07	A	3.18E-04	4.72E+03	3.97E+03	1.02E+03	7.61E+02	7.60E+02
AU195	1.86E+02	2.25E+04	2.25E+04	2.25E+04	2.25E+04	2.25E+04	2.37E+06	A	9.49E-03	2.25E+04	2.25E+04	2.20E+04	2.01E+04	1.13E+04
AU195M	3.53E-04	4.54E+02	4.54E+02	4.49E+02	4.40E+02	4.25E+02	3.22E+08	A	1.39E-06	1.92E+02	8.01E+01	2.18E-03	3.27E-21	0.00E+00
AU196	6.18E+00	5.11E+03	5.11E+03	5.11E+03	5.10E+03	5.09E+03	1.30E+08	B	3.93E-05	4.83E+03	4.57E+03	2.33E+03	1.68E+02	6.38E-06
AU197M	9.03E-05	3.34E-01	3.34E-01	3.28E-01	2.95E-01	2.40E-01	4.30E+05	D	7.63E-07	1.89E-03	9.56E-06	0.00E+00	0.00E+00	0.00E+00
AU198	2.70E+00	6.74E+03	6.74E+03	6.73E+03	6.70E+03	6.67E+03	1.44E+07	A	4.67E-04	5.93E+03	5.21E+03	1.11E+03	2.70E+00	2.62E-17
AU199	3.14E+00	7.43E+03	7.43E+03	7.42E+03	7.40E+03	7.36E+03	1.85E+07	A	4.01E-04	6.66E+03	5.96E+03	1.59E+03	9.12E+00	2.42E-14
AU200	3.36E-02	5.00E+03	4.93E+03	4.36E+03	3.32E+03	2.23E+03	9.90E+07	B	4.40E-05	1.08E+02	5.57E+01	2.01E-02	7.33E-16	0.00E+00
AU201	1.81E-02	5.18E+03	5.05E+03	3.97E+03	2.33E+03	1.05E+03	5.10E+08	B	7.78E-06	2.39E-05	1.10E-13	0.00E+00	0.00E+00	0.00E+00

Nuclide ID	Half Life (days)	Time (s) INITIAL	6.00E+01 1 min.	6.00E+02 10 min.	1.80E+03 30 min.	3.60E+03 1 hour	Threshold (Cat 2)	TS	Fraction of Cat. 2	4.32E+04 12 hours	8.64E+04 1 day	6.05E+05 1 week	2.63E+06 1 month	1.58E+07 6 months
AU202	3.33E-04	1.21E+03	2.89E+02	7.16E-04	2.50E-16	0.00E+00	4.30E+05	D	1.67E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU203	6.13E-04	1.06E+03	4.82E+02	4.13E-01	6.31E-08	3.77E-18	4.30E+05	D	9.60E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AU204	4.61E-04	1.50E+02	5.29E+01	4.56E-03	4.25E-12	1.21E-25	4.30E+05	D	1.06E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG180	3.47E-05	8.45E+00	5.00E-06	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG181	4.17E-05	2.37E+01	2.27E-04	0.00E+00	0.00E+00	0.00E+00	4.30E+05	D	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG182	1.31E-04	3.55E+01	8.95E-01	3.68E-15	0.00E+00	0.00E+00	4.30E+05	D	8.56E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG183	1.02E-04	6.42E+01	5.69E-01	1.92E-19	0.00E+00	0.00E+00	4.30E+05	D	4.47E-25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG184	3.54E-04	1.20E+02	3.13E+01	1.53E-04	2.39E-16	5.17E-34	7.30E+07	C	2.10E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG185	5.67E-04	1.96E+02	8.24E+01	3.38E-02	1.01E-09	5.25E-21	2.20E+07	C	1.54E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG186	9.58E-04	5.12E+02	3.16E+02	3.93E+00	2.26E-04	9.89E-11	1.00E+08	C	3.93E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG187	1.67E-03	1.05E+03	7.96E+02	6.57E+01	2.57E-01	6.27E-05	7.30E+06	C	9.00E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG188	2.26E-03	2.40E+03	1.96E+03	2.95E+02	4.15E+00	6.89E-03	7.00E+07	C	4.21E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG189	5.28E-03	3.70E+03	3.44E+03	1.70E+03	3.45E+02	3.16E+01	4.30E+05	D	3.95E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HG190	1.39E-02	5.36E+03	5.20E+03	3.86E+03	1.93E+03	6.84E+02	1.10E+08	C	3.51E-05	7.97E-08	1.16E-18	0.00E+00	0.00E+00	0.00E+00
HG191	3.36E-02	6.75E+03	6.66E+03	5.92E+03	4.48E+03	2.93E+03	2.90E+07	C	2.04E-04	2.59E-01	9.77E-06	0.00E+00	0.00E+00	0.00E+00
HG192	2.03E-01	9.01E+03	9.00E+03	8.82E+03	8.43E+03	7.85E+03	7.40E+06	C	1.19E-03	1.63E+03	2.93E+02	3.36E-07	0.00E+00	0.00E+00
HG193	1.59E-01	1.05E+04	1.05E+04	1.02E+04	9.59E+03	8.72E+03	6.10E+05	C	1.67E-02	9.90E+02	9.19E+01	3.75E-11	0.00E+00	0.00E+00
HG194	1.90E+05	1.13E+03	1.13E+03	1.13E+03	1.13E+03	1.13E+03	1.90E+04	C	5.97E-02	1.13E+03	1.13E+03	1.13E+03	1.13E+03	1.13E+03
HG195	4.12E-01	1.75E+04	1.74E+04	1.73E+04	1.69E+04	1.63E+04	5.30E+05	C	3.26E-02	7.39E+03	3.08E+03	8.39E-02	1.26E-19	0.00E+00
HG197	2.67E+00	1.17E+05	1.17E+05	1.17E+05	1.16E+05	1.16E+05	1.80E+05	C	6.50E-01	1.03E+05	9.04E+04	1.91E+04	4.36E+01	2.95E-16
HG203	4.66E+01	8.32E+04	8.32E+04	8.32E+04	8.32E+04	8.31E+04	1.10E+05	C	7.56E-01	8.26E+04	8.20E+04	7.50E+04	5.30E+04	5.53E+03
HG205	3.61E-03	3.60E+03	3.15E+03	9.49E+02	6.60E+01	1.21E+00	4.30E+05	D	2.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL184	1.27E-04	3.38E+00	7.71E-02	1.29E-16	0.00E+00	0.00E+00	4.30E+05	D	3.00E-22	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL186	3.18E-04	1.18E+01	2.68E+00	4.19E-06	5.26E-19	0.00E+00	4.30E+05	D	9.74E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL188	8.19E-04	1.52E+02	8.49E+01	4.37E-01	3.57E-06	8.33E-14	4.30E+05	D	1.02E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL189	1.60E-03	3.53E+02	2.16E+02	2.52E+00	1.26E-04	4.47E-11	4.30E+05	D	5.86E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL190	1.81E-03	7.03E+02	5.40E+02	4.94E+01	2.39E-01	8.03E-05	4.30E+05	D	1.15E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL191	9.99E-01	8.97E+02	7.87E+02	2.39E+02	1.68E+01	3.12E-01	4.30E+05	D	5.56E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL192	7.50E-03	1.17E+03	1.09E+03	6.16E+02	1.71E+02	2.49E+01	4.30E+05	D	1.43E-03	1.00E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TL193	1.50E-02	1.49E+03	1.44E+03	1.07E+03	5.56E+02	2.07E+02	4.30E+05	D	2.49E-03	7.15E-08	3.42E-18	0.00E+00	0.00E+00	0.00E+00
TL194	2.29E-02	1.79E+03	1.75E+03	1.45E+03	9.54E+02	5.08E+02	6.80E+07	B	2.13E-05	4.85E-04	1.31E-10	0.00E+00	0.00E+00	0.00E+00
TL195	4.83E-02	2.02E+03	2.00E+03	1.83E+03	1.50E+03	1.11E+03	3.90E+07	B	4.69E-05	1.55E+00	1.19E-03	0.00E+00	0.00E+00	0.00E+00
TL195M	4.17E-05	2.03E+01	1.95E+01	1.33E+01	5.73E+00	1.61E+00	4.30E+05	D	3.09E-05	1.24E-12	7.55E-26	0.00E+00	0.00E+00	0.00E+00
TL196	7.67E-02	2.28E+03	2.27E+03	2.14E+03	1.89E+03	1.56E+03	2.60E+07	B	8.23E-05	2.48E+01	2.70E-01	0.00E+00	0.00E+00	0.00E+00
TL197	1.18E-01	2.62E+03	2.61E+03	2.51E+03	2.32E+03	2.05E+03	1.00E+08	B	2.51E-05	1.40E+02	7.50E+00	4.03E-15	0.00E+00	0.00E+00
TL198	2.21E-01	2.65E+03	2.65E+03	2.60E+03	2.48E+03	2.33E+03	2.20E+07	B	1.18E-04	5.52E+02	1.15E+02	7.56E-07	0.00E+00	0.00E+00
TL199	3.09E-01	2.43E+03	2.43E+03	2.40E+03	2.32E+03	2.22E+03	1.40E+08	B	1.71E-05	7.94E+02	2.59E+02	3.70E-04	0.00E+00	0.00E+00
TL200	1.09E+00	1.86E+03	1.86E+03	1.86E+03	1.84E+03	1.81E+03	2.67E+07	A	6.97E-05	1.35E+03	9.85E+02	2.15E+01	6.99E-06	0.00E+00
TL201	3.04E+00	1.32E+03	1.32E+03	1.32E+03	1.32E+03	1.31E+03	1.06E+08	A	1.25E-05	1.18E+03	1.05E+03	2.71E+02	1.35E+00	1.40E-15
TL202	1.22E+01	7.20E+02	7.20E+02	7.19E+02	7.19E+02	7.18E+02	2.40E+07	A	3.00E-05	7.00E+02	6.80E+02	4.84E+02	1.28E+02	2.27E-02

EXHIBIT C

INITIAL LOOK AT SNS SPALLATION PRODUCT TRANSPORT

EXHIBIT C. INITIAL LOOK AT SNS SPALLATION PRODUCT TRANSPORT

E. C. Beahm, Chemical Technology Division, Oak Ridge National Laboratory

I. General Comments About Chemical Reactions in Mercury

Liquid mercury can act like a solvent to promote the reaction of materials that are dissolved in it. The products of reaction may or may not contain mercury. For example, metals in mercury may react to form intermetallic compounds. These compounds may be the same as those that would form without mercury or they may contain mercury. Mercury could be used as a low temperature medium for making some metal alloys.

In a Hg spallation neutron source, the spallation products can react with each other and with mercury. The rare earth-mercury phase diagrams will be very similar (with the possible exception of europium). Thus, rare earth-mercury intermetallic compounds in the Hg source would most likely contain a variety of different rare earth elements: La, Nd, Gd, Sm, etc.

Material in mercury could be in different physical forms. It may be a true solution where the elements are "dissolved" in the liquid mercury and are in the liquid state (compare to salt dissolved in water). It could also be a suspension of solid particles in mercury. This form would occur when the solubility in mercury was exceeded or when a compound formed.

II. Iodine in a Hg Spallation Neutron Source

It is <u>not</u> likely that iodine in a Hg spallation neutron source would be in the form of unreacted elemental iodine. In pure mercury it would react to form mercurous iodide Hg_2I_2. However, iodine forms compounds with spallation products such as cesium, barium, and the rare earths that are much more stable than Hg_2I_2.

The question: What does iodine do in a Hg spallation neutron source that is sparged with He at 110°C can best be answered by looking at the iodides.

The vapor pressure of I_2 over Hg_2I_2 is very low. The value calculated at 110°C for the reaction $Hg_2I_2 = 2\ Hg + I_2$ (gas) was only $\sim 10^{-16}$ atmospheres. However, mercurous iodide Hg_2I_2 can dissociate into mercury and mercuric iodide, HgI_2:

$$Hg_2I_2 = Hg + HgI_2 \text{ (gas)} \ .$$

At 110°C the partial pressure of the HgI_2 (gas) was calculated as $\sim 7 \times 10^{-6}$ atm. This is still not very high, but some iodine could be lost. However, as noted, the spallation product iodides can be much more stable than the mercury iodides. The vapor pressure of iodine species over LaI_3 was calculated as $\sim 4 \times 10^{-27}$ atm at 110°C, and the vapor pressure over CsI was only $\sim 2 \times 10^{-19}$ atm at this temperature.

It should be noted that air would react with the iodides and convert them to oxides while releasing iodine as elemental iodine. This may be a concern in an accident situation. In summary, purging with He at 110°C could remove a small amount of iodine in the form of gaseous HgI_2. If equilibrium conditions prevail with the spallation products, iodine release should be very low. Mercuric iodide gas would be trapped in the off-gas system condenser. Its vapor pressure at –20°C is only $\sim 4 \times 10^{-11}$ atm.

III. Gadolinium and Hafnium Spallation Products

Hafnium and gadolinium are very reactive with oxygen. This is true of the other rare earths as well. This means that any oxygen in the He purge gas would be scavenged to form an oxide. Thus, depending on the purity of the He, hafnium and gadolinium could be in the mercury as metals or as the oxides HfO_2 or Gd_2O_3. The solubility of Gd in He at 100°C has been reported as 5×10^{-2} atom%.[1] Several rare earth-mercury compounds are known. As noted, these compounds would most likely contain a variety of rare earth elements.

There are no data available for the solubility of hafnium in mercury, but by comparison with zirconium, it is very low. A hafnium-mercury compound Hf_2Hg could form.

In summary, gadolinium could be in the form of an oxide; it could be dissolved in liquid mercury; or it could form an intermetallic compound that may or may not contain Hg. I can't conceive of any mechanism where it could be airborne at 110°C. The vapor pressure of Gd would be less than the vapor pressure of elemental Gd at this temperature, which is negligibly small. Hafnium could be in the form of an oxide or an intermetallic compound. Both gadolinium and hafnium will scavenge oxygen either during normal operation if the He gas (or surrounding gas) is not purified or during an accident.

IV. Iron

Iron does not form intermetallic compounds with mercury. It may form compounds with other spallation products. Iron is not soluble in mercury so it would be in the form of small crystallites of Fe or a non-Hg containing intermetallic compound. Most likely these crystallites (as well as those containing gadolinium or hafnium) would be dispersed in the mercury or at the upper surface. The density of the crystallites would be much less than that of mercury. If the mercury evaporated, iron should remain in the residue rather than enter the gas phase.

References

1. F. Messing and O. C. Dean, *Solubilities of Selected Metals in Mercury: Hermex Process*, ORNL-2871, Oak Ridge Natl. Lab., Union Carbide Corp., June 1960.

EXHIBIT D

MERCURY EVAPORATION IN AN SNS ACCIDENT

EXHIBIT D. MERCURY EVAPORATION IN AN SNS ACCIDENT

C. F. Weber, CP&E Division, ORNL

The following is an attempt to quantify the evaporation behavior of liquid mercury that is spilled in a hypothetical SNS accident in the splash/shielding enclosure, which is located inside the target hot cell. Because the design is still in the conceptual stage, it is impossible to even specify the problem exactly, let alone solve it. Hence, the present analysis is only preliminary, and very approximate.

One possibility is to use the Langmuir equation to analyze this problem. This approach involves a theoretical maximum rate of evaporation into a vacuum, and is always a gross over-exaggeration of the evaporation rate.[1] Benjamin[2] performed vacuum chamber experiments and found an actual rate of between 1×10^{-5} and 4×10^{-5} g · s^{-1} compared to the theoretical rate of 5.8×10^{-5} g · s^{-1} at 20°C. He also found that exposure to air or O_2 in the presence of water vapor produced an oxide surface film that reduced evaporation by several orders of magnitude. However, the Hg pool needs to be completely quiescent, as even the slightest motion or vibration can severely disrupt the oxide skin.

The Langmuir equation is, of course, bounding; however, its conservatism is unrealistic. To obtain an estimate more reflective of a well-ventilated room near atmospheric pressure, we turn to an approach involving molecular diffusion and interface mass transport. Assumptions regarding room and puddle geometry are somewhat arbitrary, so two different cases are examined.

1. Nominal Case

We assume a 2 × 2 m puddle of Hg on the floor of a rectangular room 3 m high and with floor area 4 × 8 m. Ventilation flow refreshes the room 5 times per hour, so the flow rate is 480 m^3/h. Assuming air flow is uniform and occurs exactly parallel to the longest room dimension (i.e., the 8-m edge), the gas superficial velocity is

$$v = \frac{480}{3 \times 4} = 40 \frac{m}{h} = 0.0111 \frac{m}{s} \quad .$$

This flow rate is painfully slow, and most mass transport is probably by molecular diffusion. However, it is possible that other factors could eventually alter this scenario, so we will develop a mass transfer coefficient approach.

The flux of Hg evaporating across the gas-liquid interface can be approximated as follows:

$$\text{Flux} = K (C_l - PC_g) \quad , \qquad (1)$$

where

K = overall mass transfer coefficient, $\frac{1}{K} = \frac{P}{k_g} + \frac{1}{k_l}$,

k_g, k_l = gas and liquid film coefficients (m/s),

P= partition coefficient (inverse Henry's Law Constant),
C_g, C_l = concentrations of Hg in gas and liquid (mol/m^3).

First, assume for now that $k_l = 0$, which implies no resistance to evaporation in the liquid. (If an oxide film needs to be considered, then k_l can be chosen to represent this.) We hope to establish a maximum reasonable evaporation rate. Hence, Eq. (1) becomes

$$\text{Flux} = \frac{k_g}{P}(C_l - PC_g) = k_g(\frac{C_l}{P} - C_g) = k_g\,(C_g^* - C_g) \quad , \tag{2}$$

where C_g^* = equilibrium concentration in gas phase.

The gas film coefficient is determined from a correlation for forced convection parallel to an infinite flat plate:

$$\frac{k_g L}{D} = .664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Sc}^{\frac{1}{3}}, \quad (\text{valid for } \mathrm{Re} < 2\times 10^4) \quad , \tag{3}$$

where L = characteristic length of flow,
D = binary diffusion coefficient,
Re = Lv/ν = Reynolds number,
Sc = ν/D = Schmidt number,
ν = kinematic viscosity.

Diffusion coefficients for many gas pairs have been correlated and can be estimated.[1] For Hg and air at 90°C, we get (see Sect. 3 for details):

$$D = 0.192\,\frac{cm^2}{s} = 1.92\times 10^{-5}\,\frac{m^2}{s} \quad .$$

Assuming the flow length is the length of the Hg puddle, we have L = 2 m. From ref. 3 (p. 388), for pure air at 90°C, $\nu = 2.195\times 10^{-5}\ m^2/s$. Hence, we have

$$\mathrm{Re} = 1011,\ \mathrm{Sc} = 1.14, \text{ and } K_g = 2.12\times 10^{-6}\,\frac{m}{s} \quad .$$

The equilibrium concentration C_g^* can be determined from vapor pressure data. From ref. 4, the vapor pressure of Hg in KPa is estimated to within 1% by:

$$\log_{10} P_{Hg} = 7.150 - \frac{3212.5}{T}, \quad T < 423\ K \quad .$$

Hence, at 90°C, $P_{Hg} = 0.200$ kPa $= 2 \times 10^{-4}$ bar. Then assuming an ideal gas, the equilibrium concentration is

$$C_g^* = \frac{n}{v} = \frac{P_{Hg}}{RT} = .0066 \text{ mol/m}^3 \quad .$$

Now, assume $C_g << C_g^*$, so that Eq. (2) can be written

$$\text{Flux} = k_g \, C_g^* = 1.4 \times 10^{-8} \text{ mol/m}^2 \cdot \text{s (at 90°C)} \quad . \qquad (4)$$

This is quite low, probably because the mass transfer coefficient is not reliably predicted using a forced convection correlation with such a low velocity flow. Using purely molecular diffusion, we have from Fick's law,

$$\text{Flux} = -D \frac{dC_g}{dy} \quad .$$

Assuming the concentration profile is $C_g = C_g^*$ at the puddle surface, and $C_g = 0$ at a height of 1 m, we then have

$$-\frac{dC_g}{dy} \cong \frac{C_g^*}{1 \text{ m}} = C_g^* \quad .$$

Hence, the flux is

$$\text{Flux} = D C_g^* = 1.3 \times 10^{-7} \text{ mol/m}^2 \cdot \text{s} \quad . \qquad (5)$$

Even though it is an order of magnitude larger than Eq. (4), this value is still quite small. For example, using a volume correlation in ref. 4 and standard density from ref. 5, we calculate that a cubic meter of Hg contains:

$$n_{TOT} = 68{,}600 \text{ mol} \quad .$$

With a puddle of surface area $A = 4$ m^2, the time for 1 m^3 of Hg to evaporate [assuming only molecular diffusion, i.e., Eq. (5)] is

$$t = \frac{68{,}600}{4(1.3 \times 10^{-7})} = 1.32 \text{ x } 10^{11} \text{ s} = 4180 \text{ years} \quad .$$

2. Parametric Sensitivity Analysis

The previous section involved a best-guess estimate of how a mercury puddle might evaporate in a hypothetical SNS accident. This section involves some parameter adjustments so as to construct an overly conservative scenario—a worse-than-worst-case estimate. The general formulation is the same as in the previous study, but we make the following parameter adjustments:

(1) Temperature = 110°C (instead of 90°). This is the maximum possible. Generally, higher temperatures increase mass transfer processes. In this case, the effect is slight.
(2) Area. Assume the puddle surface is the entire splash-shielding enclosure: 4 × 8 m. The floor geometry would probably not allow this, so it is unusually conservative.
(3) Gas flow rate. Assume a slow turbulent flow parallel to the puddle surface. The forced convection correlation assumes turbulent flow for $Re \geq 2 \times 10^4$, so we assume $Re = 2 \times 10^4$, which is probably unrealistically high. Considering the entire 8-m edge parallel to flow, this is consistent with an air velocity of 6 cm/s.

From Eq. (4), the evaporative flux of mercury is:

$$\text{Flux} = k_g C_g^* \quad .$$

The equilibrium gas concentration is again calculated from the ideal gas equation and the empirical vapor pressure equation:

$$C_g^* = \frac{P_{Hg}}{RT} = 0.0183 \frac{\text{mol}}{\text{m}^3} \quad .$$

The mass transfer coefficient in Eq. (3) refers to laminar flow. Here it is determined from a correlation for turbulent plane flow:

$$\frac{k_g L}{D} = .036\ Re^{0.8}\ Sc^{.33} \quad .$$

The characteristic length is now L = 8 m, and the kinematic viscosity of air at 110°C is $\nu = 2.4 \times 10^{-5}$ m^2/s. The diffusion coefficient is calculated as before (see the next section for details) to give $D = 2.12 \times 10^{-5}$ m^2/s. Hence, we have

$$Sc = \frac{\nu}{D} = 1.134 \quad ,$$

$$k_g = \frac{D}{L}(.036\ Re^{.8}\ Sc^{.33}) = 2.745 \times 10^{-4}\ \text{m s}^{-1} \quad .$$

With this flux operating over the area of 4 × 8 m, a puddle of 1 cubic meter (68,600 mol) is evaporated as follows:

$$t = \frac{68{,}600}{32(5.024 \times 10^{-6})} = 4.267 \times 10^{8}\,\text{s} = 13.52\ \text{years} \quad .$$

Thus, in spite of the overly conservative assumptions, this estimate is still a fairly long time.

3. Calculation of Diffusion Coefficient

Over the past 50 years, the kinetic theory of gases has been developed using classical statistical mechanics, and validated on numerous binary gas pairs. The usual approach involves the following assumptions:

(1) only binary (i.e., two-particle) collisions occur,
(2) particle motion is described by classical mechanics (no quantum effects),
(3) all collisions are elastic,
(4) molecular forces operate through fixed centers of mass, and
(5) the Lennard-Jones 6–12 potential represents the intermolecular potential energy.

The theory results in the following equation:[1]

$$D_{AB} = \frac{.001858\ T^{\frac{3}{2}}\left[\frac{1}{M_A} + \frac{1}{M_B}\right]^{\frac{1}{2}}}{P\,\sigma_{AB}^{2}\,\Omega} \quad , \qquad (6)$$

where D_{AB} = diffusion coefficient of A in B or B in A (cm^2/s),
T = temperature (K),
M_A, M_B = molecular weights (200.59 for Hg, 28.8 for air),
P = pressure (atm),
σ_{AB} = interparticle "distance" of closest approach (Å),
Ω = collision integral.

The last parameter accounts for all potential energy terms, and is a function of kT/ε, where k = Boltzmann's constant and ε is the energy parameter from the Lennard-Jones potential. For each component, ε and σ are determined by fitting thermodynamic data, and are known for a great many real gas species. For air and Hg, we have

	σ	$\frac{\varepsilon}{k}$
Air	3.711	78.6
Hg	2.969	750.0

.

The mixture quantities are then determined as follows:

$$\sigma_{Air\text{-}Hg} = \frac{1}{2}(\sigma_{Air} + \sigma_{Hg}) = 3.34 \quad ,$$

$$\left(\frac{\varepsilon}{k}\right)_{Air-Hg} = \frac{(\varepsilon_{Air}\,\varepsilon_{Hg})^{\frac{1}{2}}}{k} = 243 \quad .$$

For the case in Sect. 2, where T = 383 K, then $kT/\varepsilon = 1.576$, and $\Omega = 1.175$ can be obtained from tables.[1] Substituting each of these quantities into Eq. (6) yields

$$D_{Air\text{-}Hg} = 0.2117\ \frac{cm^2}{s} = 2.117 \times 10^{-5}\ \frac{m^2}{s} \quad .$$

References

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EXHIBIT E

SOURCE TERMS FOR THE ACCIDENT SEQUENCES IN CHAPTER 4

EXHIBIT E. SOURCE TERMS FOR THE ACCIDENT SEQUENCES IN CHAPTER 4

Source term for accident sequences 22, 29, 30 & 32		Source term for accident sequences 24 & 31		Source term for accident sequence 36		Source term for accident sequence 27		Source term for accident sequence 40	
List 1		List 2		List 3		List 4		List 5	
Nuclide	Ci/hr	Nuclide	Ci	Nuclide	Ci/y	Nuclide	Ci	Nuclide	Ci
H-3	4.58E-03	H-3	7.69E-01	H3	5.07E-01	H3	6.58E-02	H3	7.31E-02
Xe-119	1.87E+01	Xe-119	3.23E+00	BE7	3.84E-01	BE7	4.98E-02	BE7	5.53E-02
I-119	1.22E+00	I-119	3.23E+00	C14	3.47E-04	C14	4.51E-05	C14	5.01E-05
Te-119	1.09E-04	Te-119	3.23E+00	V48	4.80E-05	V48	6.23E-06	V48	6.92E-06
Sb-119	1.87E-08	Sb-119	3.23E+00	V49	3.13E-04	V49	4.07E-05	V49	4.52E-05
Xe-120	1.77E+00	Xe-120	1.78E+00	CR51	1.06E-04	CR51	1.38E-05	CR51	1.53E-05
I-120	2.55E-02	I-120	1.78E+00	MN52	1.02E-04	MN52	1.32E-05	MN52	1.47E-05
Xe-121	1.73E+00	Xe-121	1.69E+00	MN54	1.51E-08	MN54	1.95E-09	MN54	2.17E-09
I-121	1.59E-02	I-121	1.69E+00	FE55	4.12E-04	FE55	5.34E-05	FE55	5.94E-05
Te-121	4.00E-08	Te-121	1.69E+00	FE59	3.53E-02	FE59	4.58E-03	FE59	5.09E-03
Xe-122	4.01E-01	Xe-122	1.18E+01	CO56	1.09E-03	CO56	1.42E-04	CO56	1.57E-04
I-122	1.10E-01	I-122	1.18E+01	CO57	6.25E-03	CO57	8.11E-04	CO57	9.01E-04
Xe-123	3.87E+00	Xe-123	1.14E+01	CO58	1.32E-02	CO58	1.72E-03	CO58	1.91E-03
I-123	5.71E-03	I-123	1.14E+01	CO60	5.33E-03	CO60	6.92E-04	CO60	7.69E-04
Te-123	1.91E-08	Te-123	1.14E+01	NI59	3.55E-03	NI59	4.61E-04	NI59	5.12E-04
Xe-125	1.47E+00	Xe-125	3.67E+01	NI63	2.48E-04	NI63	3.22E-05	NI63	3.58E-05
I-125	1.97E-05	I-125	2.47E+01						
Xe-127	1.99E-02	Xe-127	3.17E+00						
C10	1.83E-04	C10	3.07E-02						
C11	1.35E-02	C11	2.26E+00						
C14	6.77E-06	C14	1.14E-03						
N13	5.66E-02	N13	9.51E+00						
N16	5.14E-04	N16	8.63E-02						
O14	1.37E-02	O14	2.30E+00						
O15	2.56E-01	O15	4.30E+01						
AR37	7.51E-03	AR37	1.26E+00						
AR39	7.42E-06	AR39	1.25E-03						
AR41	1.93E-04	AR41	3.24E-02						
AR42	4.00E-06	AR42	6.71E-04						

EXHIBIT E (continued)

Source term for accident sequence 17		Source term for accident sequence 18		Source term for accident sequence 39		Source term for accident sequence 28		Source term for accident sequence 26	
List 6		List 7		List 8		List 9		List 10	
Nuclide	Ci/hr	Nuclide	Ci	Nuclide	Ci	Nuclide	Ci	Nuclide	Ci
HG184	2.50E-06	HG184	1.30E-05	H3	3.97E+00	H3	3.66E-05	H3	2.84E-02
HG185	3.97E-06	HG185	2.06E-05	BE7	3.24E-01	BE7	2.77E-05	BE7	1.1E-06
HG186	1.09E-05	HG186	5.68E-05	C14	2.79E-03	C14	2.51E-08	C14	8.71E-09
HG187	2.31E-05	HG187	1.20E-04	V49	2.77E-03	V48	3.46E-09	V49	8.65E-09
HG188	5.15E-05	HG188	2.67E-04	MN54	8.78E-03	V49	2.26E-08	MN54	2.74E-08
HG189	8.93E-05	HG189	4.63E-04	FE55	2.78E-01	CR51	7.65E-09	FE55	8.68E-07
HG190	1.13E-04	HG190	5.87E-04	FE59	4.88E-04	MN52	7.33E-09	FE59	1.52E-09
HG191	1.43E-04	HG191	7.40E-04	CO56	1.05E-02	MN54	1.09E-12	CO56	3.27E-08
HG192	1.88E-04	HG192	9.74E-04	CO57	7.18E-02	FE55	2.97E-08	CO57	2.24E-07
HG193	2.04E-04	HG193	1.06E-03	CO58	7.36E-03	FE59	2.54E-06	CO58	2.30E-08
HG194	1.19E-05	HG194	6.17E-05	CO60	4.66E-03	CO56	7.87E-08	CO60	1.46E-08
HG195	3.68E-04	HG195	1.91E-03	NI63	2.47E-01	CO57	4.5E-07	NI63	7.73E-07
HG197	2.47E-03	HG197	1.28E-02			CO58	9.53E-07		
HG203	1.76E-03	HG203	9.15E-03			CO60	3.84E-07		
HG205	7.59E-05	HG205	3.94E-04			NI59	2.56E-07		
						NI63	1.79E-08		

EXHIBIT E (continued)

Source term for accident sequence 34		Source term for accident sequence 37	
List 11		List 12	
Nuclide	Ci	Nuclide	Ci
H3	4.96E-03	H3	7.31E-05
BE7	2.03E-05	BE7	5.53E-05
C14	1.74E-07	C14	5.01E-08
V49	1.73E-07	V48	6.92E-09
MN54	5.48E-07	V49	4.52E-08
FE55	1.74E-05	CR51	1.53E-08
FE59	3.04E-08	MN52	1.4E-07
CO56	6.55E-07	MN54	2.17E-12
CO57	4.49E-06	FE55	5.94E-08
CO58	4.60E-07	FE59	5.09E-06
CO60	2.91E-07	CO56	1.57E-07
NI63	1.55E-05	CO57	9.01E-07
		CO58	1.91E-06
		CO60	7.69E-07
		NI63	3.58E-08

EXHIBIT F

SOURCE TERM FOR WORST-CASE BEYOND-DESIGN-BASIS LOSS OF FORCED Hg FLOW ACCIDENT

EXHIBIT F. SOURCE TERM FOR WORST-CASE BEYOND-DESIGN-BASIS LOSS OF FORCED Hg FLOW ACCIDENT

This exhibit develops the source term for the limiting beyond-design-basis (BDB) accident for the Spallation Neutron Source. This BDB source term is developed for both the 1-MW configuration and the 4-MW configuration. The target plug and associated systems are currently being developed for the 1-MW configuration, and may, after proving successful, be operated at proton beam power levels as high as 2 MW. The source term for a 2-MW configuration will be bracketed between the "1-MW" and "4-MW" cases derived in this appendix. The 4-MW configuration has not actually been detailed yet because it will require redesign and reanalysis of the target plug and Hg coolant system, and that work is not planned to begin for several years. The calculations below assume that the 4-MW configuration has geometry identical to that of the 1-MW configuration, with power level four times as high. The geometry may change somewhat when the actual 4-MW target plug is designed, although it is expected that such changes are likely to be in the direction that would moderate the accident response (i.e., by more diffuse beam focusing or larger Hg inventory, etc.). The radionuclide inventory of the 4-MW configuration is assumed to be four times as high as the 1-MW configuration since the buildup of spallation products is linear with respect to beam power level.

Table F.1. Event sequence table

Time (s, unless otherwise noted)	Event or process	Assumptions	Calculation(s)
0	Pump coastdown begins		
0+	TPS trip on pump status fails	Common mode failure of all target protection system (TPS) trips	
0++	TPS trip on pump outlet pressure fails	Run permit/beam pulse enable systems (BPS) trip(s) on same or similar process variables also assumed to fail	
0+++	TPS trip on loop flow fails		
Tcd	Loop flow coast down is over.	All damage would be prevented if TPS or BPS function per design	Tcd is TBD—assume = 5 s
t > Tcd	Local Hg boiling begins, Hg vessel steel window (front face) heat-up begins	Max. Hg heat-up rate at peak local point in Hg is ~6 %C/pulse, and is ~1.25 %C/pulse in window (@1 MW, per CDR Table 5.3-2 peak energy densities)	**1 MW**: Hg local boiling begins ~1 s after coastdown. Window steel begins melting >17 s later. **4 MW:** Hg local boiling begins <1 s after coastdown. Window steel begins melting >4 s later.

Table F.1 (continued)

Time (s, unless otherwise noted)	Event or process	Assumptions	Calculation(s)
t > Tcd	Beam heating of Hg without forced circulation causes intermittent boiling and condensation of Hg in inner ~½ of target plug; no net Hg vapor production	1. 66% of beam energy deposited in Hg (CDR Table 5.3-4). 2. Inner ½ of target plug only intermittently and partially voided during this period. 3. Inner ½ of plug holds ~0.1 m^3 of Hg	**1 MW**: Avg. Hg temp. of inner ½ of plug reaches bulk saturation (~360°C) 69 s after coastdown, i.e., 69 s = (0.1 m^3) (13.3E3 kg/m^3) * (137 J/kg°C)(250°C)/ (0.66*1E6 J/s) **4 MW:** Avg. Hg temp. of inner ½ of plug reaches bulk saturation (~360°C) ~17 s after coastdown
t < Tpps	Water-cooled shroud may fail	Water-cooled shroud can fail because of its close proximity to the Hg vessel front face, which fails on account of high temperature	N/A: effect of water-cooled shroud failure not clear. Would probably make beam cutoff by PPS occur sooner by allowing Hg to drain more rapidly out of the target plug
1 MW: Tpps = Tcd + 69 s **4 MW:** Tpps = Tcd + 17 s (Note: Tpps = time when PPS initiates beam cutoff)	Bulk boiling of Hg in target plug. PPS detects elevated neutron flux due to beam hitting shielding steel in outer part of plug	PPS cuts off the proton beam after 2 s of bulk boiling (1 s for boiling to void the target plug inboard of the shielding steel and 1 s for instrument response time)	**1 MW:** Bulk boiling does not occur because the operator would cut off the beam before 60 s **4 MW:** 2 s of bulk boiling creates: 18.1 kg of Hg vapor (~4.6 m^3 of vapor at 1 atm pressure): 18.1E3= 0.66*4 E6*2/292
t > Tpps	Hg continues to leak from failed Hg vessel front window unless it had already leaked to below the level of the bottom of the beam envelope	1. Hg will drain until level is below the bottom edge of the proton beam: this is <1/3 of total Hg inventory (by design) 2. Some of leaked Hg drains to collection tank in hot cell floor and some may drain to core vessel	

2.0 HG RELEASE CALCULATIONS

The worst case BDB loss of Hg flow accident will have two distinct phases—the initial phase in which a short period of vigorous boiling of Hg may take place and the long-term phase in which residual amounts of Hg would slowly evaporate. For this bounding analysis, the Hg vapor produced in the vigorous boiling phase is assumed to remain in vapor form and be exhausted by

the mercury enclosure ventilation without being condensed. Any cooling that takes place would condense the Hg vapor and, thus, prevent its rapid release. It is possible that some of the Hg vapor could be vented to the hot off-gas (HOG) system, but the resulting releases would be lower, so the HOG is not credited here.

The transport of Hg is addressed specifically in the next two subsections. The possibility of transport of other radionuclides is discussed in a separate subsection at the end. The possible use of a low temperature condenser and/or a sulphur-impregnated activated charcoal for Hg removal from the target cell air exhaust will be examined during Title I design; none of the calculations in this section credit the ventilation system with Hg removal capability.

2.1 SHORT TERM RELEASE

A rapid release of mercury vapor occurs due to the assumed period of vigorous Hg boiling that occurs immediately before the PPS actuates cutoff of the proton beam. As noted in the table, for the 1-MW case, it takes more than 60 s for the beam to heat the mercury in the inner part of the Hg target plug to the saturation temperature. Thus, it is very likely that the operator would interrupt this event before the bulk boiling occurred for the 1-MW target configuration. For the 4-MW case, however, the bulk boiling occurs well before 1 min has elapsed, so the PPS would be more likely to interrupt the beam than would the operator. Therefore, the short term releases would be:

4-MW configuration: 18.1 kg Hg (i.e., ~4.6 m^3 of Hg vapor) released to the mercury enclosure inside the target hot cell and thence to the environment through the target hot cell ventilation exhaust. The ~4.6 m^3 of Hg vapor that is released to the mercury enclosure in a short period of time is assumed to mix with the air and be swept out of the enclosure by the ventilation system flow. It is possible that the mixing would be poor and that much of the Hg vapor would settle to the floor and condense. The assumption that mixing is good and that condensation does not occur is conservative. Since the residence time for air flowing through the mercury enclosure is longer than 5 min, it would take the enclosure ventilation system about 10 min to sweep the bulk of this Hg vapor/air mixture from the enclosure.

1-MW configuration: no bulk boiling occurs because the operator initiates manual beam cutoff in response to multiple alarms. However, the failed Hg vessel window may result in drainage of Hg across the mercury enclosure floor. The source term for the first 10 min is conservatively estimated by assuming that the mercury enclosure exhaust air is saturated with Hg vapor during the entire period.

2.2 LONG TERM RELEASE

2.2.1 Assumptions

1. Air exhausted from the mercury enclosure is saturated with Hg vapor for 7 d after the accident when the spilled Hg is cooling from its initial temperature, which for part of the spilled Hg could be as high as the saturation temperature (357°C), back toward the normal ambient range in the enclosure.

2. After 7 d, the concentration of Hg vapor in the mercury enclosure air would be limited by evaporation from ambient temperature Hg in the catch pan sump depression. This assumption is tantamount to assuming that the drain from the catch pan sump depression to the collection tank (located below the sump depression for gravity drainage) has been inadvertently plugged. If this drain were assumed to be open, the Hg would drain to the collection tank, from which there would be negligible Hg evaporation since it has only a small opening for the drain(s) flowing into it.
3. Mercury enclosure air exhaust flow continues at the nominal 11.3 m^3/min (400 cfm) for all times after the accident. This is conservative since releases would be much lower after the accident if there were no air exhausted from the mercury enclosure.
4. Mercury enclosure air inlet temperature is 30°C (summer temperature).
5. The bounding mercury enclosure air exhaust temperature is determined as the maximum of the following: (1) the value consistent with the assumption that 100% of the decay heat energy is transferred to the air and not to structures that would serve as heat sinks (Note: immediately after beam cutoff the decay heat values are 10 kW @ 4 MW and 2.5 kW @ 1 MW. Corresponding air exhaust temperatures are 76°C for 4-MW proton beam configuration and 42°C for the 1-MW proton beam configuration) or (2) the value consistent with the normal heat load plus the additional heat load due to heat transfer from a 1 m^2 surface area of mercury at 350°C. The larger of these two choices will bound the air exit temperature for the first 7 d. By this procedure the bounding air exhaust temperature is 76°C for the 4-MW case and 73°C for the 1-MW case; thus, the 76°C value will be used for both. This procedure is conservative because it does not allow the heat input to the air to decrease after the beam cutoff.

Release for either the 4-MW or 1-MW configuration

Release over first 7 d = (7 d * (11.3 m^3/min) * (0.61 g/m^3) * (1440 min/d)
= (7 d) * 9.9 kg Hg/d = 69.5 kg Hg

Release between 7 d and 30 d for either 4-MW or 1-MW configurations

After the first 24 h, the temperature of spilled mercury has cooled to <100°C, so that mercury transport is limited by the evaporation of Hg from the catch pan sump depression (1 m^2 surface area if the catch pan drain is plugged, and the spilled Hg does not drain). As discussed in Exhibit D, this evaporation rate is estimated to be 130 g Hg/d/m^2 for evaporation from a 1 m^2 surface area at a temperature of 110°C. Assuming no further cooling of the Hg during this period is a bounding conservatism. A factor of 10 is applied to the estimate to ensure conservatism against possible correlation or geometry uncertainties.

Release (7 d to 30 d) = 1.3 kg Hg/d

2.3 EFFECT OF WATER-COOLED SHROUD FAILURE ON SHORT AND LONG TERM RELEASES (i.e., CORE VESSEL RELEASE PATHS)

The analysis above considers Hg release paths from the Hg system to the mercury enclosure inside the target hot cell, and from there to the environment via the hot cell ventilation system. No releases from the core vessel are listed because the water-cooled shroud continues to provide separation between the Hg system/target hot cell and the core vessel. Failure of the water-cooled shroud was not postulated as part of the definition of this event, but it could fail if, for example,

the Hg vessel window actually melts and molten stainless steel contacts the water-cooled shroud and softens it enough to cause its failure.

If only the inside wall of the water-cooled shroud failed, that would allow shroud cooling water to contact the Hg inside the target vessel. The water would boil, and this would displace Hg from the Hg vessel back into the Hg cooling system in the mercury enclosure. The voiding would allow the proton beam (still on because of the assumed failure of multiple TPS and BP beam cutoffs) to strike shielding steel in the outer part of the target plug. This would elevate the neutron flux levels in the target hot cell sooner and therefore bring about the PPS cutoff of the proton beam sooner. Shut-off of the beam before bulk boiling of the Hg in the target plug would result in a lower source term, or at least one without the prompt Hg vapor release resulting from a brief period of vigorous boiling.

If both walls of the double-walled, water-cooled shroud failed, this would provide an additional path for drainage of Hg from the Hg vessel, the likely effect of which would be the same as discussed in the previous paragraph for the single-wall failure; the PPS sees elevated neutron levels and cuts off the proton beam sooner than it would have otherwise and before bulk boiling of Hg occurs in the target plug.

Failure of the water-cooled shroud therefore seems to have the major beneficial effect of interrupting proton beam pulsing before bulk boiling of the mercury and thus may have a lower short term Hg release. However, the double-wall failure has another effect that must be considered—opening up an additional pathway for release of Hg and/or spallation products through the core vessel pressure relief line. As discussed in Sect. 3.1, the core vessel has a pressure relief line that actuates at 2 atm of internal pressure. Cooling water spilled from the failed shroud and Hg spilled from the target plug could mix in the bottom of the core vessel. If the water is heated to greater than 100°C, this, combined with the existing ~1 atm internal pressure of He, could create enough internal pressure to actuate the core vessel relief path (it is TBD whether this will be a rupture disc and/or relief valve). The potential for additional source term will be bounded by considering how much water a 0.1 m^3 volume of Hg at 350°C can boil (this is the volume and temperature of Hg reached just before bulk boiling occurs in the target plug, as developed in Sect. 2.1 of this exhibit). The answer is that there is enough thermal energy in 0.1 m^3 of Hg at 350°C Hg to boil about 17 kg of water and that the Hg is cooled to 120°C in the process. At the shroud-cooling water flow rate of 2.4 kg/s (CDR Table 5.3-5), and assuming that 100% of the shroud-cooling flow is lost through the postulated failure point, it would take about 7 s for this much water to flow into the core vessel. The corresponding volume would raise the core vessel's ~10 m^3 of internal free volume to a pressure greater than 2 atm, so the relief path would actuate. Evaluating the volume of steam effluent at the 1 atm post-venting pressure leads to an estimated vented volume of about 31 m^3. The amount of Hg vapor that would be in this amount of steam is bounded by assuming that the water vapor is saturated with Hg at a temperature of 120°C (saturation pressure of water at the actuation pressure of the core vessel relief path). Very little else but Hg vapor would be transported by this path because the relatively open region at the top of the core vessel provides a volume for low-velocity separation of any gross entrained droplets of Hg and because (see also Sect. 3.1 of this exhibit) the vent path is equipped with appropriate filtration and/or demisting features. Since the Hg saturation density at 120°C is 7.9 g Hg/m^3, the total mass of Hg vapor vented with the steam is 31 m^3 * 7.9 g/m^3= 245 g Hg. This is less than the prompt release estimated above for the case where bulk boiling of the Hg is assumed to occur. Therefore, it is concluded that failure of the water-cooled shroud would not increase the short term release estimated in Sect. 2.1 of this exhibit.

The effect on long-term release can be estimated by assuming that the normal core vessel purge rate (10 m^3/100 h) continues after the accident, venting 120°C helium saturated with Hg vapor (saturation density of 7.9 g/m^3). This would release 19 g Hg per day, which is small in comparison to the long-term hot cell release estimated above.

Rather than debate whether these short- and long-term core vessel releases would occur instead of—or in addition to—the hot cell releases, they are assumed to occur in addition to the hot cell releases. The total estimated release source term for this event, therefore, has been increased to include the core vessel vent path.

3.0 RELEASE AND TRANSPORT OF OTHER THAN HG RADIONUCLIDES

Besides the radioactive and nonradioactive Hg radionuclides, a range of spallation and activation products are present in the Hg. The great majority of these are nonvolatile because of their low or zero vapor pressures in the temperature range of interest (i.e., up to the boiling point of Hg). The exception to this would be any gaseous spallation products present in the mercury or any volatile nuclides such as iodine, for example. A significant inventory of gaseous nuclides is not present in the Hg before the accident because there is a continuous helium purge that removes these as they are generated. The gaseous nuclides removed include hydrogen (e.g., tritium), noble gases, and possibly some iodine(see Sect. 3.2, below). Accidents of the HOG treatment system can release the gaseous nuclides, and they are discussed in Chap. 4 of this document.

3.1 NONVOLATILE SOLIDS

Most of the spallation products are soluble in the mercury and will remain well below their solubility limits through the lifetime of the facility. The insoluble spallation products would either settle out into the bottom of the reservoir tank or would be removed by filtration. If the mercury boils in an accident, neither soluble nor insoluble spallation products would vaporize because of their very low vapor pressures (unlike iodine, discussed below). A few of the spallation product nuclides (i.e., Cs, In, Cd, Sn, I, Tl, and Pb) have melting points below the boiling point of Hg. With the exception of I (addressed as a special case in the subsection below), the amount released would be very small; however, because the boiling points for these same elements are typically over 1000°C, giving them very low vapor pressures at the mercury boiling point. The amount of nonvolatile solids released from a brief period of boiling Hg is concluded to be negligible. See also spallation product transport discussions in Sect. 3.1 and Exhibit C of this document.

Although inherent transport mechanisms are not effective for nonvolatile solids at mercury's boiling temperature, entrainment of Hg droplets in flowing gases should be considered. For the 4-MW case, a short period of vigorous bulk boiling occurs in the target plug, so it is possible that the vapor released to the mercury enclosure could entrain some small droplets of unvaporized Hg that would (being unvaporized) contain spallation products. However, there could not be an efficient droplet formation and transport process because of the high surface tension and density of mercury. The mercury enclosure is not ventilated at a high rate (residence time of air is greater than 5 min in the mercury enclosure). Furthermore, a prefilter or demister section incorporated

into the mercury enclosure ventilation should eliminate any Hg mist droplets that are created. Any droplets that do not settle out or that get past the prefilter section would then be drawn into the ventilation ductwork and could be transported to the HEPA filters. There, the Hg droplets would be caught by the HEPA filter medium. Due to the inherent barriers against mist droplet formation (Hg density, surface tension), opportunity for droplets to settle out in the mercury enclosure (very low velocity except in exit pipe), and installed liquid and solids removal stages in the ventilation exhaust system (mist eliminator, HEPA filters), it is concluded that negligible transport of solid nonvolatile spallation/activation products would occur.

For the 1-MW configuration, there was no period of bulk boiling, so there would be no opportunity to create small airborne droplets of Hg as discussed above for the 4-MW configuration.

3.2 IODINE

The iodine produced in the mercury by the proton beam will combine chemically with the Hg to form Hg_2I_2. This is a stable compound at the normal hot leg temperature of 110°C, so the iodine will not be released immediately from any mercury that is spilled, providing it is not heated above normal temperatures first. However, after a spill, exposure to oxygen in air could displace the iodine, thereby freeing it to be released.

If the Hg boils in an accident (which it does in the accident analyzed above), the temperature will reach about 360°C and the Hg_2I_2 should be assumed to decompose, releasing iodine rapidly (mainly in the form of gaseous HgI_2). To ensure a conservative source term for this event, the iodine present in the ~0.1 m^3 of Hg that is postulated to reach the boiling point is assumed to release its iodine immediately. This 0.1 m^3 of Hg is ≤14% of the total Hg, so the fractional release of iodine during the early part of the accident would be bounded as 14% of the total iodine inventory. This number will be applied to both the 1-MW or the 4-MW case because, although the 1-MW case did not experience boiling, its temperature does come close to the boiling point.

Following the short-term release of I, it must be assumed that I will continue to be released because of oxidation of Hg_2I_2 in spilled Hg. This would be a slow process, but is assumed to be complete after 30 d. For this particular event (loss of flow with consequent Hg vessel window failure), only 33% of the Hg leaks from the Hg cooling system, so it would be adequate for this particular accident sequence to postulate that a total of only 33% of the I is eventually released to the air. However, in order to make this source term applicable to similar events that might be initiated by Hg boundary failure (instead of having the Hg boundary fail as a result of the failure of two beam cutoff systems), and which could (for a leak at the bottom of the system) spill all the Hg, the iodine source term is increased to be consistent with total spillage of mercury and oxidation of all the Hg_2I_2 to release the entire iodine inventory over a period of 30 d.

4.0 SOURCE TERM SUMMARY: RELEASES TO ENVIRONMENT, WORST CASE BEYOND-DESIGN-BASIS ACCIDENT

The fractional releases are given in the following tables for a 1-MW and 4-MW target configuration. Since the releases are calculated in the previous subsections, above, in terms of mass of Hg released, it is necessary to divide by the total Hg inventory to calculate the release fraction(s). The conceptual design has a nominal 1 m^3 volume (13.6E6 kg of Hg), but continuing design activity has led to smaller volumes; a value of 10,000 kg of Hg should adequately bound the intended decrease in Hg volume.

Table F.2. Beyond-design-basis accident source term summary

Radionuclide category	Fractional release of total inventory		
	Short term (~10 min)	First 7 d	7 d through 30 d
	1-MW target configuration–fractional releases		
Hg	6.6E–5	0.8E–2	3.0E–3
Iodine	1.40E–1	2.0E–1	6.6E–1
Nonvolatile solids	Negligible	Negligible	Negligible
	4-MW target configuration–fractional releases		
Hg	1.83E–3	0.8E–2	3.0E–3
Iodine	1.4E–1	2.0E–1	6.6E–1
Nonvolatile solids	Negligible	Negligible	Negligible

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