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Microreactor Incident-Free Transportation Radiation Dose Assessment

December 2025

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U.S. DEPARTMENT of ENERGY

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Abstract

This report, prepared by Pacific Northwest National Laboratory (PNNL) for the U.S. Nuclear Regulatory Commission, provides an estimate of the radiation dose related to the transportation of microreactors following the regulatory limits established in Title 10 of the *Code of Federal Regulations* (10 CFR) 71.47(b). The transportation of irradiated microreactors poses unique challenges. Microreactors may be challenged to meet the current 10 mrem/hr (0.1 mSv/hr) limit at 2 meters (6.6 feet) from the vehicle in 10 CFR 71.47(b). The need to modify packaging to be within practical weight and size limits for shipping may limit the amount of shielding that can be applied for a microreactor transportation package design. Operational strategies that would necessitate moving a reactor within a short time after its operating life may result in higher radiation dose rates associated with lower cooling times.

This study estimates the radiation dose to maximally exposed individuals (MEIs) under the current regulatory radiation level limit of 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 ft) from the vehicle as well as alternative limits of 50, 100, and 200 mrem/hr (0.1, 0.5, 1.0, and 2.0 mSv/hr) at 2 meters (6.6 ft) from the vehicle. This analysis expands on prior incident-free transportation radiation dose assessments conducted for spent nuclear fuel (SNF) and radioactive waste transportation. The key factors analyzed include the microreactor fuel type and burnup, shipment cooling periods, shielding designs integrated into transport packaging, and exposure scenarios for MEIs for highway and rail transport. This report considers additional distances that may be associated with compensatory measures to ensure safe transport conditions under varying radiation dose limits, including enhanced routing measures, escort protocols, vehicle inspections, and operational restrictions.

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Acronyms and Abbreviations

AAR	Association of American Railroads
CFR	*Code of Federal Regulations*
cm	centimeter(s)
CSI	criticality safety index
CVSA	Commercial Vehicle Safety Alliance
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIS	environmental impact statement
EOL	end of life
FEIS	final environmental impact statement
FRA	Federal Railroad Administration
ft	foot (feet)
g	gram(s)
HALEU	high-assay low-enriched uranium
HLW	high-level waste
HPMR	Heat Pipe Microreactor
hr	hour(s)
HRCQ	highway route controlled quantity
HTGR	high temperature gas reactor
IAEA	International Atomic Energy Agency
INEEL	Idaho National Engineering and Environmental Laboratory
kg	kilogram(s)
km	kilometer(s)
LLW	low-level waste
m	meter(s)
MEI	maximally exposed individual
mph	mile(s) per hour
mrem	millirem(s)
mSv	millisievert(s)
MTHM	metric ton(s) of heavy metal
MTU	metric ton(s) of uranium
MWe	megawatt(s) electric
MWth	megawatt(s) thermal
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act of 1982
OSHA	Occupational Safety and Health Administration

PNNL	Pacific Northwest National Laboratory
ppm	part(s) per million
PWR	pressurized water reactor
rem	Roentgen equivalent man
ROD	record of decision
SEIS	supplemental environmental impact statement
SNF	spent nuclear fuel
SRS	Savannah River Site
SSR	Specific Safety Requirement
Sv	sievert(s)
TI	transport index
TRISO	TRi-structural ISOtropic
TRU	transuranic
TRUW	transuranic waste
UCO	uranium oxycarbide
WIPP	Waste Isolation Pilot Plant
wt%	weight percent
yr	year(s)

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1.0 Introduction

This report provides the results of calculations performed to assess the incident-free transportation impacts to maximally exposed individuals (MEIs) with respect to radiation dose should the exclusive use radiation level limit[1] within Title 10 of the *Code of Federal Regulations* (10 CFR) 71.47(b) of 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 feet) from the vehicle[2] be increased to 50, 100, or 200 mrem/hr for microreactors.

10 CFR 71.47 Subpart E contains the U.S. Nuclear Regulatory Commission (NRC) package approval standards, which include 10 CFR 71.47, "External radiation standards for all packages." This regulation includes the radiation dose rate limits for package approval under both non-exclusive use and exclusive use transport scenarios. 10 CFR 71.47(a) specifies radiation level limits for packages of radioactive material anticipated to be used for transport under non-exclusive use controls. This regulation limits the radiation level for NRC package approval under conditions normally incident to transportation[3] to 200 mrem/hr (2 mSv/hr) at any point on the external surface of the package. There is an additional package approval limit for the maximum radiation level at 1 meter from any external surface of the package, which must also not exceed 10 mrem/hr (0.1 mSv/hr). This limit is defined in terms of the transport index (TI)[4].

For packages in transit, the radiation level is limited under U.S. Department of Transportation (DOT) regulations under 49 CFR 173.441.

International standards for both package approval and in transit radiation levels are established by the International Atomic Energy Agency (IAEA) Specific Safety Requirement (SSR)-6 (IAEA 2018).

These radiation level limits apply to a transportation package without regard for the mode (e.g., truck, rail, or barge) of shipment. Microreactors are expected to be transported as "exclusive use," as defined in 49 CFR 173.403. Exclusive use refers to the sole control by a single consignor of a conveyance, ensuring all loading and unloading is handled per their instructions by radiologically trained personnel, with written guidelines provided to the carrier for maintaining

[1] The regulations in 10 CFR Part 71 use the terminology of "radiation level" with the units of mrem/hr and mSv/hr being in terms of dose equivalent rate. IAEA regulations have replaced the terminology of "radiation level" with "radiation dose rate." Therefore throughout this document the terminology "radiation level" and "radiation dose rate" are used somewhat interchangeably and refer to the dose equivalent rate.

[2] 10 CFR 71.47(b)(3) states "at any point 2 meters (80 in) from the outer lateral surfaces of the vehicle (excluding the top and underside of the vehicle); or in the case of a flat-bed style vehicle, at any point 2 meters (6.6 feet) from the vertical planes projected by the outer edges of the vehicle (excluding the top and underside of the vehicle)."

[3] Applicants for NRC Type B transportation certificates of compliance often conservatively analyze the package under 10 CFR 71.71, "Normal conditions of transport," to meet the dose rate limits in 10 CFR 71.47; however, these limits apply to a shipment as prepared for transport under conditions normally incident to transportation, while 10 CFR 71.51 defines that under the 10 CFR 71.71 "normal conditions of transport," the package (among other requirements) has no significant increase in external surface radiation levels.

[4] The TI is used to designate the degree of control to be exercised by the carrier during transport. The TI is important in 71.47(a), as it is an established radiation dose rate limit (of 10) that must be assessed/met. In 71.47(b), there is no detail related to a TI limit; however, the TI must still be assessed, and the resulting value must be placed on the Radioactive label assigned to the package (i.e., Radioactive Yellow-II or Radioactive Yellow-III).

shipment controls. If the package is transported under exclusive use controls, the DOT radiation dose rate limits can be relaxed and account for the properties of the conveyance vehicle. A maximum package external radiation level limit of 1,000 mrem/hr (10 mSv/hr) under conditions normally incident to transportation is allowed in a closed vehicle if the 200 mrem/hr (2 mSv/hr) radiation level limit is met on the external surface of the vehicle.

The details for the NRC package approval standards under of the exclusive use radiation dose rate limits are in 10 CFR 71.47(b).

1.1 Background on the Limit of 10 mrem/hr at 2 meters in 10 CFR 71.47

The origins and rationale for the exclusive use regulation limiting external radiation levels to 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 feet) reveal an effort to harmonize national and international standards for radiation safety during transport. According to the NRC 10 CFR Part 71 Statements of Consideration (NRC 1987), this limit was implemented to reduce radiation exposure to the general public while aligning regulations with those of DOT and IAEA. The Statements clarify the policy direction as follows:

> *It was suggested that external radiation level limits (as well as other provisions) be excluded from NRC regulations in favor of deferring to DOT regulations. However, the Commission resolved that all Type B and fissile material package requirements would remain within NRC's framework. Radiation level and temperature restrictions were integrated into the "Package Standards" subpart as part of design review requirements.*
>
> *The wording of the external radiation level limits was aligned closely with corresponding DOT regulations to ensure clarity. Furthermore, the limit of 10 mrem/hr at 2 meters was made consistent with IAEA regulations. While this limit applies to the vertical surfaces of vehicles, exemptions were made for space above and below the vehicle, recognizing the limited likelihood of public exposure in those areas. This approach contrasts with surface radiation limits, which apply to all exposed areas of a vehicle—upper and lower surfaces included—in order to better protect workers operating around these vehicles.*

The corresponding IAEA limit of 0.1 mSv/hr (10 mrem/hr) at 2 meters (6.6 feet) is given in Paragraph 573 of SSR-6 (IAEA 2018):

> *573. For consignments under exclusive use, the dose rate shall not exceed:*
> *(c) 0.1 mSv/h at any point 2 m from the vertical planes represented by the outer lateral surfaces of the vehicle, or, if the load is transported in an open vehicle, at any point 2 m from the vertical planes projected from the outer edges of the vehicle.*

The development of the 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 feet) limit within the IAEA transport regulation traces back to earlier iterations of IAEA transport regulations for radioactive materials. Starting in 1961 when IAEA first published its regulations on the transport of radioactive materials, the radiation limits at the surface of the package were derived to limit the exposure to radiation-sensitive materials, such as film, and workers carrying packages close to their body. For controlling the number of packages in one vehicle, in the United States, the "radiation unit" concept was developed as a simplified system, which evolved into the TI system. Using this system, transportation workers could simply tally a unified measure of "radiation units" labeled on packages to ensure compliance with safety thresholds (Fairbairn 1973).

As Fairbairn (1973) describes, when deriving radiation control limits, international regulators recognized the ability to segregate packages with higher radiation levels from people and radiation-sensitive materials to keep exposures within acceptable limits. The 1961 IAEA regulations set a “40 radiation unit” limit for limiting the number of packages carried in one vehicle but allowed larger numbers of packages with higher levels of radiation—up to 50 packages—if appropriate segregation distances were maintained (Fairbairn 1973). This restriction on the number of packages was primarily intended to mitigate the risks associated with contamination from transportation accidents. By the 1964 regulations, the “40 radiation unit” limit was increased to “50 transport indices.” The change from “radiation unit” to “transport index” was made to also control the number of fissile packages for criticality safety. For the number of packages stowed during road or rail transport, the equivalent of a total/cumulative TI of 50 was used by recognizing 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 feet) as a “full load” (IAEA 1964).

Fairbairn (1973) explained this equivalence:

> *The theoretical maximum dose rate at 2 meters from the surface of a vehicle carrying 50 transport indices is 12.5 mrem/h; this may be safely rounded down to 10 mrem/h because the actual dose rate will most likely be below the theoretical figure. At this level the effects of radiation external to the vehicle during transit can safely be ignored. On this basis the 1964 regulations introduced 10 mrem/h at 2 m from the outer surface of the vehicle as a limit for road and rail vehicles carrying radioactive material in labeled packages as a full load—removing the application of the 50 transport index limit (Fairbairn 1973).*

A value of 0.125 mSv/hr (12.5 mrem/hr) was derived using the inverse square law for how radiation diminishes with distance. If there was a maximum TI of 50, this would mean a radiation dose rate of 0.50 mSv/hr (50 mrem/hr) at 1 meter (3.3 feet). Using the $1/R^2$ law at 2 meters, $0.50/2^2$ = 0.125 mSv/hr (12.5 mrem/hr), and as stated above, this was rounded down to 0.1 mSv/hr (10 mrem/hr).

The “exclusive use” definition was introduced in the 1973 IAEA regulations (IAEA 1987). Exclusive use refers to shipments reserved for the sole use of a consignor throughout transportation, with enhanced provisions for ensuring radiation safety, including potentially higher radiation dose limits. The “exclusive use” radiation dose rate limit of 0.1 mSv/hr (10 mrem/hr) at 2 meters (6.6 feet) became the established standard for radioactive consignments transported under these conditions (IAEA 1987). In addition, the criticality safety index (CSI) replaced the TI for limiting the number of fissile packages, separating the requirement from that of limiting radiation exposure.

Further discussion on the origins of the TI system and its relationship to radiation dose limits can be found in the IAEA Technical Basis Document (IAEA 2017). This document connects earlier applications of the TI system to radiation dose rate limits set for surface radiation and provides historical context for these measures. For instance, early regulations incorporated limits like the 0.005 mSv/hr (0.5 mrem/hr) surface radiation dose rate for category I-WHITE packages, reflecting efforts to protect undeveloped photographic film even more stringently than exposed people. It explains:

> *(a) 0.005 mSv/h at surface: This surface limit was derived, not from consideration of radiation effects on persons, but from the more limiting effect on undeveloped photographic film. Evaluation of the effect of radiation on sensitive X-ray film in 1947*

showed that threshold fogging occurred at an exposure of 0.15 mSv. A surface limit was subsequently set in the 1961 edition of the regulations at 0.1 mSv, linked to a nominal maximum exposure time of 24 h.

Additionally, for packages with higher levels of radiation, a radiation dose rate limit of 0.1 mSv/hr (10 mrem/hr) at 1 meter (3.3 feet) was modeled in part on considerations of film protection during transport. As documented in regulations, these radiation dose rate guidelines were based on observed transit times and separation distances commonly practiced in the late 1940s:

(a) mSv/h at 1 m – For the purposes of limiting the radiation dose to film and to persons, the dose of 0.1 mSv discussed in (a) above was combined with the exposure rate at 1 m from the package and an exposure time of 1 hour to establish the 10 times TI limitation of the 1964, 1967, and 1973 editions of the regulations (10 "radiation units" in the 1961 edition of the regulations). This was based upon an assumed transit time of 24 hours and the conventional separation distance of 4.5 m (15 feet) between parcels containing radium in use by the US Railway Express Company in 1947.

The 0.1 mSv/hr (10 mrem/hr) at 2 meters (6.6 feet) from vehicles under exclusive use appears to be the result of the evolution of regulations dating back to 1961 aimed at being a practical limit and a safety limit to reduce exposure to radiation-sensitive cargo, such as film, and to workers and the public.

2.0 Prior Assumptions for Maximally Exposed Individuals

Historic information was examined to determine previous scenarios for determining the exposure to the MEI. This is historical information and is summarized below.

Chen et al. (2002) discuss the following exposure scenarios defined by a given distance, duration, and frequency of exposure to a specific receptor:

- Crew Members. Truck and rail crew members are assumed to be occupational radiation workers and would be monitored by a dosimetry program. Therefore, the maximum allowable radiation dose would be 5 rem/yr (50 mSv/yr). As an administrative procedure, the U.S. Department of Energy (DOE) limits radiation doses to DOE workers to 2 rem/yr (20 mSv/yr).
- Inspectors (Truck and Rail). Inspectors are assumed to be either Federal or State vehicle inspectors. Inspectors are not monitored by a dosimetry program. An average exposure distance of 3 m (9.8 ft) and an exposure duration of 30 minutes are assumed.
- Rail-Yard Crew Member. A rail-yard crew member is not monitored by a dosimetry program. An average exposure distance of 10 m (32.8 ft) and an exposure duration of 2 hours are assumed.
- Resident (Truck and Rail). A resident is assumed to live 30 m (98.4 ft) from a site entrance route (truck or rail). Shipments pass at an average speed of 24 km/hr (15 mph), and the unshielded resident is exposed. Cumulative radiation doses are assessed for each site based on the number of shipments entering or exiting the site, assuming that the MEI resident is present for 100% of the shipments.
- Person in a Traffic Obstruction (Truck and Rail). A person is assumed to be stopped next to a radioactive material shipment (e.g., because of traffic slowdown). The unshielded person is assumed to be exposed at a distance of 1 m (3.3 ft) for a duration of 30 minutes.
- Person at a Truck Service Station. A person is assumed to be exposed at an average distance of 20 m (65.6 ft) for a duration of 2 hours. This receptor could be a worker at a truck stop.
- Resident near a Rail Stop. A resident is assumed to live near a rail classification yard. The unshielded resident is assumed to be exposed at a distance of 200 m (656 ft) for a duration of 20 hours.

The following are discussed in Section J.1.3.2.2 of DOE (2002):

- Crew Members. In general, truck crew members would receive the highest radiation doses during incident-free transportation (see discussions below). The analysis assumed that the crews would be limited to a total job-related exposure of 2 rem/yr (20 mSv/yr).
- Inspectors (Truck and Rail). Inspectors would be Federal or State vehicle inspectors. On the basis of information provided by the Commercial Vehicle Safety Alliance (CVSA), the analysis assumed an average exposure distance of 1 meter (3 feet) and an exposure duration of 1 hour.
- Rail-Yard Crew Member. For a rail-yard crew member working in a rail classification yard assembling trains, the analysis assumed an average exposure distance of 10 m (32.8 ft) and an exposure duration of 2 hours.

- Resident. The analysis assumed that this MEI is a resident who lives 30 meters (98.4 feet) from a point where shipments would pass. The resident would be exposed to all shipments along a particular route.
- Individual Stuck in Traffic (Truck or Rail). The analysis assumed that a member of the public could be 1.2 meters (3.9 feet) from the transport vehicle carrying a shipping package for 1 hour. Because these circumstances would be random and unlikely to occur more than once for the same individual, the analysis assumed the individual to be exposed only once.
- Resident near a Rail Stop. The analysis assumed a resident who lives within 200 meters (656.2 feet) of a switchyard and an exposure time of 20 hours for each occurrence. The analysis of exposure for this MEI assumes that the same resident would be exposed to all rail shipments to the repository.
- Person at a Truck Service Station. The analysis assumed that a member of the public (a service station attendant) would be exposed to shipments for 49 minutes for each occurrence at a distance of 16 meters (52.5 feet). The analysis also assumed that this individual would work at a location where all truck shipments would stop.

The following national scenarios are discussed in Section G.5.1.2.1 of DOE (2008) for DOE workers:

- Escort. An escort 27 m (88.6 ft) from the rail package. This person would be exposed for 2,000 hours per year. The 27-meter distance includes the length of the buffer railcar between the last spent nuclear fuel (SNF) rail car and the escort car.
- Inspector. An inspector 1 m (3.3 ft) from the rail or truck for 1 hour per package. This person's radiation dose was based on a working year of 2,000 hours, which results in the person's exposure to 23 percent of the rail or truck packages.
- Truck Driver. A truck driver who would drive shipments that contained loaded packages for 1,000 hours per year.
- Rail-Yard Crew Member. A rail-yard crew member 10 m (32.8 ft) from the rail package for 2 hours per package. This person's radiation dose was based on a working year of 2,000 hours, which results in the person's exposure to 23 percent of the rail packages.

For members of the public, DOE evaluated the following scenarios in Section G.5.1.2.1 of DOE (2008):

- Resident. Typically, there is an 18-meter (59.0-foot) buffer zone around rail lines that is railroad property, within which people cannot build homes. Therefore, DOE estimated the radiation dose to a resident living 18 m (59.0 ft) from a rail line. This individual was assumed to be exposed to all loaded rail packages as they pass by en route to the repository.
- Resident. A resident 200 m (656.2 ft) from a rail yard. This person would be exposed for 2 hours per package.
- Person Stuck in Traffic. A person stuck in a traffic jam next to the package for 1 hour. The person would be 1.2 m (3.9 ft) from the package.
- Resident. A resident 30 m (98.4 ft) from a road or highway. This individual would be exposed to all loaded truck packages as they passed by en route to the repository.
- Person at a Service Station. This person would be exposed for 49 minutes to each truck package at a distance of 16 m (52.5 ft).

The following Nevada-specific scenarios are discussed in Section G.5.1.2.2 of DOE (2008) for DOE workers:

- Escort. An escort 27 m (88.6 ft) from the rail package. This person would be exposed for 2,000 hours per year. The 27-meter (88.6-foot) distance includes the length of the buffer railcar between the last rail package car and the escort car.
- Inspector. An inspector 1 m (3.3 ft) from the rail or truck package for 1 hour per package. This person's radiation dose was based on a working year of 2,000 hours, which results in the person's exposure to 23 percent of the rail or truck packages.
- Rail-Yard Crew Member. This crew member was 10 meters (32.8 feet) from the rail package for 2 hours per package. This person's radiation dose was based on a working year of 2,000 hours, which results in the person's exposure to 23 percent of the rail or truck packages.

The following Nevada-specific scenarios were evaluated in Section G.5.1.2.2 of DOE (2008) for members of the public:

- Resident. Typically, there is an 18 m (60 ft) buffer zone around rail lines that is railroad property and within which people cannot build homes. Therefore, DOE estimated the radiation dose to a resident living 18 meters (60 feet) from a rail line. This individual was assumed to be exposed to all loaded rail packages as they passed by en route to the repository.
- Resident. In some cases, individuals could have access to locations that are closer than 18 meters (60 feet) from a rail line. For example, Nevada Agency for Nuclear Projects (2002) states that in the Las Vegas area, individuals could be 15, 20, 30, 35, 40, 100, and 160 meters (resp. 49.2, 65.6, 98.4, 114.8, 131.2, 328.1, and 524.9 feet) from the rail line. In the area of the Reno Trench, an individual could be as close as 5 meters (16.4 feet) from the rail line. Therefore, radiation doses were estimated for individuals at these distances from the rail line. These locations were not permanently occupied by residents. However, to provide a conservative estimate of potential impacts, they were assumed to be exposed to all loaded packages that passed through Las Vegas or Reno en route to the repository.
- Resident. In Nevada, Interstate Highway 15, the Las Vegas beltway, and U.S. Highway 95 would be used for truck shipments. There are typically buffer zones along interstate highways and beltways so people cannot build homes much closer than about 30 meters (98.4 feet) from the road. However, U.S. Highway 95 passes through Indian Springs on the way to the repository. In Indian Springs, an individual could reside as close as 24 meters (78.7 feet) from the highway. Therefore, the radiation dose was estimated for an individual who resided at this location and who was exposed to all loaded truck packages as they passed by en route to the repository.
- A Person Stuck in a Traffic Jam. This person is assumed to be next to the package for 1 hour. The person would be 1.2 meters (3.9 feet) from the package.
- A Person at a Service Station. This person would be exposed for 49 minutes to each truck package at a distance of 16 meters (52.5 feet).
- Resident. A resident living near the staging yard would be exposed to all loaded packages at the yard for a duration of 2 hours per package as assumed in Nevada Rail Partners (2007).

The following are from the NRC's advanced reactor environmental impact statement (EIS) (NRC 2006) for the MEI under normal conditions:

- Truck Crew Member. Truck crew members would receive the highest radiation doses during incident-free transport because of their proximity to the loaded shipping container for an extended period of time. The analysis assumed that crew member radiation doses are limited to 0.02 Sv (2 rem) per year.
- Inspectors. Radioactive shipments are inspected by Federal or State vehicle inspectors, for example, at State ports of entry. Assessments assumed that inspectors would be exposed for 1 hour at a distance of 1 m (3.3 ft) from the shipping containers.
- Resident. The analysis assumed that a resident lives 30 m (98.4 ft) from the point where a shipment would pass and would be exposed to all shipments along a particular route. These radiation dose estimates are based on an individual located 30 m (98.4 ft) from the shipments that are traveling 24 km/hr (15 mph).
- Individual Stuck in Traffic. This scenario addresses potential traffic interruptions that could lead to a person being exposed to a loaded shipment for one hour at a distance of 1.2 m (3.9 ft). The analysis assumed that this exposure scenario would occur only one time to any individual.
- Person at a Truck Service Station. This scenario estimates radiation doses to an employee at a service station where all truck shipments to/from the advanced reactors would stop. The assessment assumed that this person is exposed for 49 minutes at a distance of 16 m (52.5 ft) from the loaded shipping container.

The following are discussed in Appendix H of DOE (2012) for the Hanford tank closure. The hypothetical MEI radiation doses were accumulated over a single year for all transportation shipments. However, for the scenario involving an individual caught in traffic next to a shipping container, the radiological exposures were calculated for only one event because it was considered unlikely that the same individual would be caught in traffic next to all containers for all shipments. For truck shipments, the maximally exposed transportation worker would be the driver, who was assumed to have been trained as a radiation worker and to drive shipments for up to 2,000 hours per year, resulting in an accumulated exposure of 2 rem (0.02 Sv) per year. The maximum exposure rate for a member of a truck crew who is not a radiation worker would be 2 millirem (0.02 mSv) per hour (10 CFR 71.47(b)(4)).

- Individual Stuck in Traffic. This scenario evaluates the radiation dose to a person caught in traffic being exposed to a loaded shipment for 30 minutes at a distance of 1.2 m (3.9 ft) from the surface of the shipping container.
- Resident. This scenario evaluates the radiation dose to a resident living 30 meters (98.4 feet) from the highway used to transport the shipping container.
- Person at a Truck Service Station. This scenario evaluates the radiation dose to a service station worker working at a distance of 16 meters (52.5 feet) from the shipping container for 50 minutes.

The following three hypothetical scenarios were also evaluated for railcar shipments. For rail shipments, the maximally exposed transportation worker would be an individual inspecting the cargo at 1 meter (3.3 feet) from the shipping container for 1 hour.

- Rail-Yard Crew Member. This scenario evaluates the radiation dose to an employee working at a distance of 10 m (32.8 ft) from the shipping container for 2 hours.

- Resident. This scenario evaluates the radiation dose to a resident living 30 meters (98.4 feet) from the rail line where the shipping container is being transported.
- Resident. This scenario evaluates the radiation dose to a resident living 200 meters (656.2 feet) from a rail stop during classification and inspection for 20 hours.

The following exposure scenarios were evaluated in the Prairie Island Indian Community Transportation Dose Assessment (Maheras et al. 2023; Westra et al. 2023, 2024, 2025). These potential exposure scenarios were based on incident-free transport of SNF, meaning that it assumes that the SNF transportation occurs without any accidents. In this incident-free transportation radiation dose assessment, the following exposure scenarios were evaluated, which incorporated field data collected during the Prairie Island Field Team's surveys:

- Exposures at Grade Crossings. The radiation doses were estimated at a distance of 3 meters (9.8 feet) from the rail line for pedestrians and people in vehicles (Table 1). The 3-meter (9.8-foot) distance was based on measurements made at the Prairie Island Indian Community. Distances were measured using a Bushnell Bone Collector laser range finder (Figure 1).
- Exposures Along Frontage Roads. The radiation doses were estimated at a distance of 18 meters (59 feet) from the rail line (Table 1).
- Exposures at Residences, Churches, and Tribal Buildings. Table 1 lists the distances at which radiation doses were estimated for these locations.
- Radiation Doses to Bison That Live in Paddocks Along the Rail Line. The distance to the front bison paddock was estimated to be 83 meters (272.3 feet) (Table 1).

Radiation doses were estimated for a shipment of five transportation packages for four cases: (1) the five transportation packages with the highest radiation dose rates, (2) the five transportation packages with the lowest radiation dose rates, (3) five transportation packages with the average radiation dose rate, and (4) five transportation packages with the median radiation dose rate.

Table 1. Exposure location distances.

Location	Distance
Grade Crossing	3 m (9.8 ft)
Frontage Road	18 m (59.1 ft)
Residences (minimum distance evaluated)	15 m (49.2 ft)
Residences (maximum distance evaluated)	60 m (196.9 ft)
Church	35 m (114.8 ft)
Public Safety Building	95 m (311.7 ft)
Front Bison Paddock	83 m (272.3 ft)

Figure 1. Bushnell Bone Collector laser range finder.

For exposures at residences, radiation doses were estimated for a case where people were assumed to be outside (and therefore unshielded) and for a case where people were assumed to be inside a structure and shielded. Three types of structures were evaluated: a wood frame structure, a manufactured home structure, and a concrete structure. Table 2 lists the shielding factors for the three types of structures. For exposures at the church and the Public Safety Building, radiation doses were estimated for a case where people were assumed to be inside a structure and shielded. For people in vehicles (such as at a railroad crossing as a train passes), shielding was also used to estimate the radiation doses.

Radiation doses were estimated for four train speeds, 10, 25, 40, and 50 mph (resp. 16, 40, 64, and 80 km/hr). Ten miles per hour (16 km/hr) would be representative of the speed that a train would be traveling when exiting PINGP, 25 mph (40 km/hr) corresponds to the Federal Railroad Administration (FRA) speed limit for Class 2 track, 40 mph (64 km/hr) corresponds to the FRA speed limit for Class 4 track, and 50 mph (80 km/hr) corresponds to the maximum speed allowed by Association of American Railroads (AAR) Publication OT-55 for a key train transporting SNF (AAR 2019).

Radiation doses were also estimated assuming that a train was stopped. Based on discussions with Prairie Island Indian Community staff, an exposure time of 15 minutes was used.

Table 2. Shielding factors.

Structure	Gamma Radiation Shielding Factor	Neutron Radiation Shielding Factor
Outside (Unshielded)	1.0	1.0
Vehicle	0.60	1.0
Wood Frame Structure	0.74	0.48
Manufactured Home Structure (vinyl siding)	0.82	1.0
Concrete Structure	0.38	0.18

2.1 Summary of Previous MEI Exposure Times and Distances

The assumptions for the various MEI scenarios from each reference are summarized in Table 3. The exposure durations were estimated for a single year, except for certain cases, such as an individual stuck in traffic, where this was assumed to be a single event.

Table 3. Summary of maximally exposed individual radiation dose assumptions.

Individual	Distance	Exposure Duration	Maximum Allowable Dose	Reference
Crew Member/ Truck Driver	-	-	5 rem/yr (0.05 Sv/yr), 2 rem/yr (0.02 Sv/yr; DOE worker)	Chen et al. 2002
	-	-	2 rem/yr (0.02 Sv/yr)	DOE-STD-1098-99, Article 211
	-	1,000 hours per year for loaded packages	-	DOE 2008, Section G.5.1.2.1
	-	-	2 rem/yr (0.02 Sv/yr)	NRC 2006
Escort	27 m (88.6 ft)	2,000 hours per year	-	DOE 2008, Section G.5.1.2.1
Inspectors (Truck and Rail)	3 m (9.8 ft)	30 minutes	-	Chen et al. 2002
	1 m (3 ft)	1 hour	-	DOE-STD-1098-99, Article 211
	1 m (3.3 ft)	1 hour	-	DOE 2008, Section G.5.1.2.1
	1 m (3.3 ft)	1 hour	9–18 mSv/yr (900–1800 mrem/yr), assuming 0.14 mSv (14 mrem) per shipment	NRC 2006
Rail Yard Crew Member	10 m (32.8 ft)	2 hours	-	Chen et al. 2002
	10 m (32.8 ft)	2 hours	-	DOE-STD-1098-99, Article 211
	10 m (32.8 ft)	2 hours	-	DOE 2008, Section G.5.1.2.1
Resident (Truck and Rail)	30 m (98.4 ft)	Shipments pass at 24 km/h (15 mph), radiation dose is based on number of shipments	-	Chen et al. 2002
	30 m (98.4 ft)	Resident would be exposed to all shipments along a particular route	-	DOE-STD-1098-99, Article 211
	18 m (59.1 ft) from a rail line	Resident would be exposed to all loaded rail packages as they pass by en route to the repository	-	DOE 2008, Section G.5.1.2.1
	30 m (98.4 ft) from a road/highway	Resident would be exposed to all loaded truck packages as they pass by en route to the repository	-	DOE 2008, Section G.5.1.2.1
	30 m (98.4 ft) from where a shipment would pass	Shipments travel at 24 km/h (15 mph)	0.00027–0.00055 mSv/yr (0.027–0.055 mrem/yr)	NRC 2006
	30 m (98.4 ft)	-	-	DOE 2012, Appendix H

Individual	Distance	Exposure Duration	Maximum Allowable Dose	Reference
Person Stuck in Traffic	1 m (3.3 ft)	30 minutes	-	Chen et al. 2002
	1.2 m (3.9 ft)	1 hour	-	DOE-STD-1098-99, Article 211
	1.2 m (3.9 ft)	1 hour	-	DOE 2008, Section G.5.1.2.1
	1.2 m (3.9 ft)	1 hour, assumed to occur only one time to any individual	0.016 mSv (1.6 mrem)	NRC 2006
	1.2 m (3.9 ft)	30 minutes	-	DOE 2012, Appendix H
Person at Truck Service Station	20 m (65.6 ft)	2 hours	-	Chen et al. 2002
	16 m (52.5 ft)	49 minutes, assumed individual is present where all truck shipments would stop	-	DOE-STD-1098-99, Article 211
	16 m (52.5 ft)	49 minutes to each truck	-	DOE 2008, Section G.5.1.2.1
	16 m (52.5 ft)	49 minutes, assumed individual is present where all truck shipments would stop	0.044–0.09 mSv/yr (4.4–9 mrem/yr), assuming 0.0007 mSv (0.07 mrem) per shipment	NRC 2006
	16 m (52.5 ft)	50 minutes	-	DOE 2012, Appendix H
Resident near a Rail Stop	200 m (656.2 ft)	2 hours per package	-	DOE 2008, Section G.5.1.2.1
Resident near a Rail Yard	200 m (656.2 ft)	20 hours	-	Chen et al. 2002
	200 m (656.2 ft)	20 hours	-	DOE-STD-1098-99, Article 211
	200 m (656.2 ft)	20 hours	-	DOE 2012, Appendix H

2.2 Number of Shipments

The annual number of shipments of SNF can be estimated by using the estimated receipt rate of 3,000 metric ton(s) of heavy metal (MTHM) per year (Gadey et al. 2025) for a future Federal consolidated storage facility. Although there are multiple capacities for spent fuel transportation packages,12.5 metric tons of uranium (MTU) per package can be considered an average. This is based on an average pressurized water reactor (PWR) assembly mass of 0.45 MTU and an average package capacity of 28 assemblies (actual range is 24–37). Using these estimates, this equates to about 240 spent fuel shipments per year. It should be noted that a shipment in this context is a single transportation package. It is expected that these packages will be transported mostly by rail with a single consist containing 5 to 7 spent fuel packages. Therefore, it is possible for certain MEIs to have 5–7 times the exposure from that of a single package. Some spent fuel transportation packages may be shipped as a single heavy haul package in areas where rail lines are not available.

The numbers of shipments for SNF and high-level waste (HLW) were estimated in other references and are repeated below; however, these are multi-year shipping campaigns and per year shipments may not be easily derived.

Appendix J of DOE (2002) states for a shipping campaign expected to last 24 years:

> *Under the mostly legal-weight truck scenario for the Proposed Action, DOE would transport a total of 11,785 truck shipments of DOE spent nuclear fuel and high-level radioactive waste (one high-level waste canister per shipment) to the repository. In addition, DOE would transport 300 shipments of naval spent nuclear fuel by rail from the Idaho National Engineering and Environmental Laboratory to the repository (one naval spent nuclear fuel canister per rail cask). For [the expanded inventory case > 70,000 metric tons of heavy metal (MTHM)] under the mostly legal-weight truck scenario, the analysis estimated 26,001 DOE spent nuclear fuel and high-level radioactive waste truck shipments, as well as the 300 naval spent nuclear fuel shipments by rail.*
>
> *Under the mostly rail scenario for the Proposed Action, the analysis estimated that DOE would transport 2,128 railcar shipments of DOE spent nuclear fuel and high-level radioactive waste (five high-level waste canisters per shipment), as well as the 300 shipments of naval spent nuclear fuel. For [the expanded inventory case > 70,000 MTHM] under this scenario, DOE would transport 4,954 railcar shipments of DOE spent nuclear fuel and high-level radioactive waste, as well as the 300 shipments of naval spent nuclear fuel.*

Section 3.4 of (Chen et al. 2002) states the following:

> *Under DOE's Record of Decision (ROD) for the conduct of its Spent Fuel Management Program through the year 2035 (May 30, 1995), approximately 575 shipments of naval SNF will be made by rail to INEEL [Idaho National Engineering and Environmental Laboratory] from six sites (Kesselring, Norfolk, Newport News, Pearl Harbor, Portsmouth, and Puget Sound). While insufficient data are available regarding specific transport variables to accurately assess the total number and modal mix of other DOE shipments necessary for implementation, the ROD estimates that there will be a maximum of 3,655 shipments (to INEEL and SRS [Savannah River Site] combined), assuming that all shipments are by truck, with the exception of Naval SNF. In addition to the naval SNF, these projected shipments include about 546 shipments of special-case commercial SNF from 11 non-DOE origins; 1,008 shipments of foreign research reactor SNF through eight potential ports of entry; 519 shipments of domestic university research reactor SNF from 35 university reactors; and 1,007 intrafacility shipments of DOE-owned SNF from eight DOE weapons complex facilities.*
>
> *Under the Nuclear Waste Policy Act (NWPA) as amended, it is anticipated that SNF assemblies will eventually be transported from 72 commercial sites and five DOE sites throughout the United States to a geologic repository. If most SNF and HLW can be transported by rail, about 9,600 rail shipments and 1,080 truck shipments would be needed over a 24-year period. If legal-weight truck transportation must be used, about 53,000 truck shipments and 300 rail shipments (of naval SNF) would be needed. An additional 10,000 rail shipments or 40,000 legal-weight truck shipments of SNF and 1,500 rail shipments or 6,700 truck shipments of HLW may also be required.*
>
> *Other shipments of DOE radioactive waste are also expected to increase over the next several years. Approximately 38,000 truck shipments to the WIPP [Waste Isolation Pilot Plant] of TRUW [transuranic waste] are anticipated from about 22 sites over the next 35 years. Anticipated treatment and disposal of DOE low-level waste (LLW) could result in*

another 25,000 to 95,000 truck shipments over approximately 20 years, depending on the final regionalization strategy chosen.

3.0 Microreactor Transportation Assumptions

3.1 Conceptual Framework

Given the limited availability of detailed information on emerging microreactor concepts, coupled with the constrained timeframe of this project, the most plausible theoretical definition of a microreactor is based on representative designs where public information was available and that are currently furthest in development, such as those proposed by Westinghouse, X-energy, and Radiant. These designs align with the criterion of being readily transportable via heavy haul truck and rail, making them suitable benchmarks for this analysis. The microreactor is assumed to be factory produced, fueled, sealed, and deployed as a CONEX container style package prepared for transport and transported as a piece of cargo containing the reactor vessel and associated flanged off ducting exclusively. The balance of plant items (e.g., intermediate heat exchanger, power conversion unit, operations control unit, piping, etc.) of the theoretical microreactor are assumed to be packaged similarly and to be conducted under alternate transport initiatives. As such, systems external to the reactor are not considered as part of this study.

As discussed in the following sections, heavy haul truck would be the mass limiting transport configuration of the two transport modes considered. For initial simplicity, this evaluation primarily focuses on microreactors that are fueled with high-assay low-enriched uranium (HALEU) (<20% enrichment) TRi-structural ISOtropic (TRISO) fuel assembled in compacts for a prismatic/assembly type reactor core structure as opposed to pebble bed. Further, as a primary focus, it is assumed that the microreactor relies on either heat pipe or high temperature gas reactor (HTGR) heat exchange for power conversion.

A microreactor of no greater magnitude than 20 MWth with a theoretical efficiency to yield as high as 7 MWe peak power output during operation is assumed to maintain heavy haul truck transportability. A fuel mass of approximately 1.5 MTU and a 10-year operating life are required to complement the assumed reactor definition and provide an economically viable high density microreactor power generation solution, respectively. Although some vendors have proposed transporting microreactors several times prior to the end of life (EOL), the microreactors assumed within this assessment are conservatively assumed to be at EOL with their fuel consumed and to be prepared for retrieval shipment (transport back to the factory source for recycling or final disposition) after being allowed to cool for a specific duration prior to retrieval. The EOL assumption bounds that of any intermediate life shipments due to higher burnup. Cooling durations of 1 day, 30 days, and 1, 2, and 3 years prior to retrieval are selected to establish the associated potential radiation dose rate sensitivity to the receptor.

Typical design features of the recently proposed microreactors include some operational shielding that is integrated between the reactor and CONEX cargo packaging. This shielding is typically designed to remain in place during final transport initiatives. Additional transport shielding is also anticipated to be added to external surfaces of the CONEX cargo packaging when prepared for transport to reduce external radiation dose rates to permissible levels.

3.2 Shipment Modes

Microreactors could be transported by highway, rail, and barge/vessel. The transport of an irradiated microreactor by air is unlikely because of the radiation dose rate, weight, and

plutonium content, i.e., the amount of plutonium contained in the microreactor would make the shipment subject to NRC's current plutonium air transport regulations.

A microreactor prepared for highway shipment would likely weigh in the range of 50 to 70 tons without additional transport shielding, with a gross vehicle weight of 70 to 100 tons. However, some microreactors could weigh much more, such as the eVinci design microreactor[1], which would weigh 365 tons as configured for shipment. This shipment would need to be made by heavy haul truck, and in some States, the shipment would qualify as a superload[2]. Heavy haul truck shipments are subject to State-specific permitting requirements, and superloads are subject to increased permitting requirements.

For rail shipments, a microreactor weighing in the range of 50 to 70 tons would be well within the capabilities of the U.S. rail system to ship. A microreactor that weighed 365 tons would have to be shipped using a 16- or 20-axle shiftable railcar.

For the weights discussed above, shipment by barge or vessel would also be feasible, but likely only for those deployment sites without highway or direct rail access. The primary exposures would likely be for workers.

3.3 Number of Shipments

There are two general use cases for the deployment of microreactors. The first use case is the deployment of microreactors without onsite storage. In this case, the microreactor reactor would be deployed from a factory to an operating site (such as a data center or power generating station), operated, and then returned to the factory after some period of cooling. This scenario has been discussed by Westinghouse for their eVinci microreactor. In this use case, an MEI would likely be located near the microreactor factory, and this individual could be exposed to microreactors shipped from several deployment sites. At this time, the number of shipments that an individual might be exposed to is unknown; it has been postulated that there may be as many as 50 shipments per year. For the analysis presented here, the radiation dose from an individual microreactor shipment as well as 10 shipments per year were assumed.

The second use case is the deployment of microreactors with onsite storage occurring at a reactor operating site. In this case, the microreactor SNF would remain at the reactor site as is currently occurring at the existing utility sites. This is likely the plan for most microreactor vendors (e.g., X-energy is planning for a Spent Fuel and Isotope Storage Facility integrated into the power plant). Eventually, the stored microreactors would be shipped offsite for storage or disposition. The MEI would likely be located near the storage or disposition site, and this individual could be exposed to microreactors shipped from several deployment sites. As with the first use case, the number of shipments that an individual might be exposed to is also unknown; it has been postulated that there may be as many as 50 shipments per year. For the analysis presented here, the radiation dose from an individual microreactor shipment as well as 10 shipments per year were assumed.

The two microreactor use cases discussed above have been espoused by various microreactor vendors, and there is currently no consensus on which use case will dominate.

[1] Although Westinghouse has announced it is no longer pursuing this reactor design, it is referenced here as information about this design is publicly available.
[2] Definitions and requirements for a "superload" are defined by each state.

3.4 Additional Controls

Additional controls in the form of compensatory measures may be used to reduce the risks associated with transporting microreactors containing irradiated fuel. Many of these measures are already required by other requirements (e.g., DOT, State requirements), and it is possible that compensatory measures that are required through other non-NRC requirements could be credited as part of the NRC transportation package approval.

NRC regulations in 10 CFR 71.5 require that licensees who ship radioactive material or offer radioactive material for transport comply with the DOT regulations in 49 CFR Part 107, the DOT Hazardous Materials Regulations in 49 CFR Parts 171–180, and the DOT Federal Motor Carrier Safety Administration Regulations in 49 CFR Parts 390–397. These regulations include requirements for packaging, marking and labeling, placarding, accident reporting, shipping papers and emergency information, hazardous material employee training, security plans, and hazardous material carrier/shipper registration. Specifically, microreactors containing irradiated fuel shipped by highway would contain a highway route controlled quantity (HRCQ) of radioactive materials (>3000 A_2) and would need to meet the routing requirements in 49 CFR Part 397. This requires transport to be conducted using interstates, beltways around cities, and State-identified preferred routes. Transport on these types of roads could be considered if there is potential for higher radiation dose rates because these types of roads are typically of higher quality and capacity than other roads.

A microreactor containing irradiated fuel shipped by highway would also likely be subject to a CVSA Level VI inspection (CVSA 2024) [see 49 CFR 385.415(b)]. This inspection would also be considered as a potential compensatory measure should higher radiation dose rates be needed for transportation.

Microreactors transported by highway would also likely be overweight/overdimension loads and would require State permitting when transported by highway. Typical permit conditions include maximum length, width, and height requirements; escort vehicle requirements; pole car requirements; law enforcement escort requirements; and route survey requirements. These permit conditions could be considered as potential compensatory measures should higher radiation dose rates be needed during transportation.

Escort vehicles are designed to travel with oversized loads to ensure the safety of the load, the driver and other motorists. They help navigate the route, warn about potential obstacles and communicate with the truck driver to avoid incidents. Each State has its own regulations regarding escort vehicles and may require a front escort, rear escort, or both and may include requirements for local law enforcement escort.

Potential compensatory measures related to radiation dose rates could involve radiation dose rate buffer areas around a microreactor transportation package that are larger than the current radiation dose rate requirement of 10 mrem/h (0.1 mSv/hr) at 2 m (6.6 ft) from the conveyance contained in DOT and NRC regulations (see 49 CFR 173.441 and 10 CFR 71.47), making it possible to create a larger exclusion zone if higher radiation dose rates were needed during transportation.

Other potential compensatory measures include:

- real-time health/fitness onboard monitoring/diagnostics of the microreactor package;
- escorting the microreactor forward and aft for the entire route;

- travel at reduced speeds;
- closure of public roadways during transport;
- choosing a route that avoids bodies of water (balanced by quality of road);
- controls for bridges over bodies of water (bridge inspection, speed reduction, close bridge to other traffic);
- judicious use of time-of-day and day-of-week restrictions;
- avoiding shipping during severe weather; and
- conducting training for emergency responders along the route.

A safe haven is defined in NUREG-0561 (NRC 2013) as a readily recognizable and accessible site at which security is present or from which, in the event of an emergency, the transport crew can notify and wait for local law enforcement agency response. A safe haven is an area that can provide prudent security measures when a shipment is removed from transit because of an elevated threat condition. NRC security regulations in 10 CFR Part 73 require the identification of safe havens for highway transport of SNF. A microreactor containing irradiated fuel would also be subject to this same requirement. However, people could be exposed to radiation from the microreactor while at a safe haven.

3.5 Proposed Exposure Scenarios

The following sections discuss the potential exposure scenarios for highway and rail transport. The baseline scenarios are postulated to be applicable generically to any radioactive material shipment. The microreactor specific scenarios include additional scenarios that might be applicable for microreactor shipments only. Additional distances are evaluated in some microreactor specific scenarios to investigate dose to MEIs if an additional buffer zone (discussed in Section 3.4) were instituted for a microreactor shipment.

3.5.1 Highway Transport

3.5.1.1 Baseline Scenarios for Workers

Truck Drivers. Truck drivers involved in the shipment of commodities such as SNF are typically radiation workers and are limited by the occupational exposure limits for radiation workers, i.e., 5 rem/year (0.05 Sv/year; 10 CFR 20.1201(a)(1)(i)). The location of the truck driver would be approximately 5 meters (16 feet) from a truck transportation package based on transport on a tractor-trailer truck. For a heavy haul truck shipment, the truck driver would be located 30 meters (98.4 feet) from the transportation package.

An example of a heavy haul shipment to illustrate the distance between the driver and the package is the San Onofre Nuclear Generating Station reactor vessel head shipment shown in Figure 2.

Figure 2. San Onofre Nuclear Generating Station Unit 1 reactor pressure vessel transport (photos courtesy of the Nevada Department of Transportation).

Additional photographs illustrating the distance between the driver and the package can be found in ANS (2020). The reactor pressure vessel weighed 670-tons and required six large trucks to push and pull it. As a microreactor would not be that heavy, pusher trucks would not be required.

Truck Inspectors. CVSA's operational policies do not require certified Level VI inspectors to participate in a radiation protection program. CVSA does strongly recommend to members that their inspectors be a part of a radiation protection program, however each member state must decide for themselves. It was assumed that workers who conduct CVSA Level VI inspections will be limited by Occupational Safety and Health Administration (OSHA) occupational exposure limits and that the areas around the package will be deemed a restricted area, i.e., limit of 5 rem/year (50 mSv/year; 29 CFR 1910.1096(b)(1)). Realistic inspection times and exposure distances are 1 hour and 1 meter (3.3 feet), respectively.

3.5.1.2 Baseline Scenarios for the Public

Person Stuck in Traffic. For persons stuck in traffic next to a shipment, an exposure distance of 1.2 meters (3.9 feet) and an exposure time of 1 hour were assumed.

Truck Escorts. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, an exposure distance of 60 meters (197 feet) was assumed. This distance is based on typical distances for escorts enforcement that would drive in front of or behind the package as required by state requirements for heavy haul and superload transport.

Person at Service Station. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, it will be assumed that a member of the public (a service station attendant) would be exposed to shipments for 49 minutes (Griego et al. 1995) for each occurrence at a distance of 16 meters (52 feet).

Resident Along Route. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, it will be assumed that a nearby resident lives 30 meters (98.4 feet) from a point where shipments would pass. The resident would be exposed to all shipments along a particular route.

Person Exposed at a Safe Haven. Persons could be exposed at safe havens if shipments were delayed en route due to mechanical problems, bad weather, or hazardous road conditions or other unanticipated problems. The Yucca Mountain final environmental impact statement (FEIS) (DOE 2002) and the Repository supplemental environmental impact statement (SEIS) (DOE 2008) did not evaluate exposures at safe havens.

3.5.1.3 Microreactor Transport Scenarios for Workers

Truck Drivers. Truck drivers involved in the shipment of microreactors would be radiation workers and would be limited by occupational exposure limits for radiation workers, i.e., 5 rem/year (50 mSv/year; 10 CFR 20.1201(a)(1)(i)). Because of the weight of the microreactor, a heavy haul truck would likely be used, which means that the truck driver would be located further from the microreactor than 5 meters (16 feet). In this analysis, an exposure distance of 30 meters (98.4 feet) will be used. In addition, supplemental shielding could be installed in the occupied spaces of the vehicle (e.g., truck cab and sleeper, if present) to further limit radiation doses to truck drivers.

Truck Inspectors. CVSA's operational policies do not require certified Level VI inspectors to participate in a radiation protection program. CVSA does strongly recommend to members that their inspectors be a part of a radiation protection program, however each member state must decide for themselves. It was assumed that workers who conduct CVSA Level VI inspections will be limited by Occupational Safety and Health Administration (OSHA) occupational exposure limits and that the areas around the package will be deemed a restricted area, i.e., limit of 5 rem/year (50 mSv/year; 29 CFR 1910.1096(b)(1)). Realistic inspection times and exposure distances are 1 hour and 1 meter (3.3 feet), respectively.

3.5.1.4 Microreactor Transport Scenarios for the Public

Person Stuck in Traffic. For the highway transport of microreactors, it will be assumed that an exclusion zone would be present around the microreactor that would limit the distance that a member of the public could be from the microreactor. In this analysis, exposure distances of 10, 20, and 30 meters (resp. 32.8, 65.6, and 98.4 feet) will be assumed. An exposure time of 1 hour will be assumed.

Truck Escorts. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, an exposure distance of 60 meters (197 feet) will be assumed.

Person at Service Station. For the highway transport of microreactors, it will be assumed that an exclusion zone would be present around the microreactor that would limit the distance that a person could be from the microreactor. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, it will be assumed that a member of the public (e.g., a service station attendant) would be exposed to shipments for 49 minutes (Griego et al. 1995) for each occurrence at distances of 16, 20, and 30 meters (resp. 52.5, 65.6, and 98.4 feet).

Resident Along Route. For truck-sized transportation packages shipped on a tractor-trailer truck and for rail-sized transportation packages shipped on heavy haul trucks, it will be assumed that a nearby resident lives 30 meters (98.4 feet) from a point where shipments would pass. The resident would be exposed to all shipments along a particular route.

Person Exposed at a Safe Haven. The Waste Isolation Pilot Plant has established criteria for the selection of safe havens (i.e., safe parking areas) (CBFO 2022). The parking area selection hierarchy has been developed to incorporate two factors: (1) the desirability of a particular type of parking and (2) the driver's ability to reach that parking area under different types of emergencies.

- First Choice—Department of Defense or Department of Energy facilities
- Second Choice—Specific types of places (possibly, but not necessarily pre-designated by States) (e.g., truck stops, State highway department sheds/yards, ports of entry, National Guard units)
- Third Choice—Factors to avoid:
  - Highly populated areas
  - Areas that are difficult to evacuate in case of emergency (e.g., hospitals, schools)
  - Industrial areas (e.g., refineries)
  - Areas with difficult access
  - Crowded parking areas
  - Parked trucks carrying flammables or explosives
  - Poorly lighted areas
  - Highway shoulders
  - Residential areas
  - Areas with numerous pedestrians
  - Areas without driver services (e.g., food)

Based on the criteria above, in the event that a microreactor had to park at a safe haven, it will be assumed that the area around the microreactor could be secured out to a distance of 50 meters (164.0 feet). It will also be assumed that a reactor would be parked overnight, i.e., 12 hours.

3.5.2 Rail Transport

3.5.2.1 Baseline Scenarios for Workers

Rail Escorts. In contrast to truck escorts, who would typically be members of local law enforcement agencies and not necessarily radiation workers, rail escorts were assumed to be radiation workers. Rail escorts will be assumed to be located 27 meters (88.6 feet) from the microreactor being transported.

Railyard Workers. This assumption was based on SNF being shipped as part of a train that complies with AAR Standard S-2043 (AAR 2024). As such, railyard workers would conduct periodic walk-around inspections at railyards, but extensive inspections of railcars would not be required. In addition, Class I or Class IA brake tests are also required. These brake tests typically take 60–90 minutes although a worker would not be in close proximity to a spent fuel carrying railcar for this entire time. In this analysis, it was assumed that a worker was 10 meters (32.8 feet) from a rail package for 10 minutes. This is a refinement of the Yucca Mountain

scenario from Table 3 considering the additional requirements for the AAR Standard S-2043 rail consist.

3.5.2.2 Baseline Scenarios for the Public

Persons Exposed at Grade Crossings. The radiation doses will be estimated at a distance of 3 meters (9.8 feet) from the rail line for pedestrians and people in vehicles. The 3-meter (9.8-foot) distance was based on measurements made at the Prairie Island Indian Community but are representative of typical grade crossings.

Persons Exposed at Residences. Exposures at residences along railroad tracks will be evaluated at two distances—15 meters (49.2 feet) and 60 meters (196.9 feet). These distances were based on measurements made at the Prairie Island Indian Community but are representative of typical distances to residences along rail lines. Residents will be assumed to be outside and unshielded.

Residents near a Rail Stop. Exposures for residents near rail stops will be evaluated at a distance of 200 meters (656.2 feet), based on data from Chen et al. (2002), DOE (2002), DOE (2008), and DOE (2012). Residents will be assumed to be exposed for two hours, which is representative of rail shipments made using a dedicated train.

3.5.2.3 Microreactor Transport Scenarios for Workers

Rail Escorts. In contrast to truck escorts, who would typically be members of local law enforcement agencies and not necessarily radiation workers, rail escorts will be assumed to be radiation workers. Rail escorts will be assumed to be located 27 meters (88.6 feet) from the microreactor being transported.

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3.5.2.4 Microreactor Transport Scenarios for the Public

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Residents near a Rail Stop. Exposures for residents near rail stops will be evaluated at a distance of 200 meters (656.2 feet), based on data from Chen et al. (2002), DOE (2002), DOE (2008), and DOE (2012). Residents will be assumed to be exposed for two hours per package, which is representative of rail shipments made using a dedicated train.

4.0 Source Term

Previous incident-free transportation radiation dose assessments to individuals have assumed that the radiation dose rate of the transportation shipment is at the regulatory limit of 10 mrem/hr (0.1 mSv/hr) at 2 meters (6.6 feet). It is important to understand the characteristics of the radiation field to be able to understand how this radiation field behaves as a function of the distance from the package. The radiation dose that a person receives may be due to exposure to a combination of gamma and neutron radiation at particular energy spectra based on the source nuclides.

The design of the reactor and the shielding materials within the transportation package would affect the characteristics of the radiation field surrounding the package and the exposure that individuals would receive. The source terms are primarily dictated by the fuel type, the amount of initial uranium present, the fuel burnup achieved, and the post-irradiation cooling time after shutdown after which the reactor is transported.

4.1 Assumptions and Inputs to Source Term Calculations

This section discusses the radiation source term calculations performed, including the reactor operating parameters and materials that are subject to neutron activation.

4.1.1 Fuel Type and Initial Enrichment

Microreactors have been proposed with many different design and operating strategies, such as liquid sodium cooled, gas cooled TRISO based, and metallic fuel with heat pipes. The various reactor types and operating strategies will have a significant effect on the source term. The majority of microreactors implement a TRISO-based design based on HALEU fuel.

The radiation dose assessment presented here uses HALEU TRISO-based fuel elements as it is a more common fuel type proposed for advanced microreactors. A prismatic graphite block design using 19.75 wt% enriched uranium is used as the design basis microreactor for this work.

4.1.2 Initial Uranium Loading and Final Burnup

The amount of uranium initially loaded and the EOL fuel burnup are both important considerations in developing the source term. Little information related to the fuel loading or burnup is formally documented by the reactor vendors for their designs; however, the power levels and expected operating lifetimes of the reactor designs are available. These parameters are also closely linked in terms of the amount of total energy that can be extracted from the core. Westinghouse indicates that the power level of the eVinci™ microreactor would be 15 MWth with an expected operational life of 8 years (Westinghouse Electric Company n.d.). The study performed in (Germonpre and Buongiorno 2024) indicates that the Westinghouse eVinci™ reactor would use a fuel loading of 0.880 MTU.

Reactor burnup levels have a large impact on the source term characteristics in that a higher burnup, especially with a harder neutron spectrum, causes more actinide buildup. This has a much larger effect on neutron source term spectra. Although neutron radiation is generally a much lower contributor to the overall radiation dose, it can still have a significant contribution to an MEI if transportation packages do not contain sufficient neutron shielding. Characterizing the

neutron source term can be important due to other effects such as secondary gamma productions where neutrons interact with common materials, such as iron or hydrogenous materials, and produce high energy gamma rays. Representative depletion models for prismatic block TRISO reactors of the Heat Pipe Microreactor (HPMR) model from (Hartanto et al. 2025a) can reasonably approximate the neutron energy spectrum that would be experienced by the TRISO-based microreactors. The envelope of reactor power levels and lifetimes included in Section 3.1 includes reactors having power levels of up to 20 MWth and core lifetimes of 10 years. However, it is recognized that some of the microreactors are much smaller and can reasonably be expected to have thermal outputs in the 3.5 MWth range. To account for the potential variation in designs, two microreactor concepts are analyzed in this work. For the larger concept, it is likely that the uranium loading would be increased to account for the increased operational duty. Scaling (10/8 years × 20/15 MWth) 0.880 MTU up from the eVinci power and lifetime yields a uranium mass of 1.466 MTU, which can be conservatively rounded to 1.5 MTU. With a total energy demand of 10 years at 20 MWth and a uranium loading of 1.5 MTU, the final fuel burnup would be 48,667 MWd/MTU. So, the source term for the larger reactor will be based on enrichment of 19.75 wt% and a burnup of 48,667 MWd/MTU with a core loading of 1.5 MTU for the larger reactor. The uranium loading for the smaller microreactor concept is scaled down from the larger variant by a factor of 3.5/20 to arrive at an initial loading of 0.2625 MTU. Within the context of this report, these are referred to as the 3.5 MWth variant and the 20 MWth variant.

4.1.3 Cooling Time

The cooling time has a significant impact on source spectra as it determines which nuclides will be present at the time an individual could be exposed. Shorter lived fission products have higher energy gammas than longer lived fission products.

To account for the variation in the operational strategies of the different reactor vendors, multiple cooling times will be used within the analysis, including 1 day, 30 days, and 1 and 3 years post-irradiation.

4.1.4 Activation Products

Beyond fuel-derived source terms, structural activation significantly contributes to microreactor radiation dose rates during transport operations. The compact geometry of microreactor designs results in a high neutron flux at structural components in close proximity to the active core, combined with extended operating lifetimes (3–20 years). This makes structural activation the dominant radiation dose rate contributor at transport-relevant cooling times.

Activation primarily occurs in Type 316 stainless steel components used extensively for the heat pipes, pressure boundaries, core supports, and internal shielding. For example, heat pipe reactor designs (e.g., eVinci™, NuScale LMTM, and Oklo Aurora) present unique challenges, as hundreds of sodium-filled stainless steel heat pipes penetrate the core and experience high neutron fluences over operational lifetimes. Carbon steel pressure vessel materials undergo activation to a lesser extent.

The dominant long-term activation product is ^{60}Co, produced from trace cobalt impurities in nickel bearing components via the activation of ^{59}Co. Despite low concentrations, the large thermal neutron capture cross section (37.2 barns) of ^{59}Co leads to substantial ^{60}Co production. With a 5.27-year half-life and high-energy gamma emissions (1.17 and 1.33 MeV), ^{60}Co controls external radiation dose rates for up to approximately 20 years post-shutdown.

Since the entire reactor vessel and internal components are transported together, highly activated structures (e.g., heat pipes, vessel internals, core supports) cannot be easily separated or left behind. Although vendors may specify low-cobalt materials to minimize activation, practical engineering and supply chain constraints limit achievable purity levels. Commercial-grade stainless steel typically contains 500–1000 ppm cobalt, while nuclear-grade specifications may achieve <500 ppm but cannot eliminate cobalt entirely. Other structural materials including carbon steel vessels, Inconel components, and metallic coolants also undergo activation regardless of impurity control.

Structural activation is calculated for steel components such as the reactor vessel, heat pipes, and core supports with geometries representative of compact transportable reactor designs. A cobalt impurity level of 500 ppm was used. ^{60}Co activation during operation accounts for both neutron-induced production and radioactive decay, with activation rates scaled linearly for the 3.5 MWth and 20 MWth design variants studied in this work. The ^{60}Co source term was evaluated since it dominates external radiation dose rates beyond one year of cooling due to its intermediate half-life and high-energy gamma emissions.

4.2 Source Term Calculations

The microreactor concepts considered here have sources associated with the depleted fuel, the activation of the heat pipes within the core of the reactor and the activation of the vessel material that surrounds the core. The sources from the fuel and activation of the heat pipe material are directly calculated by depletion; however, the activation of the vessel requires an additional calculation.

4.2.1 Fuel Depletion Source Terms

The radiation source terms used for this work were derived from available models of graphite-moderated heat pipe microreactors. The depletion models used for this work are based on the assemblies in the HPMR calculations used in Hartanto et al. (2025b). The models consist of a single TRISO fueled, graphite moderated, and heat pipe cooled assembly. The assembly contains 24 fuel elements and 7 heat pipes, all encapsulated within a graphite monolith. The TRISO region of the fuel element is modeled as a smeared mixture of the graphite and uranium oxycarbide (UCO) fuel. The enrichment used for the calculation is 19.75 wt% ^{235}U. The heat pipe material is modeled as a mixture of the sodium coolant material and stainless-steel pipe material. The calculations are performed with the SCALE 6.3.2 version of the TRITON code using KENO-VI for the transport calculations. A radial view of the TRITON model is shown in Figure 3.

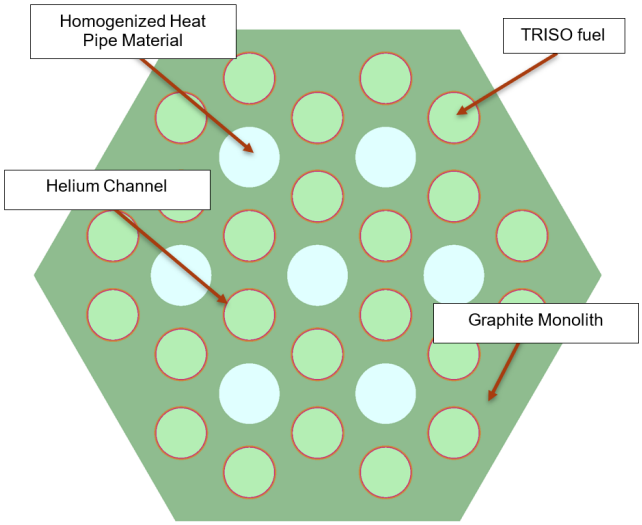

Figure 3. Radial view of the HPMR TRITON model used to generate the fuel depletion and heat pipe activation source terms.

The TRITON calculations were performed with an irradiation period of 10 years with a specific power of 13.33 MW/MTU for a final burnup of 48,667 MWd/MTU. At the end of the irradiation period, the mixture information from the fuel material information was extracted from the TRITON composition file and decayed to periods of 1 day, 30 days, 1 year, and 3 years using the SCALE 6.3.2 version of ORIGEN. The resulting source spectra can be directly read by the MAVRIC calculations discussed in Section 5.3. There are two microreactors used for this work: one with a 1.5 MTU initial core loading and one with a 0.2625 MTU initial core loading. The source terms generated by TRITON are output on a 1 MTU basis by default and are scaled to the appropriate initial uranium loading in the MAVRIC calculations to account for the variation in reactor size.

Figure 4 and Figure 5 show the gamma and neutron spectra from the microreactor fuel for the various cooling times, respectively, which are also compared to a typical PWR SNF assembly, although the PWR energy spectra are not plotted using the same group structure. In general, this shows that the microreactor energy spectra for the shorter cooling times (1 day, 30 days) have significantly higher gamma and neutron energies than those of the longer cooling time fuel.

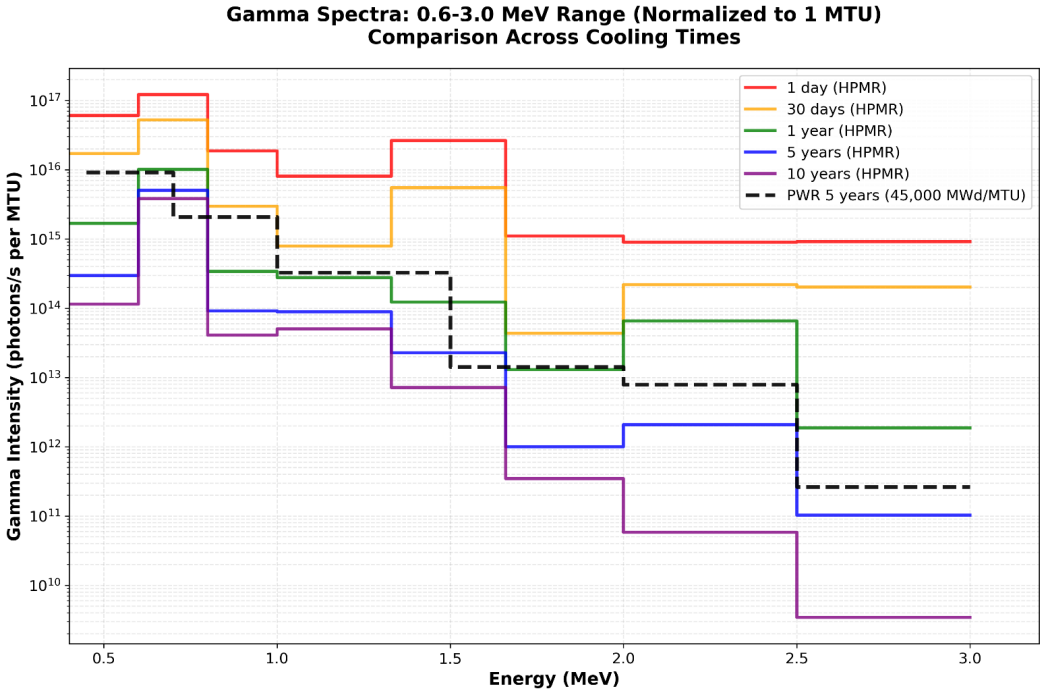

Figure 4. Gamma spectra from the fuel.

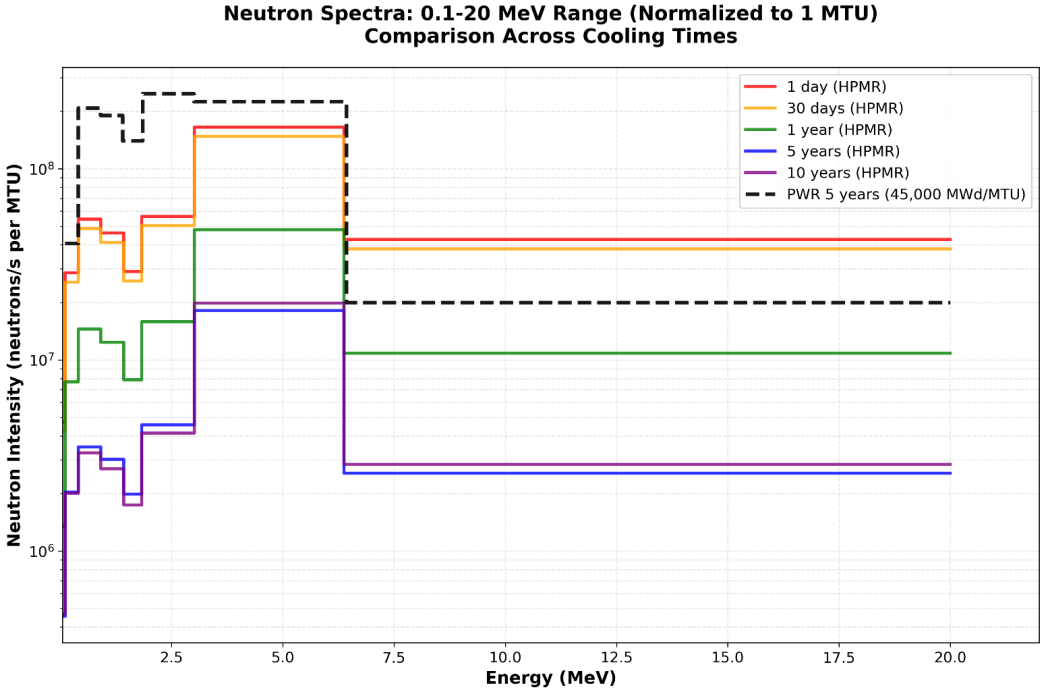

Figure 5. Neutron spectra from the fuel.

4.2.2 Heat Pipe Activation Calculations

The heat pipes that transport the heat out of the core are a significant gamma source for the microreactor variants considered here. The activation source term from the heat pipes was

calculated by inputting the flux tallied from the TRITON calculations in the heat pipe region into an ORIGEN irradiation calculation for the materials. The total amount of sodium and stainless steel was homogenized from the TRITON model for the activation calculation. The activation calculations assumed that there is 500 ppm ^{59}Co impurity in the stainless-steel heat pipe material. The heat pipe material was then decayed following irradiation with ORIGEN to the cooling times considered. The activation calculations were performed for one assembly's worth of heat pipe materials, so the final sources were scaled up by the appropriate factors for the 3.5 and 20 MWth variants of the microreactors considered in this work.

Figure 6 shows the activity of top activation products from the structural elements per assembly. At one day, activation from ^{24}Na is the dominant contributor to the overall activity, but with a half life of 15 hours, this quickly decays. At the 1 month cooling time, the activity from the activation products is dominated by the activation from ^{60}Co.

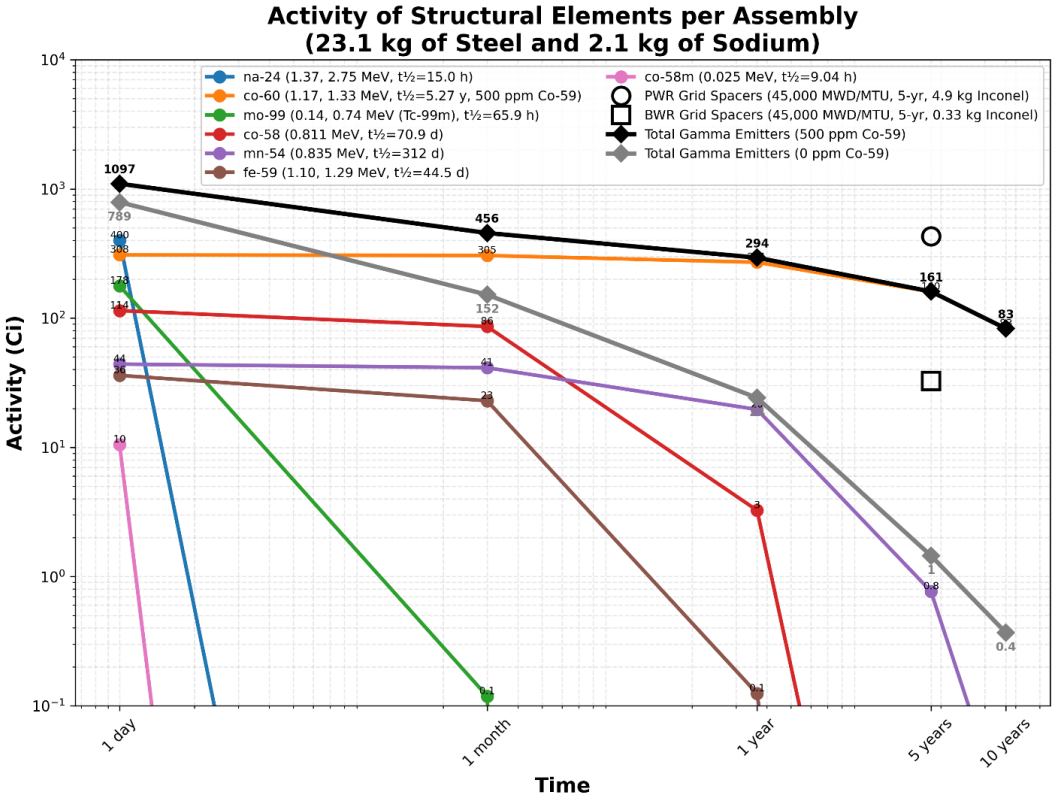

Figure 6. Activity of structural elements per assembly.

4.2.3 Vessel Activation Calculations

The analysis was performed in three steps. First, the SCALE/CSAS6 criticality code modeled the 1.5 MTU core configuration to calculate the neutron energy spectrum at the vessel location. The CSAS calculation is power-independent and establishes only the neutron spectrum. Second, this spectrum was used with the MCNP Monte Carlo transport code to model neutron interactions with the vessel. The vessel is an annular cylinder of SS316 stainless steel with an inner radius of 140 cm (55 in.), an outer radius of 147 cm (58 in.), and a height of 462 cm (182 in.), giving a total vessel volume of 1.822 cubic meters (64.3 cubic feet). The steel composition included ^{59}Co at 1 g/kg as an impurity. MCNP calculated the activation reaction rate

throughout the vessel volume of 9.45×10^{-8} reactions per source neutron. Third, a Python script was used to convert these reaction rates to absolute activities for 20 MW operation using standard activation equations. The calculations account for both the buildup of ^{60}Co during operation and its radioactive decay with a half-life of 5.27 years.

The 3.5 MWth variant is assumed to have the same thickness of vessel material; however, the reactor is smaller in diameter and length, so the total volume of the vessel is lower. The 3.5 MWth variant is assumed to have a vessel inner radius of 90.93 cm (36 in.) and a vessel outer radius of 97.93 cm (39 in.). For the 3.5 MWth variant, the source was scaled by the volume ratio of 0.416 to account for the decreased vessel volume.

5.0 Package Design

No microreactor designs have yet been approved under the NRC regulations in 10 CFR Part 71 for transportation; therefore, details about package design are speculative at this stage. This section presents the reactor and packaging design assumptions used to perform the radiation dose rate calculations.

5.1 Inherent Reactor Shielding

The reactor design fundamentally affects both the radiation source characteristics and the inherent shielding materials present within the reactor assembly. As described in Section 4.0, this analysis focuses on TRISO-based prismatic fuel designs with HALEU enrichment as representative of several emerging microreactor concepts. For TRISO-based designs, the graphite moderator material surrounding the fuel compacts inherently provides neutron shielding through moderation and absorption. Additionally, reactor pressure vessels or containment structures, typically constructed of carbon steel, stainless steel, or low-alloy steel with wall thicknesses ranging from 5 to 15 centimeters (2 to 5.9 inches) depending on the design pressure and structural requirements, contribute gamma shielding before external transport package shielding is considered. A stainless-steel reactor vessel was assumed with a wall thickness of 7 centimeters (2.8 inches), which provides additional gamma and neutron shielding. These inherent shielding materials represent the baseline attenuation present in the reactor assembly before external transport package shielding is applied.

The reactor model used in this work originated by simplifying the generic HPMR model from Hartanto et al. (2025a) shown in Figure 7.

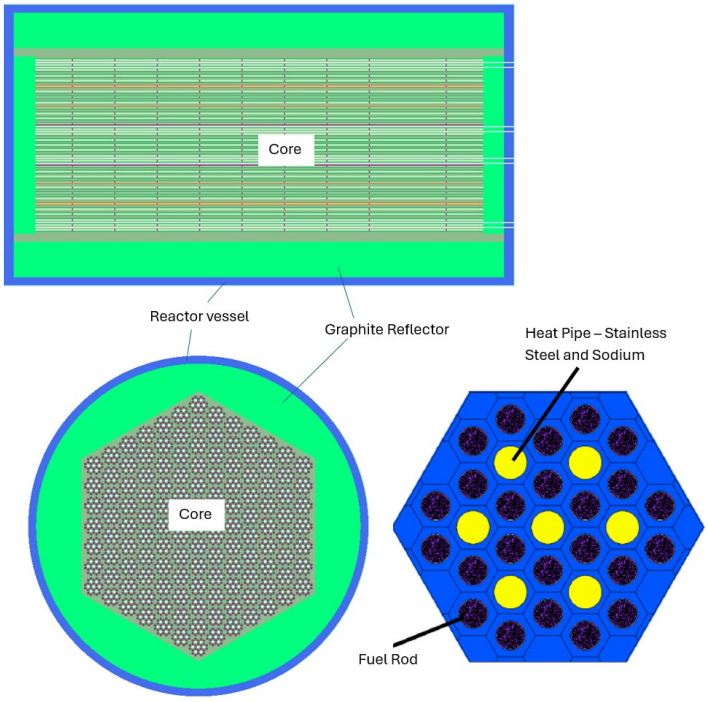

Figure 7. Generic HPMR developed by Idaho National Laboratory.

5.2 External Shielding Materials and Configuration

The external shielding applied to transport packages must address both high-energy gamma radiation and neutron emissions from the irradiated core. For microreactors with cooling times in the range considered in this study (1 day to 3 years), radiation dose rates are controlled by gamma emitters from fission products, structural activation, and neutron sources as described in Section 4.0. The relative contribution of each radiation component to the overall radiation dose rate depends on the reactor design, burnup, and cooling time. Heavy materials such as lead and steel are typically used to provide effective gamma attenuation. Hydrogenous materials such as polyethylene can be used to provide neutron moderation and absorption, with borated variants (borated polyethylene) offering enhanced thermal neutron capture. The external shielding for the models within this work was modeled as carbon steel for gamma attenuation, with thicknesses ranging from 10 to 40 cm (3.9 to 16 in.) to target the desired radiation dose rate at 2 meters (6.6 feet). Additional neutron shielding was not required due to the relatively low contribution from neutron radiation.

5.3 Package Dimensions and Configuration

It is desirable for a packaged microreactor to fit within a standard CONEX box with external dimensions of 30 feet (9 meters) in length, 8 feet (2.4 meters) in width, and 8 feet 6 inches (2.6 meters) in height. The CONEX box configuration offers advantages for intermodal transport compatibility across road, rail, and maritime shipment modes. There is experience and available equipment for handling containers using this standard size, and this would look visually indistinguishable from other cargo. However, achieving regulatory radiation dose rate compliance while remaining within these dimensional limits presents engineering challenges. Microreactor core dimensions vary by design, but representative compact reactor cores range from approximately 1.5 to 3 meters (4.9 to 9.8 feet) in diameter and 1.5 to 2.5 meters (4.9 to 8.2 feet) in height, depending on the specific technology (i.e., HTGR, heat pipe, or other configurations) and power rating. When external shielding of sufficient thickness is added to meet radiation dose rate targets, the total package dimensions may approach or exceed the internal dimensions of standard ISO containers (2.44 meters [8 feet] in width, 2.70 meters [8.9 feet] in height for high-cube variants).

A cylindrical geometry for the packaging was assumed for convenience. This design was simplified by homogenizing the core and placing layers in concentric cylinders around the core. The core region consists of a mixture of homogenized TRISO fuel particles, cladding, and graphite monolith, with a density of 1.9027 g/cm^3.

The diameter of the 20 MWth reactor variant discussed in Section 4.0 including the reflector and the vessel exceeds the width of a standard CONEX box. Therefore, when evaluating the radiation doses for this variant, the reactor and vessel design is assumed to be a special package wider than a standard CONEX box. The radius is 1.1653 m (3.822 ft), and the height is 4.42 m (14.5 ft). This is surrounded by a graphite reflector that is 23.47 cm (9.24 in.) thick radially and axially. This layer is surrounded by a 7 cm (2.8 in.) thick stainless steel vessel. The resulting vessel has external dimensions of a radius of 1.47 m (4.8 ft) and a height of 5.0294 cm (16.5 ft). The carbon steel shielding is then added to the outside of the vessel to establish shielding thicknesses corresponding to each target radiation dose rate at 2 meters (6.6 feet).

For the 3.5 MWth variant that fit inside a standard CONEX box (all but the 1 day cooled cases), the package is assumed to be as wide as a standard CONEX box (8 ft [2.4 m]). The radius is

0.6746 m (2.2 ft), and the height is 2.5588 m (8.4 ft). This is surrounded by a graphite reflector that is 23.47 cm (9.24 in.) thick radially and axially. This layer is surrounded by a 7 cm (2.8 in.) thick stainless steel vessel. The resulting external dimensions of the vessel are a radius of 1.0093 cm (3.3 ft) and a height of 3.2282 cm (10.6 ft). The carbon steel shielding is then added to the inside of the CONEX box to establish shielding thicknesses corresponding to each target radiation dose rate at 2 meters (6.6 feet).

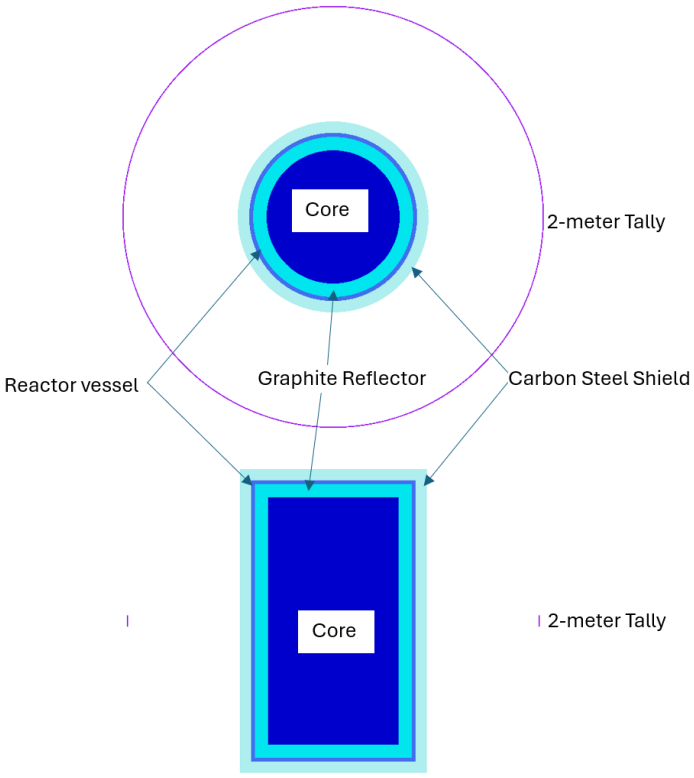

Figure 8. Simplified microreactor package (top: X-Y axial view, bottom: X-Z radial view).

5.4 Shield Thickness Results

The 3-D Monte Carlo MAVRIC code from SCALE 6.3.2 was used to calculate the radiation dose rate at 2 meters (6.6 feet) radially from the package surface at the axial center. The 1977 ANS/ANSI 6.1.1 fluence-to-dose rate conversion factors were used to convert the MAVRIC calculated fluence rate to a radiation dose rate based on the guidance in NRC (2020).

A 20 cm (7.9 in.) height and 2 cm (0.79 in.) thick cylindrical region tally was used. The results of the calculations that determine the various shield thicknesses for each case are shown in Figure 9 for the 20 MWth variant and Figure 10 for the 3.5 MWth variant. The total radiation dose rate was plotted as a function of the shield thickness to determine the shield thickness that would result in a target radiation dose rate of 10, 50, 100, and 200 mrem/hr at 2 meters (6.6 feet). Logarithmic interpolation was used to determine the shielding thickness at which the target radiation dose rate at 2 meters (6.6 feet) will be achieved, and the interpolated results are also shown in Table 4 for the 20 MWth variant and Table 5 for the 3.5 MWth variant. These results show that if the 2-meter (6.6-foot) regulatory radiation dose rate limit from 10 CFR 71.47 was increased to 200 mrem/hr (2 mSv/hr), then the shielding can be reduced by approximately 8–10 cm (3.1–3.9 in.), depending on the reactor cooling time. This assumes a carbon steel

shield; other shield materials (e.g., lead) would show different changes in shielding thickness. Also, the difference in shield thickness decreases with increasing cooling times.

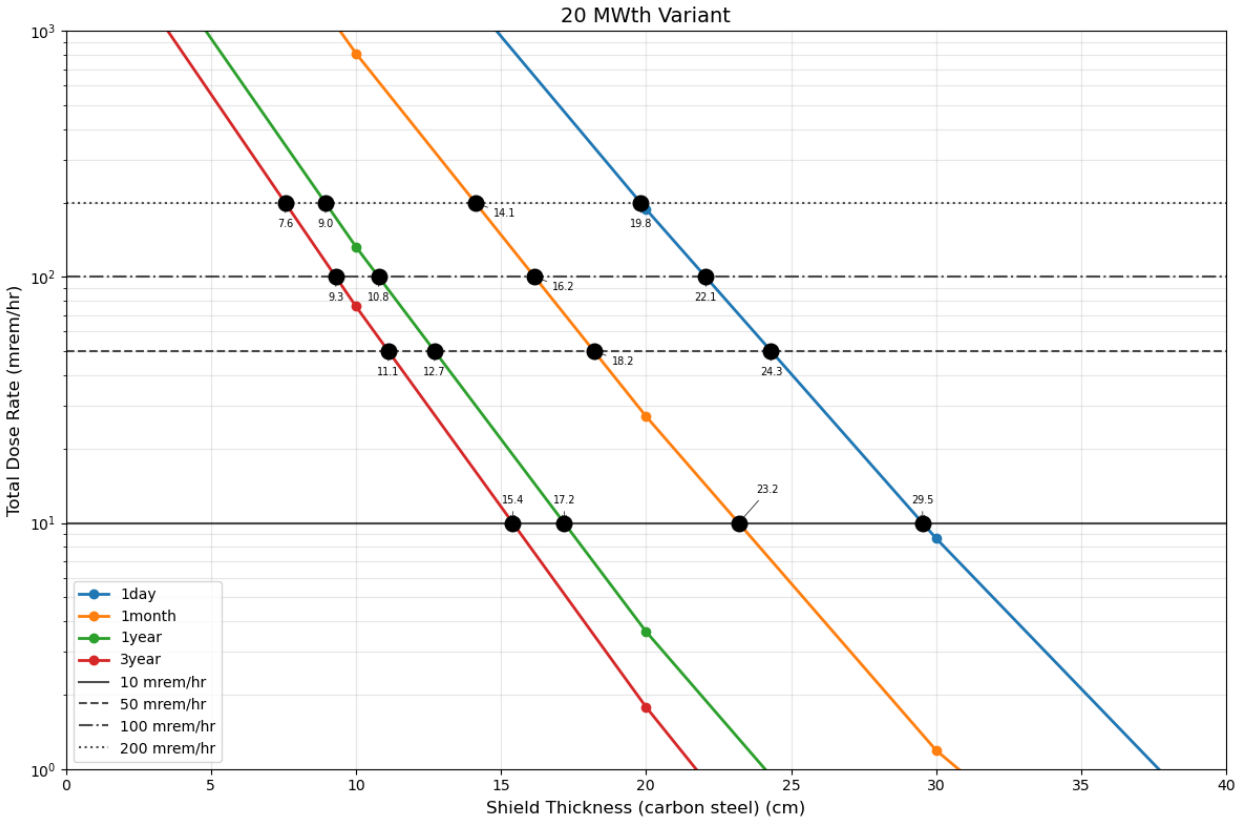

Figure 9. Total radiation dose rate as a function of the shield thickness for the 20 MWth variant.

Table 4. Shield thickness in centimeters for each target radiation dose rate at 2 meters (6.6 feet) for the 20 MWth variant.

Cooling time	10 mrem/hr (0.1mSv/hr)	50 mrem/hr (0.5 mSv/hr)	100 mrem/hr (1 mSv/hr)	200 mrem/hr (2 mSv/hr)
1 day	29.53	24.31	22.06	19.82
1 month	23.19	18.20	16.16	14.12
1 year	17.18	12.71	10.79	8.95
3 years	15.41	11.12	9.31	7.56

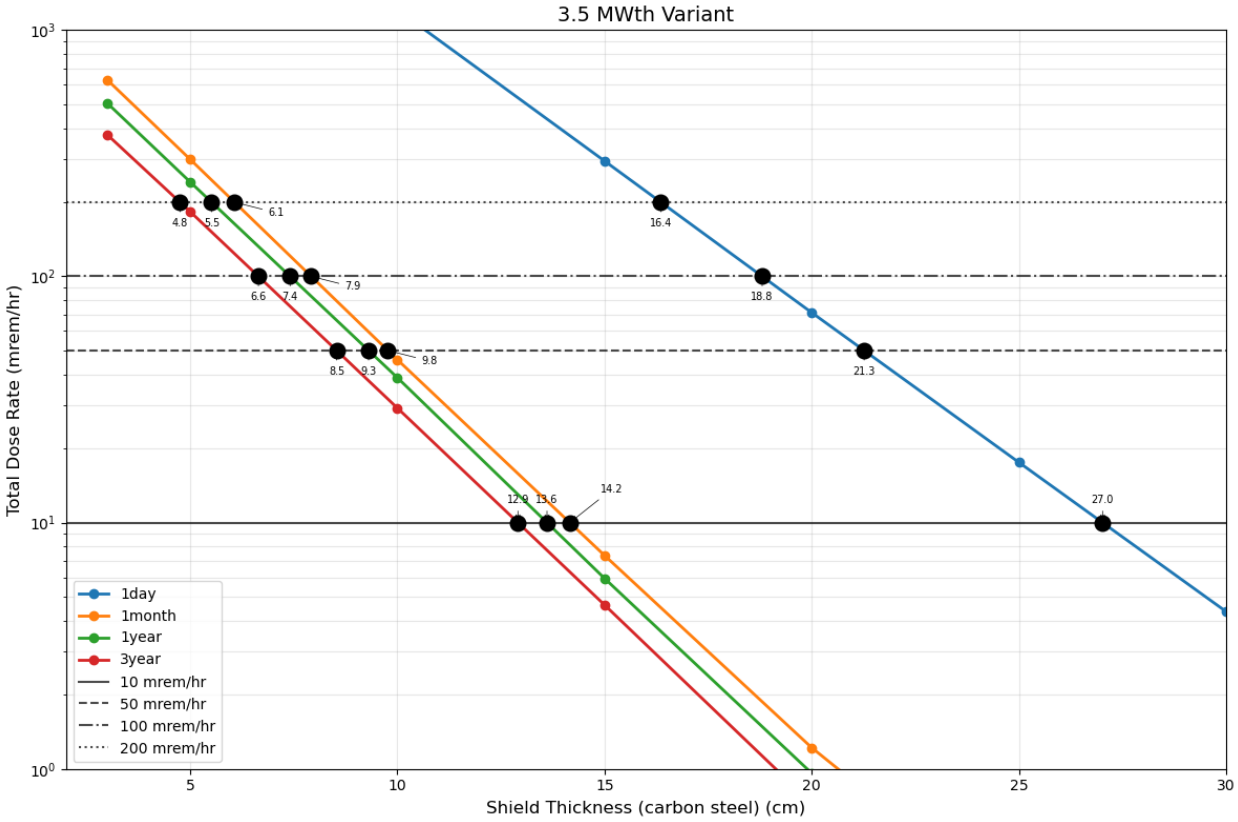

Figure 10. Total radiation dose rate as a function of the shield thickness for the 3.5 MWth variant.

Table 5. Shield thickness in centimeters for each target radiation dose rate at 2 meters (6.6 feet) for the 3.5 MWth variant.

Cooling time	10 mrem/hr (0.1 mSv/hr)	50 mrem/hr (0.5 mSv/hr)	100 mrem/hr (1 mSv/hr)	200 mrem/hr (2 mSv/hr)
1 day	27.02	21.26	18.80	16.36
1 month	14.16	9.77	7.92	6.07
1 year	13.61	9.31	7.41	5.52
3 years	12.91	8.53	6.65	4.75

6.0 Dose Calculation for the Maximally Exposed Individual

The 20 MWth variant discussed using the shield thicknesses in Table 4 was modeled using MAVRIC to calculate the radiation dose rate as a function of the distance from the package surface. This model includes a layer of soil to account for groundshine and sufficient air above and around the package to account for skyshine. In this model, the reactor is elevated to represent transport on either a truck or rail car. The center of the package is maintained at 3.1 m (10.2 ft) from the ground, and external carbon steel shielding is adjusted based on the thickness of the shield, which places the bottom of the reactor approximately 1.2 m (3.9 ft) (depending on the shield thickness) above the ground.

The radiation dose rate versus distance calculations were divided into three calculations. A meshtally was used to calculate the radiation dose at all distances except for the farthest distance at 200 meters (656.2 feet), where a region tally was used. The meshtally closest to the package was placed from 1 to 24 meters (3.3 to 78.4 feet) using a width of 10 cm (3.9 in.) and a length of 10 cm (3.9 in.) for distances up to 5 meters (16.4 feet), and a length of 20 cm (7.9 in.) for distances of 5 to 24 meters (16 to 78.4 feet). The intermediate range tallies 27–60 m (89–197 ft) from the package are 1 meter (3.3 feet) wide and 2 meters (6.6 feet) long. The region-tally at 200 meters (656.2 feet) is 4 m (13.1 ft) wide and 8 m (26.2 ft) long. All tallies are 2 meters (6.6 feet) from the ground in height, similar to the height of a human receptor. A sample view of the MAVRIC model showing the meshtally is shown in Figure 11.

The 2-meter (6.6-foot) tally in the calculations to determine the thickness of the shield discussed in Section 5.0 was placed around the axial center of the package, similar to a calculation that may be done to support licensing; however, the radiation dose rates calculated for the MEI are based on the tallies on the ground. This is to simulate more realistic radiation doses to individuals who may be walking or working around the package. Therefore, distances are referenced from the plane coincident with the outer surface of the package.

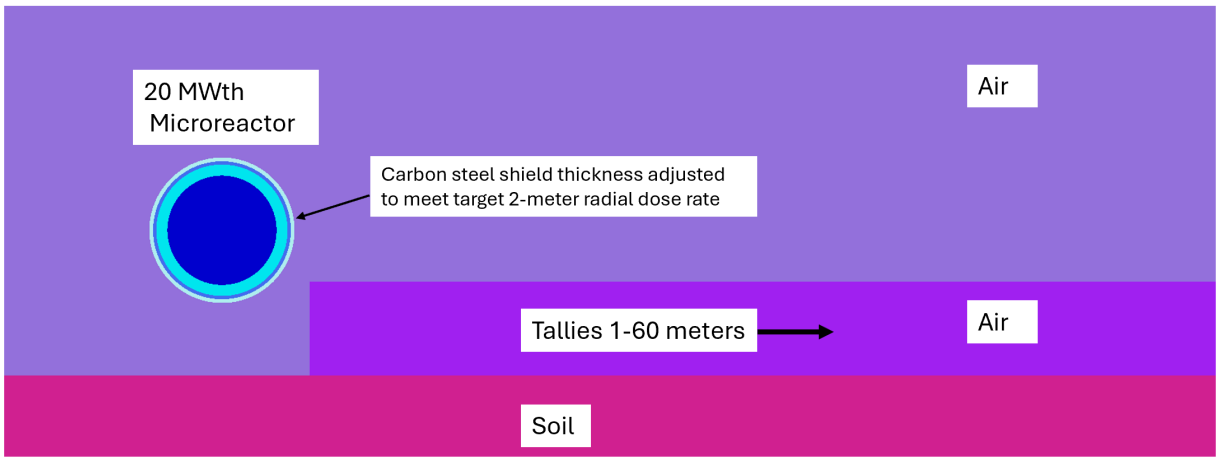

Figure 11. 2-D view of the MAVRIC model used to calculate the radiation dose versus distance.

The radiation dose rate to distance data were generated separately for each source term component, including gammas from fuel, neutrons, ^{60}Co activation from the vessel, ^{60}Co activation from the heat pipes, and other activation products in the heat pipes. The dose rate versus distance results for the combinations of shielding thickness and cooling time

corresponding to 50 mrem/hr (0.5 mSv/hr) at 2 meters (6.6 feet) are shown in Figure 12. This shows the contribution from the various source term components for the varying cooling times and shield thicknesses. All other radiation dose versus distance data for other shield thicknesses and cooling times are located in Appendix A.

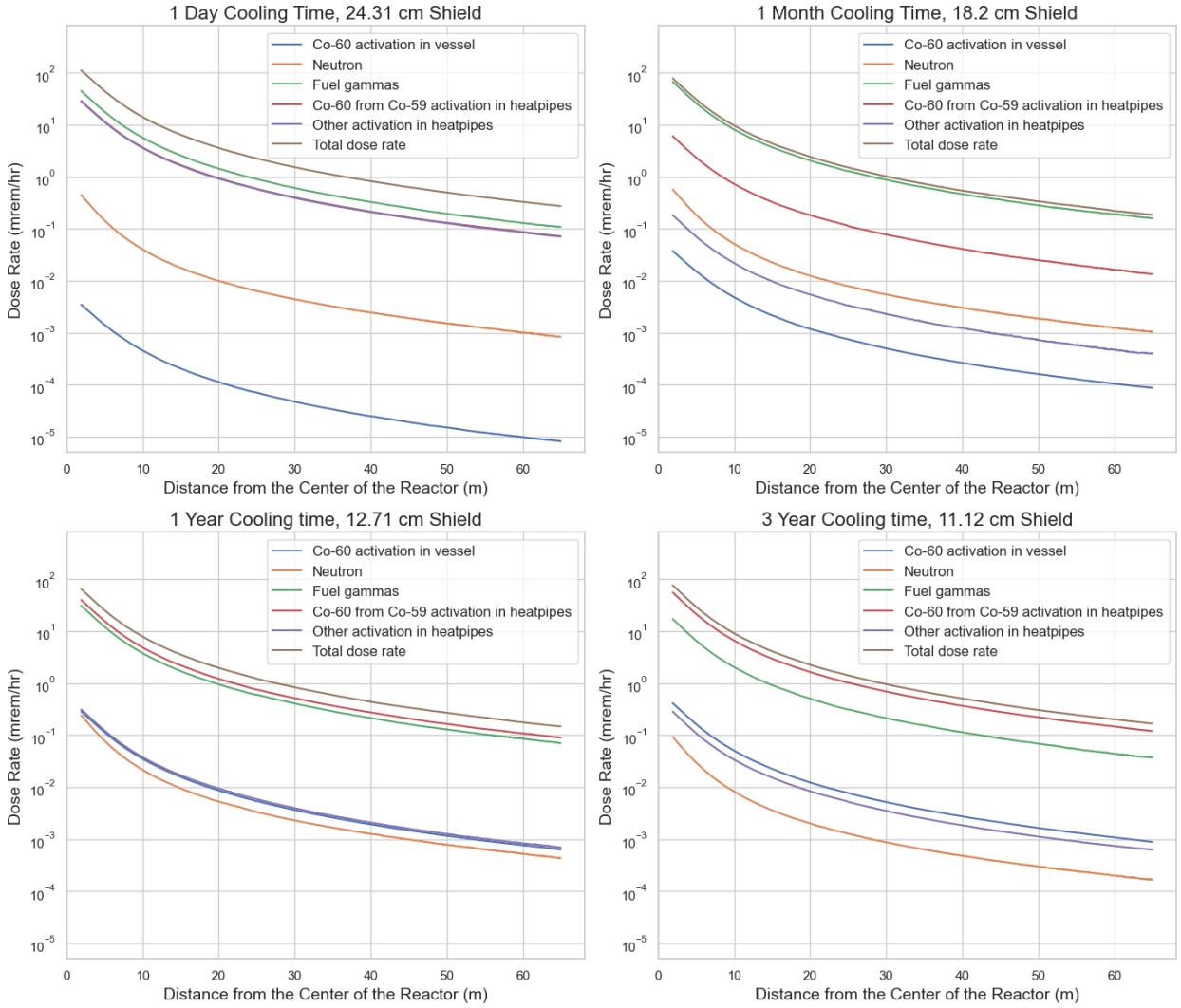

Figure 12. Dose rate versus distance from all source term components for the 20 MWth variant for four cooling times and the shield thickness adjusted so that radiation dose rate is 50 mrem/hr (0.5 mSv/hr) at 2 meters (6.6 feet).

Figure 12 shows that, for a 1-day cooing time, there is significant contribution from the activation of other materials besides ^{59}Co, but for all other cooling times studied, the source from other activation products is a far lower contribution. The radiation dose from fuel gammas dominates for the shorter cooling times; however, for 1- and 3-year cooling times, the radiation dose from ^{60}Co from the heat pipes becomes the dominant contributor to the radiation dose. The contribution from the activated vessel is proportionally small, with the neutron radiation dose also being a very small contributor. As the neutron radiation dose is such a small contribution, the radiation dose from n–gamma reactions has been neglected. It has been shown in Radulescu and Stefanovic (2023) that this can be the most significant contribution to the radiation dose very far from an SNF storage cask (>700 m); however, as the distances used

within this evaluation were not as large and with the neutron radiation dose so proportionally low, the radiation dose from n–gamma reactions was assumed to be insignificant.

Figure 13 shows the total radiation dose rate as a function of the distance with the distance calculated as the distance from the outer radius of the package surface. For each cooling time, the shield thickness was adjusted so that the calculated radiation dose rate at 2 meters (6.6 feet) from the package surface is 50 mrem/hr (0.5 mSv/hr). This shows that the shorter cooling times contribute to proportionally higher radiation doses farther from the reactor. This is because the higher energy gammas with shorter decay times contribute proportionally more to the radiation dose at larger distances, as they travel farther than lower energy gammas. The radiation dose to distance curve for the one-day cooling time does not appear to intersect at the same starting point despite these reactor and shield thickness combinations being determined with the same radiation dose rate at 2 meters (6.6 feet). This offset is likely because the shielding thicknesses were calculated using a tally placed 2 meters (6.6 feet) in the radial direction from the center of the package (see Figure 7), while the tallies for these radiation dose rate versus distance data were placed on the ground (Figure 11). Larger shield thicknesses also result in proportionally higher radiation doses at larger distances because the shield attenuates the lower energy gammas, resulting in a radiation field from higher energy gammas that are more likely to travel farther distances. Additional radiation dose rate versus distance data for other target radiation dose rate levels (10 mrem/hr [0.1 mSv/hr], 100 mrem/hr [1 mSv/hr], and 200 mrem/hr [2 mSv/hr]) at 2 meters (6.6 feet) are located in Appendix A.

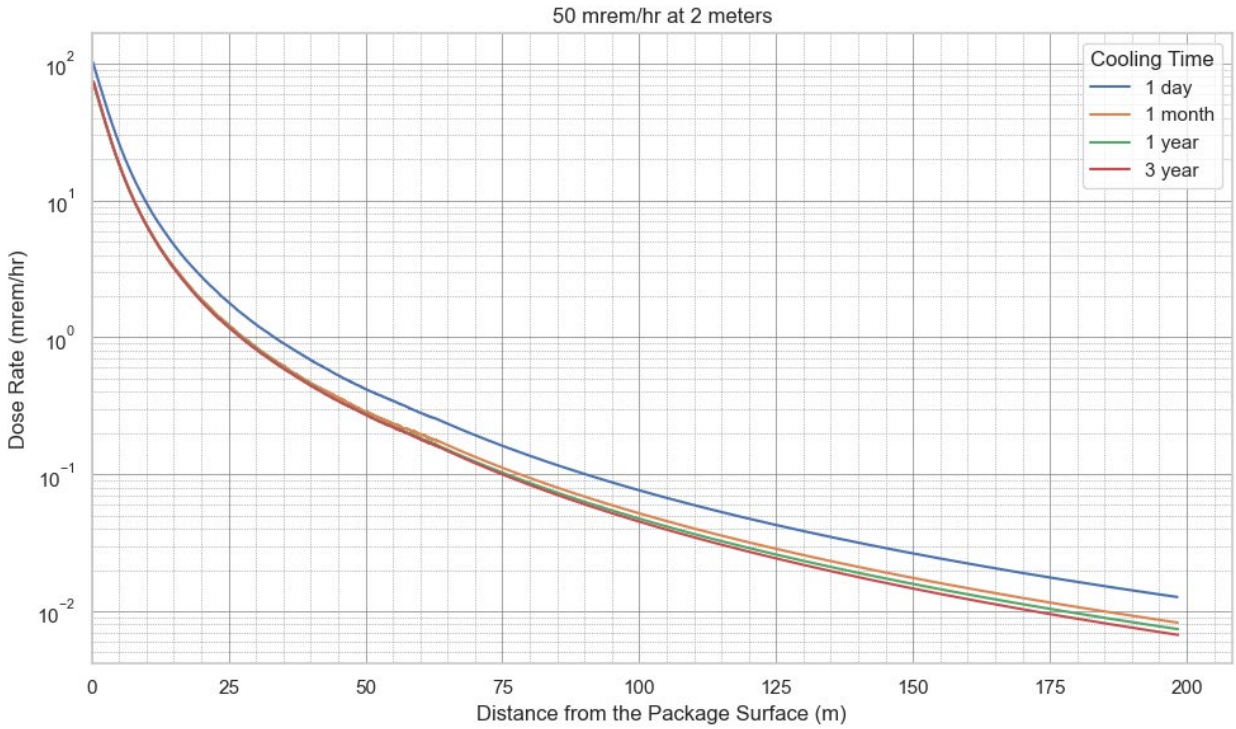

Figure 13. Total radiation dose rate versus distance data for four cooling times and the shield thickness adjusted so that the radiation dose rate is 50 mrem/hr (0.5 mSv/hr) at 2 meters (6.6 feet).

For calculating the radiation dose rate at the specified location of the the MEIs, the 1-month cooling time was used, as this is conservative in comparison to the other cooling times studied,

with the exception of the 1-day cooling time, but it is very unlikely that a microreactor would be transported after only 1 day of cooling time. The radiation dose rate versus distance data used for determining the radiation dose to the MEIs is shown in Figure 14.

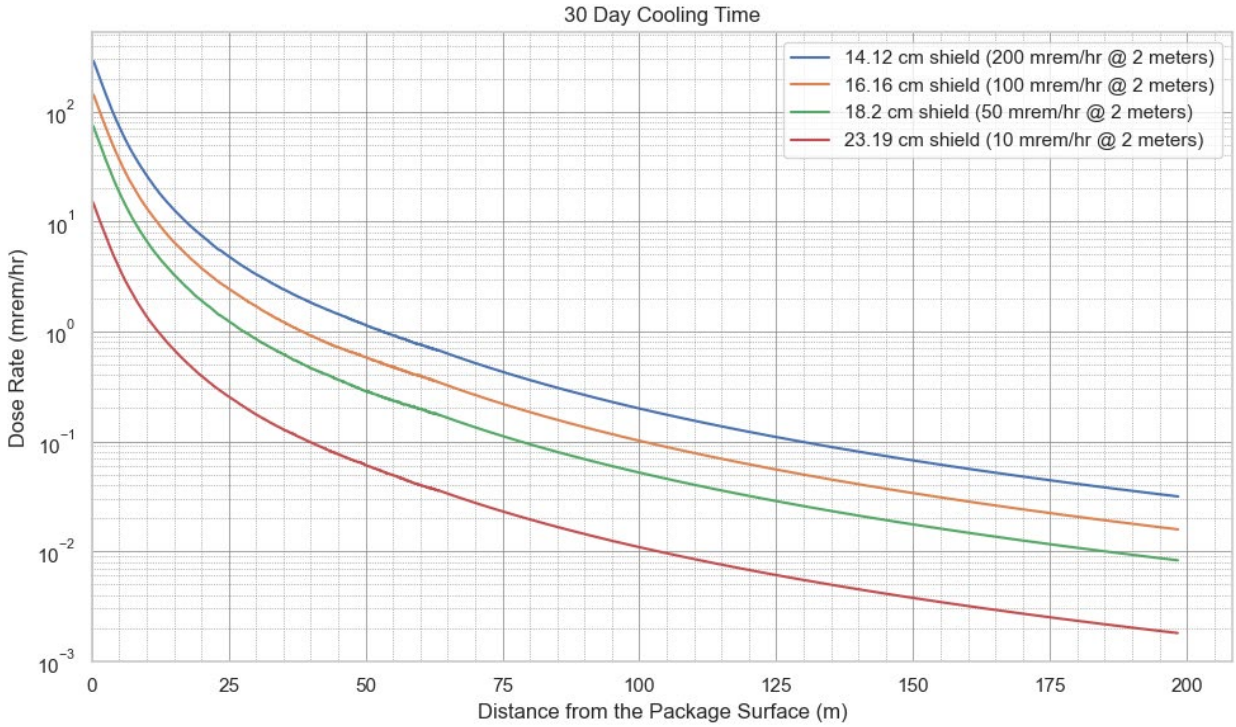

Figure 14. Total radiation dose rate versus distance for all 30-day cooling time scenarios.

Radiation dose to MEIs was calculated by determining the radiation dose rate from Figure 14 at the distance an individual is expected to occupy and multiplying this radiation dose rate by the amount of time the individual is expected to be at that location. Based on NRC (2020), the 1977 ANS/ANSI 6.1.1 fluence-to-dose rate conversion factors are used to convert the MAVRIC calculated gamma and neutron fluence rate to radiation dose rates in all calculations within this report. However, other conversion factors corresponding to specific regulatory dose limits (e.g., to the lens of the eye, skin, or extremities, or to total effective whole-body dose equivalent) may be more appropriate depending on the limit being evaluated. In addition, if calculated values are to be compared with measured values from dosimeters or survey instruments, the conversion factors used in this report may differ from those used in the calibration of the measurement devices.

6.1 Dose from a Moving Truck or Train

Equation (1) and Figure 15 were used to calculate the radiation dose from a moving truck or train. The radiation dose at each meter of travel was calculated based on the minimum distance to the reactor and the time needed to travel 1 meter (3.3 feet) based on the speed of the truck or train and multiplied by 2 to account for the coming and going of the moving truck or train. This radiation dose was summed from the minimum distance to the receptor up to 500 meters (1640.4 feet) as any additional distance was determined to have insignificant additional contribution to the radiation dose. The farthest MAVRIC calculated radiation dose rate was at

200 meters (656.2 feet), so all radiation dose rates beyond 200 meters (656.2 feet) were extrapolated using a logarithmic extrapolation.

$$\text{Total Dose} = 2 \times \sum_{N=1}^{N_{D=500}} DR \times \text{time} \quad (1)$$

where N = step number, step size is 1 meter

DR = the interpolated or extrapolated radiation dose rate at the distance D from the package surface based on the hypotenuse of the triangle formed using the minimum distance (min D) and the distance traveled (N × step size)

time = the amount of time it takes to travel 1 step size (1 meter [3.3 feet]) based on the speed S of the train or truck (time = step size/S)

$N_{D=500}$ = the number of steps needed for D to be 500 meters, calculated as follows:

$$N_{D=500} = \frac{\sqrt{(500\ \text{m})^2 - (\min D)^2}}{1\ \text{m}} \quad (2)$$

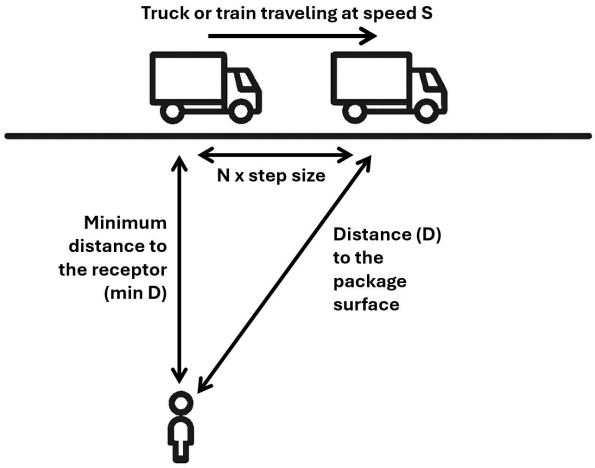

Figure 15. Distances used for moving truck or train scenarios.

The data in Table 8 and Table 9 are for a baseline assumption that a truck or train travels 15 mph (24 km/hr). This was used as a representative speed that is conservative. Radiation doses using other truck and train speeds from Table 6 and Table 7 were also calculated with the results presented in Table 10.

Table 6. Truck speeds for calculating the radiation dose from a moving package.

Scenario	Speed
Half residential	10 mph (16 km/hr)
Baseline	15 mph (24 km/hr)
Residential	20 mph (32 km/hr)
Typical speed limit	35 mph (56 km/hr)
Maximum speed	50 mph (80 km/hr)

Table 7. Train speeds for calculating the radiation dose from a moving package.

Scenario	Speed
Track Class 1	10 mph (16 km/hr)
Baseline	15 mph (24 km/hr)
Track Class 2	20 mph (32 km/hr)
Track Class 3	40 mph (64 km/hr)
OT-55 Maximum Speed	50 mph (80 km/hr)

6.2 Results of the Maximally Exposed Individual Radiation Dose Calculations

The results of the radiation dose calculations to the MEIs are shown in Table 8 for truck transport and Table 9 for rail transport. The dose rate data used to determine the dose rate for these calculations are shown in Figure 15. This data was interpolated at the distances discussed in Section 3.5 for each exposure scenario and multiplied by the time to get the total radiation dose per shipment and multiplied by 10 to estimate the radiation dose to MEIs assuming 10 microreactor shipments a year. As 50 per year was discussed as a theoretical maximum, these data should be multiplied by 5 to get radiation dose estimates for MEIs with 50 shipments/year. Most of the values are in terms of millirem (mrem). Some of the MEI exposures are in terms of hours per year and are independent of the number of shipments in which case the dose is calculated as a yearly maximum corresponding to the number of yearly hours expected of exposure. In some instances, MEI is expressed as the occupational dose limit of 5 rem/year (50 mSv/year), in which case the number of hours to reach this limit is determined. Additional moving truck and train scenarios for MEIs are provided in Table 10.

6.2.1 Comparison with RISKIND Calculations

The radiation doses to MEIs were also calculated using RISKIND. RISKIND (Yuan et al. 1995) is a tool that has been used in previous transportation risk analyses in environmental assessments and environmental impact statements to determine the dose to the MEIs in DOE (2002), DOE (2008), DOE (2012) and is recommended for calculating the dose to the MEIs in Chen et al. (2002). The dose rate versus distance data that RISKIND uses as default are based on a light water reactor SNF source term with a 10-year decay time. As discussed in Section 4.0, the nuclides contributing to the dose for microreactors are different than traditional light water reactor SNF. This is primarily due to the shorter cooling times and a higher proportion of activation products that results in radionuclides present with higher energy gammas that have a higher likelihood of penetrating shielding materials and traveling longer distances. Therefore, using RISKIND with the default data resulted in much lower doses to MEIs than that of the MAVRIC calculated doses discussed earlier for distances farther away from the package when normalizing to the dose rates of interest at 2 meters (6.6 feet).

A 6th degree polynomial was fit to the MAVRIC radiation dose rate versus distance data for the 30-day decay time for the range of 1–65 meters (3.3–213.3 feet), 18.2 cm (7.17 in.) shield case corresponding to the 50 mrem/hr (0.5 mSv/hr) at 2 meters (6.6 feet) target radiation dose rate shown in Figure 16.

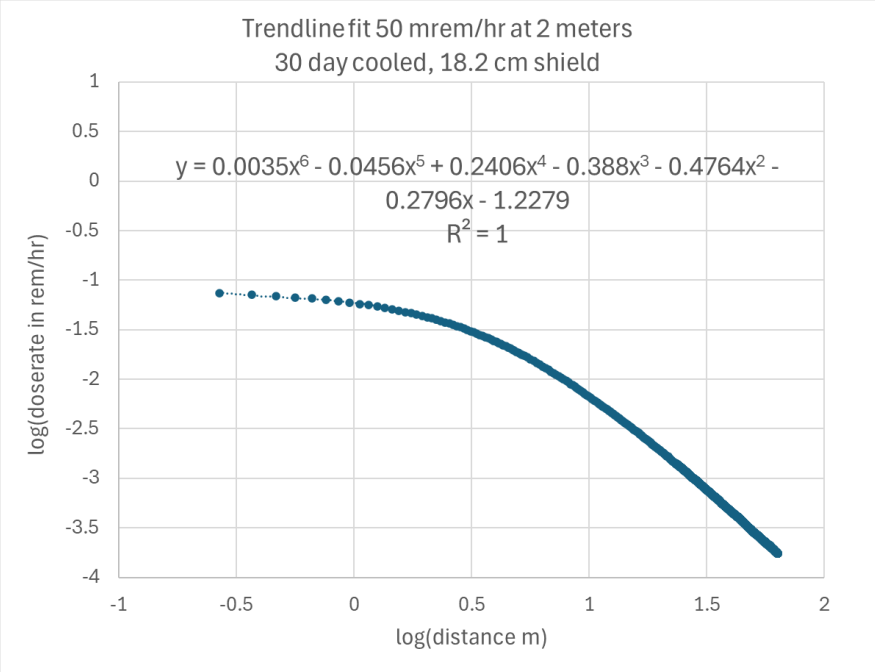

Figure 16. Trendline fit for determining the RISKIND coefficients.

The polynomial coefficients were input into RISKIND to perform the analyses. The RISKIND analyses were normalized to 1 mrem/hr (0.01 mSv/hr) at 1 meter (3.3 feet) from the package, and these results were scaled by the MAVRIC calculated radiation dose rates at 1 meter (3.3 feet) from the package for each of the target radiation dose rate levels. The results of the comparison show good agreement with the largest difference for the radiation dose estimates at the 200 meter (656.2 foot) location. This is likely because the polynomial coefficients derived for the data did not extend to 200 meters (656.2 feet). The MAVRIC versus RISKIND comparisons are shown in Table 11 and Table 12.

The RISKIND calculations are not needed for the current evaluation discussed in this report since the detailed 3-D Monte Carlo MAVRIC calculations were performed. However, RISKIND is a quicker tool with an easy to use user interface in comparison to performing detailed 3-D Monte Carlo calculations and could potentially be used in the future to perform dose estimates for additional MEI studies for microreactors. The comparison in Table 11 and Table 12 shows that using the polynomial fitting coefficients from Figure 16 provides good agreement with the MAVRIC results. The polynomial fit could be extended to farther distances if an even better fit is desired at farther distances, but the current comparison shows that RISKIND in this case calculates a higher dose, which is conservative for the 200 m (656.2 ft) location, which is outside of the range of the polynomial fit. In addition, the method for calculating the dose from a moving truck or train is different than what is presented in this report, and the good agreement with RISKIND provides assurance that the method used in this report is reasonable.

Table 8. Calculated dose to maximally exposed individuals for truck transport.

Highway													
Population group		Scenario	Distance (meters)	Time	Total dose in mrem unless otherwise noted							
					10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
					per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year
Workers	Baseline	Truck drivers tractor trailer	5	until 5 rem/year	1327 hr/year (3.77 mrem/hr)		271 hr/year (18.44 mrem/hr)		136 hr/year (36.7 mrem/hr)		69 hr/year (72.87 mrem/hr)	
		Heavy haul truck drivers	30	until 5 rem/year	28,514 hr/year (0.18 mrem/hr)		5,854 hr/year (0.85 mrem/hr)		2,947 hr/year (1.70 mrem/hr)		1,508 hr/year (3.32 mrem/hr)	
		Truck inspectors	1	1 hour	11.66	116.58	58.57	585.71	114.73	1147.27	232.55	2325.49
	Micro-reactor	Truck drivers	30	until 5 rem/year	28,514 hr/year (0.18 mrem/hr)		5,854 hr/year (0.85 mrem/hr)		2,947 hr/year (1.70 mrem/hr)		1,508 hr/year (3.32 mrem/hr)	
		Truck inspectors	1	1 hour	11.66	116.58	58.57	585.71	114.73	1147.27	232.55	2325.49
Public	Baseline	Person stuck in traffic	1.2	1 hour	10.97	109.69	55.01	550.07	107.87	1078.71	218.20	2181.97
		Truck escorts	60	2000 hr/year	79.91 mrem/year		393.09 mrem/year		783.60 mrem/year		1,514.99 mrem/year	
		Person at service station	16	49 minutes	0.50	4.96	2.40	24.03	4.77	47.72	9.33	93.26
		Resident along route	30	truck moving at 24 km/hr	0.00061	0.0061	0.0029	0.029	0.0058	0.058	0.011	0.11
	Micro-reactor	Person stuck in traffic	10	1 hour	1.37	13.68	6.66	66.57	13.30	133.03	26.27	262.69
			20	1 hour	0.39	3.94	1.91	19.10	3.77	37.67	7.48	74.83
			30	1 hour	0.18	1.75	0.85	8.54	1.70	16.96	3.32	33.16
		Truck escorts	60	2000 hr/year	79.91 mrem/year		393.09 mrem/year		783.60 mrem/year		1,514.99 mrem/year	
		Person at service station	16	49 minutes	0.50	4.96	2.40	24.03	4.77	47.72	9.33	93.26
			20	49 minutes	0.32	3.23	1.57	15.66	3.09	30.89	6.14	61.36
			30	49 minutes	0.14	1.44	0.70	7.00	1.39	13.91	2.72	27.19
		Resident along route	30	truck moving at 24 km/hr	0.00062	0.0062	0.0030	0.030	0.0058	0.058	0.012	0.12
		Person near safe haven	50	12 hours	0.73	7.31	3.43	34.33	7.00	69.95	13.73	137.35

Table 9. Calculated dose to maximally exposed individuals for rail transport.

Rail													
Population group		Scenario	Distance (meters)	Time	Total dose in mrem unless otherwise noted							
					10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
					per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year
Workers	Baseline	Rail escort	27	2000 hr/year	437.92 mrem/year		2,112.00 mrem/year		4,207.34 mrem/year		8,217.46 mrem/year	
		Railyard workers	10	10 minutes	0.23	2.33	1.13	11.32	2.26	22.62	4.47	44.66
	Micro-reactor	Rail escort	27	2000 hr/year	437.92 mrem/year		2,112.00 mrem/year		4,207.34 mrem/year		8,217.46 mrem/year	
		Railyard workers	10	10 minutes	0.23	2.33	1.13	11.32	2.26	22.62	4.47	44.66
Public	Baseline	Persons exposed at grade crossings	3	train moving at 24 km/hr	0.0043	0.043	0.021	0.21	0.042	0.42	0.083	0.83
		Persons exposed at residences	15	train moving at 24 km/hr	0.0013	0.013	0.0064	0.064	0.013	0.13	0.025	0.25
			60	train moving at 24 km/hr	0.00026	0.0026	0.0013	0.013	0.0025	0.025	0.0049	0.049
		Residents near a rail stop	200	2 hours	0.0036	0.036	0.017	0.17	0.032	0.32	0.063	0.63
	Micro-reactor	Persons exposed at grade crossings	3	train moving at 24 km/hr	0.0043	0.043	0.021	0.21	0.042	0.42	0.083	0.83
		Persons exposed at residences	15	train moving at 24 km/hr	0.0013	0.013	0.0064	0.064	0.013	0.13	0.025	0.25
			60	train moving at 24 km/hr	0.00026	0.0026	0.0013	0.013	0.0025	0.025	0.0049	0.049
		Residents near a rail stop	200	2 hours	0.0036	0.036	0.017	0.17	0.032	0.32	0.063	0.63

Table 10. Additional moving truck and train scenarios for maximally exposed individuals.

Minimum distance in meters	Scenario	Speed	Total dose in mrem							
			10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
			per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year	per shipment	10 shipments/year
Truck										
30	Half Residential	10 mph	0.00092	0.0092	0.0044	0.044	0.0087	0.087	0.017	0.17
	Baseline	15 mph	0.00061	0.0061	0.0029	0.029	0.0058	0.058	0.011	0.11
	Residential	20 mph	0.00046	0.0046	0.0022	0.022	0.0044	0.044	0.0086	0.086
	Typical speed limit	35 mph	0.00026	0.0026	0.0013	0.013	0.0025	0.025	0.0049	0.049
	Maximum speed	50 mph	0.00018	0.0018	0.00088	0.0088	0.0017	0.017	0.0034	0.034
Rail										
3	Track Class 1	10 mph	0.0065	0.065	0.032	0.32	0.063	0.63	0.12	1.24
	Baseline	15 mph	0.0043	0.043	0.021	0.21	0.042	0.42	0.083	0.83
	Track Class 2	20 mph	0.0032	0.032	0.016	0.16	0.031	0.31	0.062	0.62
	Track Class 3	40 mph	0.0016	0.016	0.0079	0.079	0.016	0.16	0.031	0.31
	OT-55 Maximum Speed	50 mph	0.0013	0.013	0.0063	0.063	0.013	0.13	0.025	0.25
15	Track Class 1	10 mph	0.0020	0.020	0.0095	0.095	0.019	0.19	0.037	0.37
	Baseline	15 mph	0.0013	0.013	0.0063	0.063	0.013	0.13	0.025	0.25
	Track Class 2	20 mph	0.00098	0.0098	0.0047	0.047	0.0094	0.094	0.018	0.18
	Track Class 3	40 mph	0.00049	0.0049	0.0024	0.024	0.0047	0.047	0.0092	0.092
	OT-55 Maximum Speed	50 mph	0.00039	0.0039	0.0019	0.019	0.0038	0.038	0.0074	0.074
60	Track Class 1	10 mph	0.00039	0.0039	0.0019	0.019	0.0037	0.037	0.0073	0.073
	Baseline	15 mph	0.00026	0.0026	0.0013	0.013	0.0025	0.025	0.0048	0.048
	Track Class 2	20 mph	0.00020	0.0020	0.00095	0.0095	0.0019	0.019	0.0036	0.036
	Track Class 3	40 mph	0.000098	0.00098	0.00047	0.0047	0.00093	0.0093	0.0018	0.018
	OT-55 Maximum Speed	50 mph	0.000078	0.00078	0.00038	0.0038	0.00074	0.0074	0.0015	0.015

Table 11. Comparison of MAVRIC and RISKIND calculated doses to maximally exposed individuals for truck transport.

Highway													
Distance		Scenario	Minimum distance (meters)	Time	Total dose in mrem unless otherwise noted							
					10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
					MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND
Workers	Baseline	Heavy haul truck drivers	30	until 5 rem/year	28,514 hr/yr (0.18 mrem/hr)	30,873 hr/yr (0.15 mrem/hr)	5,854 hr/yr (0.85 mrem/hr)	6,097 hr/yr (0.82 mrem/hr)	2,947 hr/yr (1.70 mrem/hr)	3,112 hr/yr (1.61 mrem/hr)	1,508 hr/yr (3.32 mrem/hr)	1,535 hr/yr (3.26 mrem/hr)
		Truck inspectors	1	1 hour	11.66	11.57	58.57	58.57	114.73	114.73	232.55	232.55
	Micro-reactor	Truck drivers	30	until 5 rem/year	28,514 hr/yr (0.18 mrem/hr)	30,873 hr/yr (0.15 mrem/hr)	5,854 hr/yr (0.85 mrem/hr)	6,097 hr/yr (0.82 mrem/hr)	2,947 hr/yr (1.70 mrem/hr)	3,112 hr/yr (1.61 mrem/hr)	1,508 hr/yr (3.32 mrem/hr)	1,535 hr/yr (3.26 mrem/hr)
		Truck inspectors	1	1 hour	11.66	11.57	58.57	58.57	114.73	114.73	232.55	232.55

Table 11. (cont.) Comparison of MAVRIC and RISKIND calculated doses to maximally exposed individuals for truck transport.

Highway													
Distance		Scenario	Minimum distance (meters)	Time	Total dose in mrem unless otherwise noted							
					10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
					MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND
Public	Baseline	Truck escorts	60	2000 hr/year	79.91 mrem/yr	76.35 mrem/yr	393.09 mrem/yr	386.57 mrem/yr	783.60 mrem/yr	757.20 mrem/yr	1,514.99 mrem/yr	1,534.83 mrem/yr
		Person at service station	16	49 min	0.50	0.47	2.40	2.40	4.77	4.70	9.33	9.53
		Resident along route	30	truck moving at 16 km/hr	0.00092	0.00094	0.0044	0.0047	0.0087	0.0093	0.017	0.019
				truck moving at 24 km/hr	0.00061	0.00062	0.0029	0.0032	0.0058	0.0062	0.011	0.013
				truck moving at 32 km/hr	0.00046	0.00047	0.0022	0.0024	0.0044	0.0047	0.0086	0.0095
				truck moving at 56 km/hr	0.00026	0.00027	0.0013	0.0013	0.0025	0.0026	0.0049	0.0053
				truck moving at 80 km/hr	0.00018	0.00019	0.00088	0.00094	0.0017	0.0018	0.0034	0.0037
	Micro-reactor	Person stuck in traffic	10	1 hour	1.37	1.27	6.66	6.44	13.30	12.62	26.27	25.58
			20	1 hour	0.39	0.37	1.91	1.87	3.77	3.67	7.48	7.44
			30	1 hour	0.18	0.16	0.85	0.82	1.70	1.61	3.32	3.26
		Truck escorts	60	2000 hr/year	79.91 mrem/yr	76.35 mrem/yr	393.09 mrem/yr	386.57 mrem/yr	783.60 mrem/yr	757.20 mrem/yr	1,514.99 mrem/yr	1,534.83 mrem/yr
		Person at service station	16	49 min	0.50	0.47	2.40	2.40	4.77	4.70	9.33	9.53
			20	49 min	0.32	0.31	1.57	1.58	3.09	3.10	6.14	6.28
			30	49 min	0.14	0.14	0.70	0.70	1.39	1.38	2.72	2.79
		Resident along route	30	truck moving at 16 km/hr	0.00092	0.00094	0.0044	0.0047	0.0087	0.0093	0.017	0.019
				truck moving at 24 km/hr	0.00061	0.00062	0.0029	0.0032	0.0058	0.0062	0.011	0.013
				truck moving at 32 km/hr	0.00046	0.00047	0.0022	0.0024	0.0044	0.0047	0.0086	0.0095
				truck moving at 56 km/hr	0.00026	0.00027	0.0013	0.0013	0.0025	0.0026	0.0049	0.0053
				truck moving at 80 km/hr	0.00018	0.00019	0.00088	0.00094	0.0017	0.0018	0.0034	0.0037
		Person near safe haven	50	12 hours	0.73	0.68	3.43	3.46	7.00	6.77	13.73	13.72

Table 12. Comparison of MAVRIC and RISKIND calculated doses to maximally exposed individuals for rail transport.

Rail													
Distance		Scenario	Minimum distance (meters)	Time	Total dose in mrem unless otherwise noted							
					10 mrem/hr at 2 meters		50 mrem/hr at 2 meters		100 mrem/hr at 2 meters		200 mrem/hr at 2 meters	
					MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND	MAVRIC	RISKIND
Workers	Baseline and Microreactor	Rail escort	27	2000 hr/year	437.92 mrem/year	416.45 mrem/year	2,112.00 mrem/year	2,108.54 mrem/year	4,207.34 mrem/year	4,130.16 mrem/year	8,217.46 mrem/year	8,371 mrem/year
		Railyard workers	10	10 minutes	0.23	0.22	1.13	1.11	2.26	2.18	4.47	4.42
Public	Baseline and Microreactor	Persons exposed at grade crossings	3	train moving at 16 km/hr	0.0065	0.0078	0.032	0.039	0.063	0.077	0.12	0.16
				train moving at 40 km/hr	0.0032	0.0028	0.016	0.014	0.031	0.028	0.062	0.056
				train moving at 64 km/hr	0.0016	0.0017	0.0079	0.009	0.016	0.017	0.031	0.035
				train moving at 80 km/hr	0.0013	0.0014	0.0063	0.007	0.013	0.014	0.025	0.028
		Persons exposed at residences	15	train moving at 16 km/hr	0.0020	0.0021	0.0095	0.011	0.019	0.021	0.037	0.042
				train moving at 40 km/hr	0.00098	0.00083	0.0047	0.0042	0.0094	0.0083	0.018	0.017
				train moving at 64 km/hr	0.00049	0.00052	0.0024	0.0026	0.0047	0.0052	0.0092	0.010
				train moving at 80 km/hr	0.00039	0.00042	0.0019	0.0021	0.0038	0.0041	0.0074	0.0084
		Persons exposed at residences	60	train moving at 16 km/hr	0.00039	0.00046	0.0019	0.0023	0.0037	0.0046	0.0073	0.0093
				train moving at 40 km/hr	0.00020	0.00019	0.00095	0.00094	0.0019	0.0018	0.0036	0.0037
				train moving at 64 km/hr	0.00010	0.00012	0.00047	0.00059	0.00093	0.0011	0.0018	0.0023
				train moving at 80 km/hr	0.00008	0.000093	0.00038	0.00047	0.00074	0.00092	0.0015	0.00186
		Residents near a rail stop	200	2 hours	0.0036	0.0062	0.017	0.032	0.032	0.062	0.063	0.13

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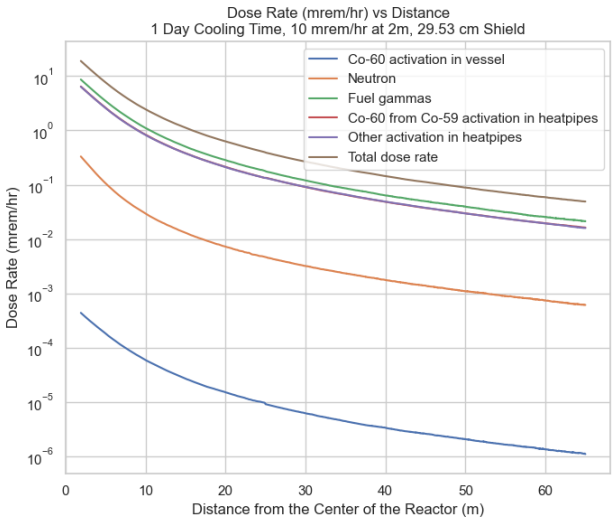
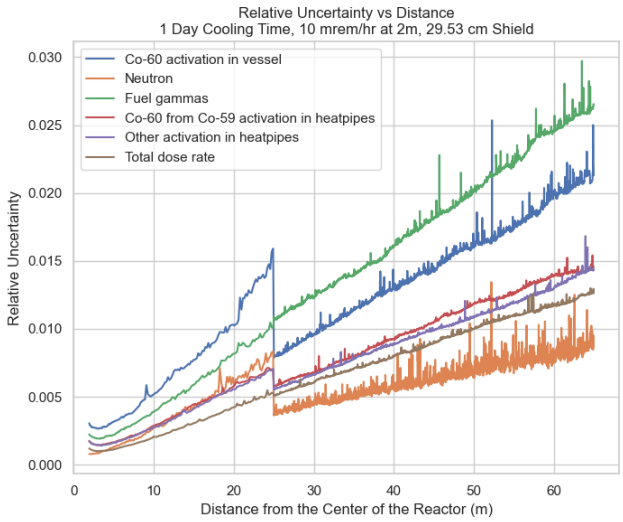
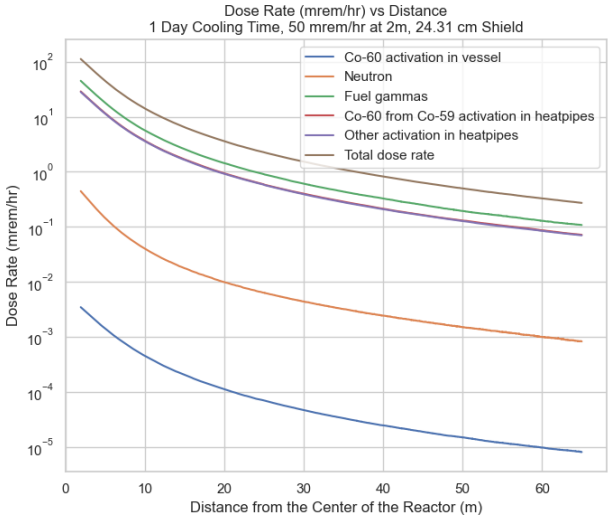
Appendix A – Additional Dose Rate Versus Distance Data

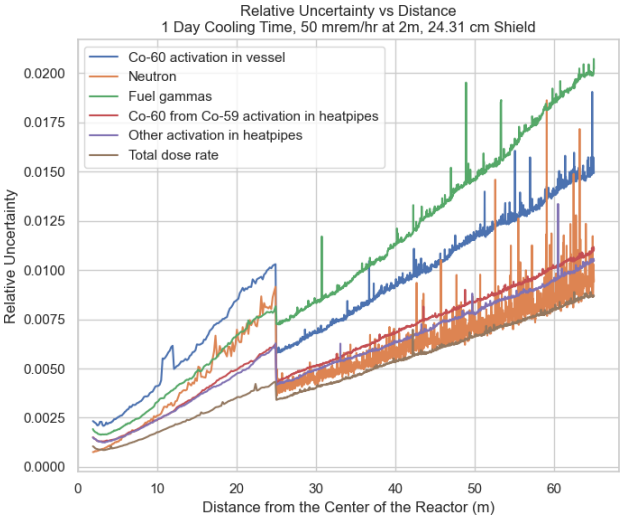
A.1 Dose Versus Distance Data for the Source Term Component for All Cooling Times and Shield Thicknesses

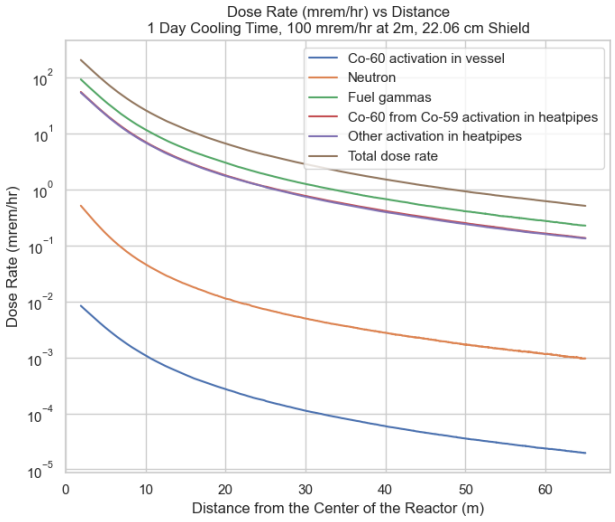
The figures in this appendix show all of the radiation dose rate versus distance data and Monte Carlo uncertainties for the 1–60 meter range for each source term component in the MAVRIC calculations. With the exception of a couple of points, all uncertainties are below 10%. Distances are referenced from the reactor center.

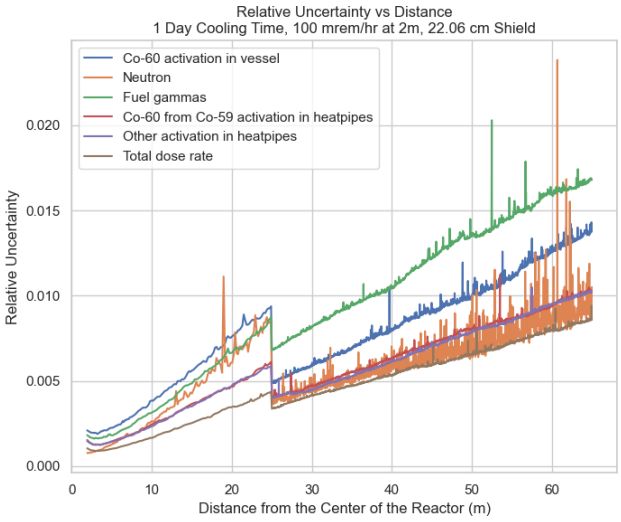


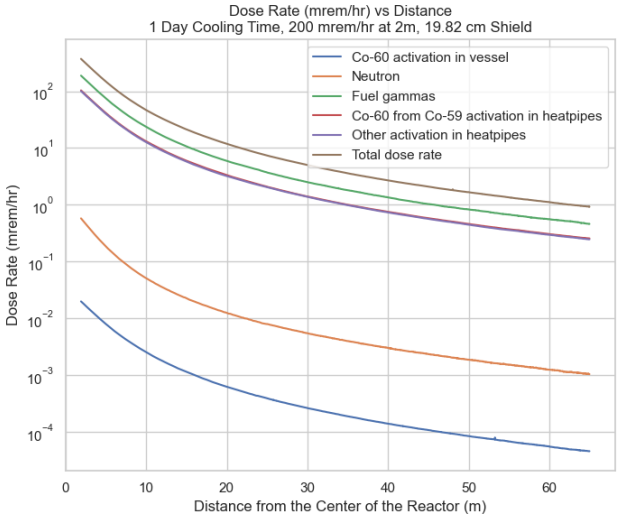







Dose Rate (mrem/hr) vs Distance
1 Day Cooling Time, 100 mrem/hr at 2m, 22.06 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)


Relative Uncertainty vs Distance
1 Day Cooling Time, 100 mrem/hr at 2m, 22.06 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
1 Day Cooling Time, 200 mrem/hr at 2m, 19.82 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
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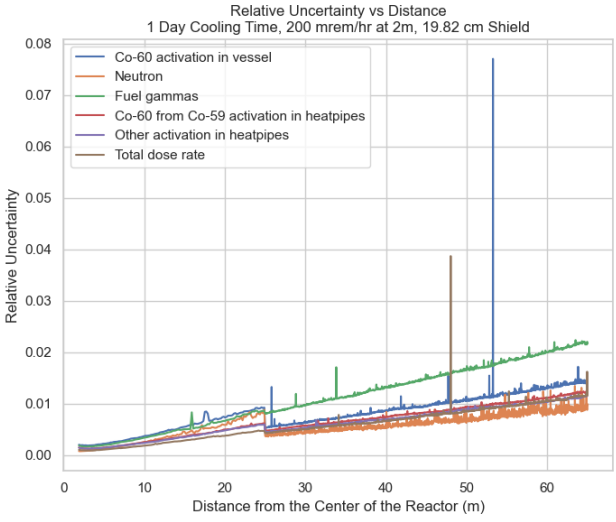
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)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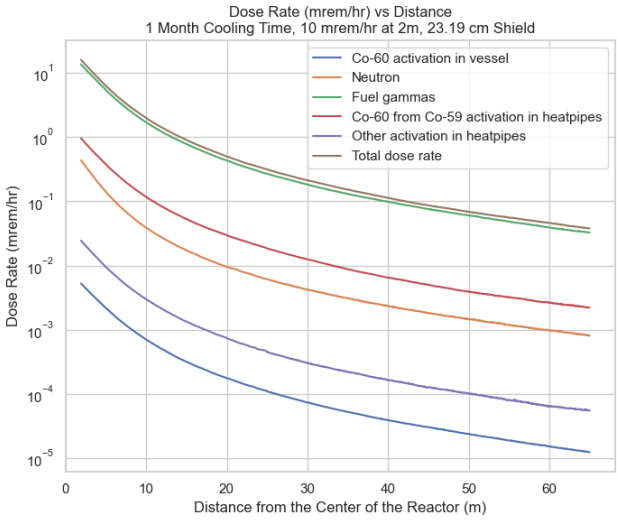
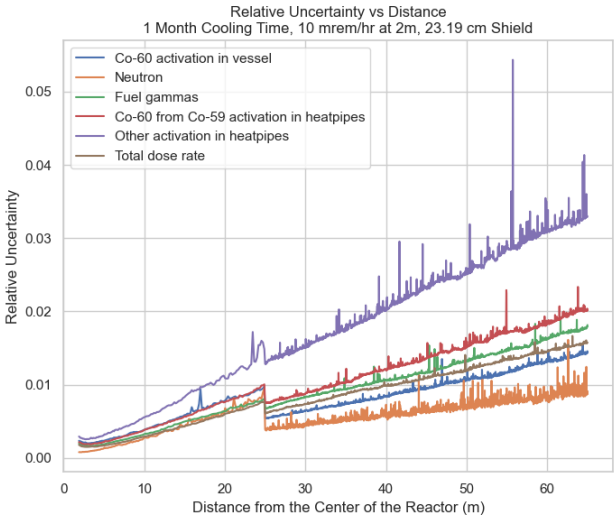
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
1 Month Cooling Time, 10 mrem/hr at 2m, 23.19 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)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Fuel gammas
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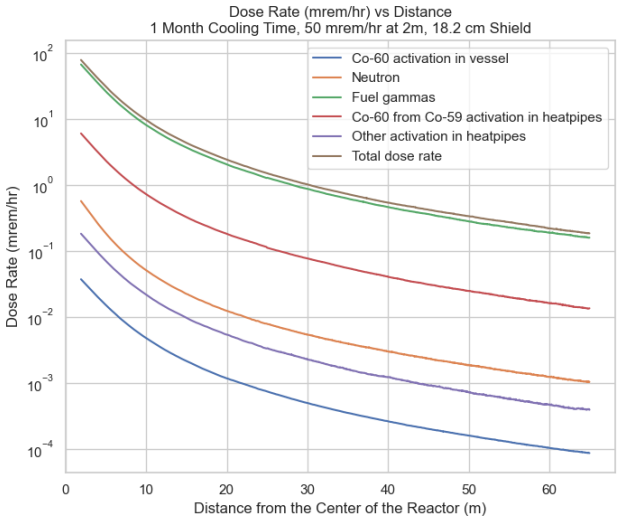
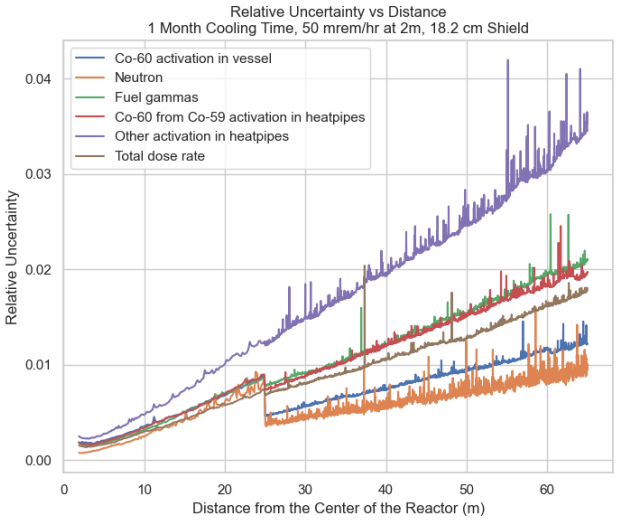
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
1 Month Cooling Time, 50 mrem/hr at 2m, 18.2 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)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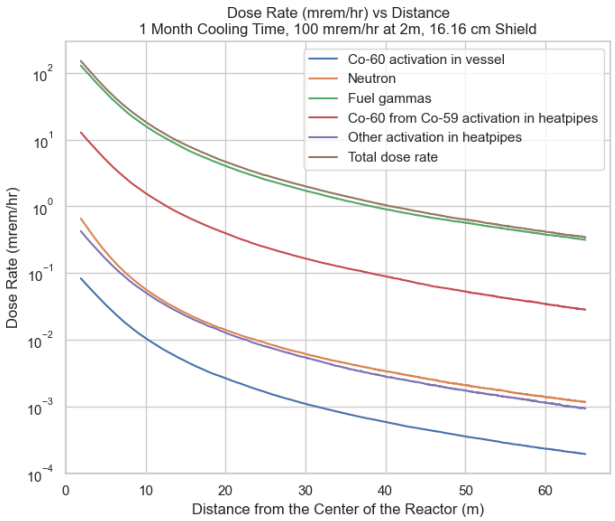
1 Month Cooling Time, 50 mrem/hr at 2m, 18.2 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
1 Month Cooling Time, 100 mrem/hr at 2m, 16.16 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
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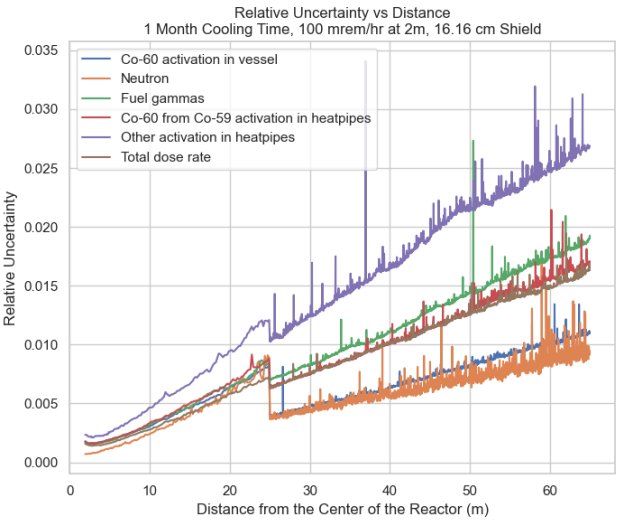
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)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Fuel gammas
Co-60 from Co-59 activation in heatpipes
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Total dose rate
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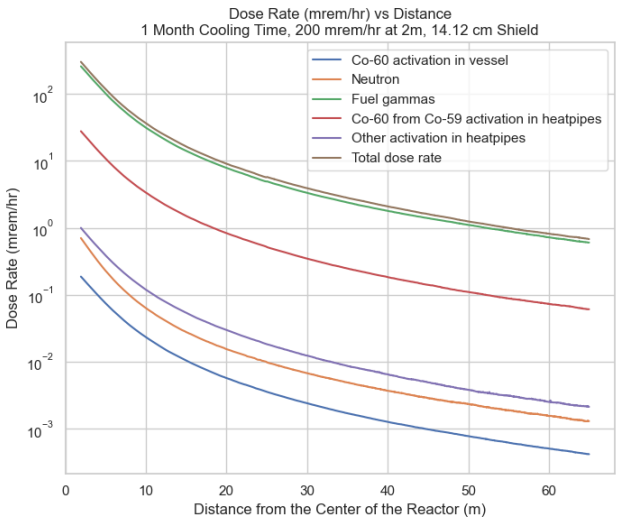
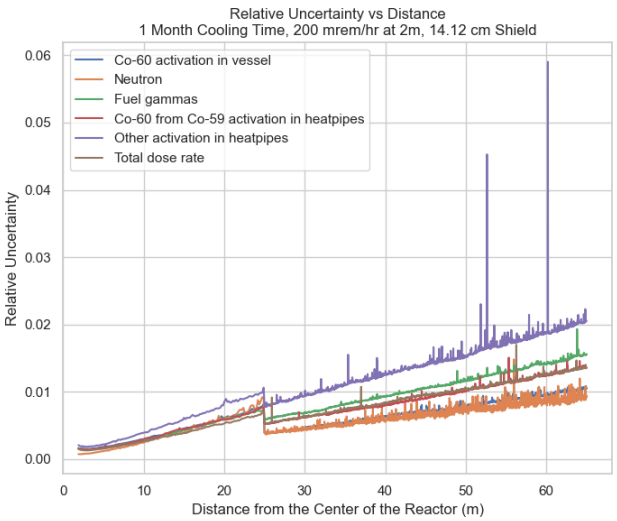
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
1 Month Cooling Time, 200 mrem/hr at 2m, 14.12 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)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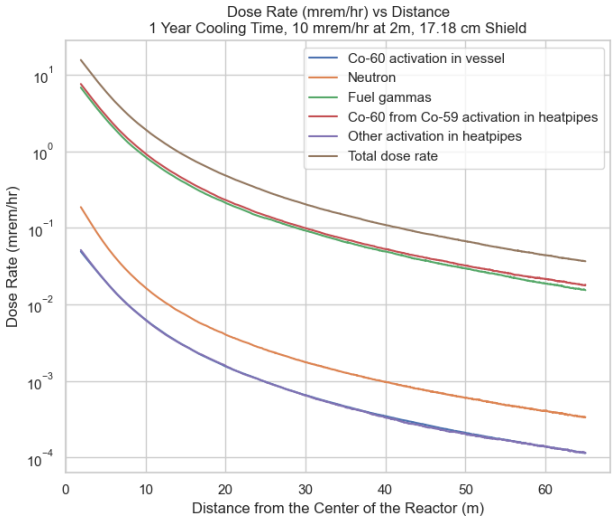
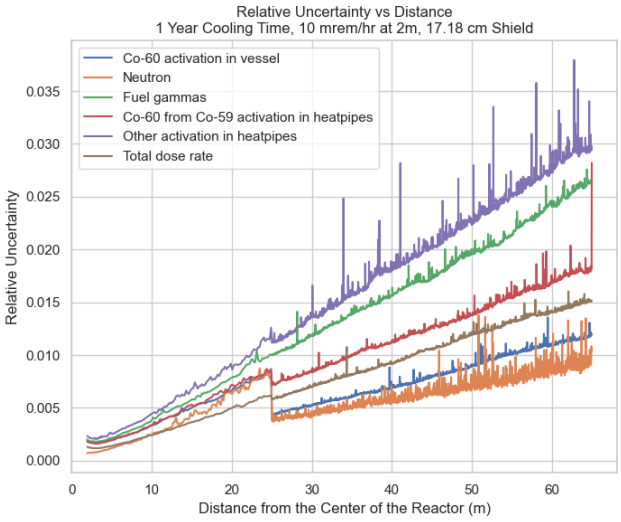
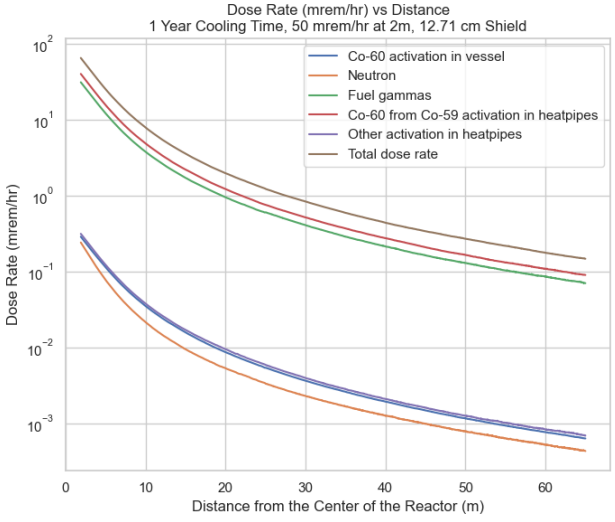
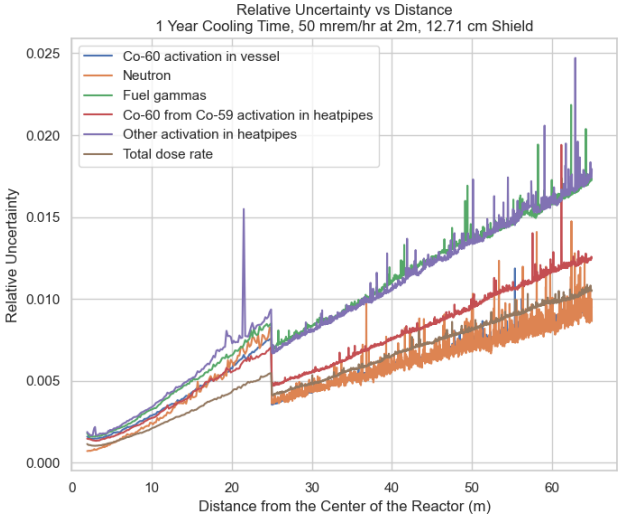
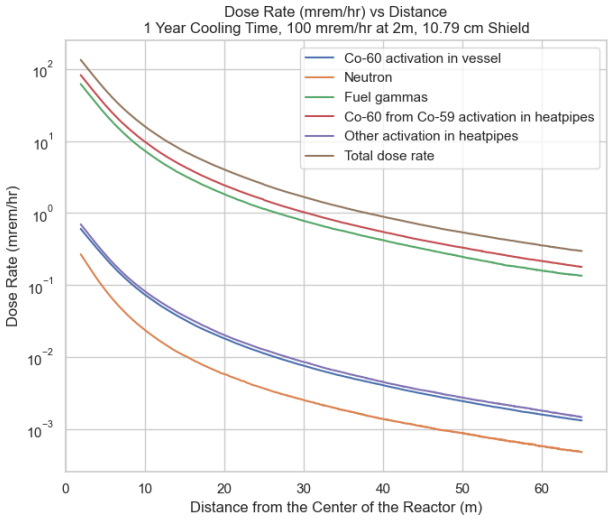
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

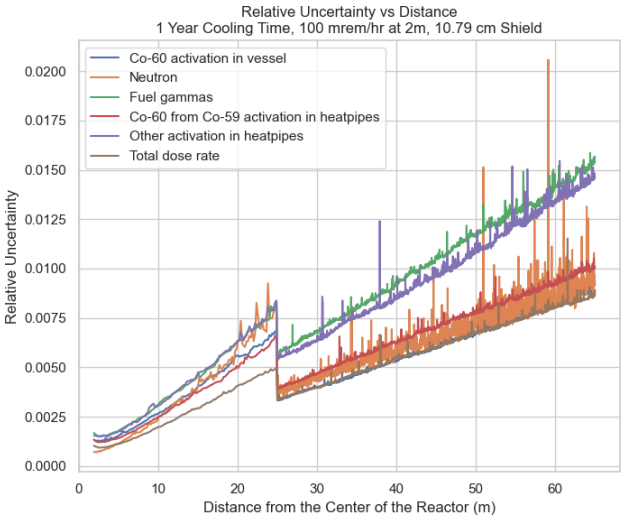

Dose Rate (mrem/hr) vs Distance
1 Year Cooling Time, 10 mrem/hr at 2m, 17.18 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)

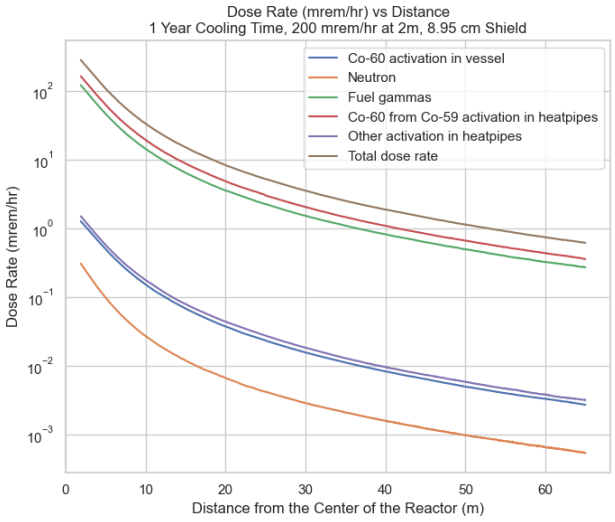

Relative Uncertainty vs Distance
1 Year Cooling Time, 10 mrem/hr at 2m, 17.18 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

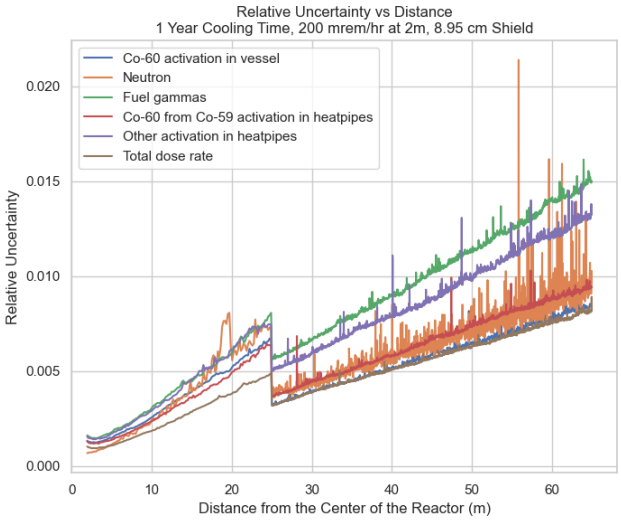

Dose Rate (mrem/hr) vs Distance
1 Year Cooling Time, 50 mrem/hr at 2m, 12.71 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)

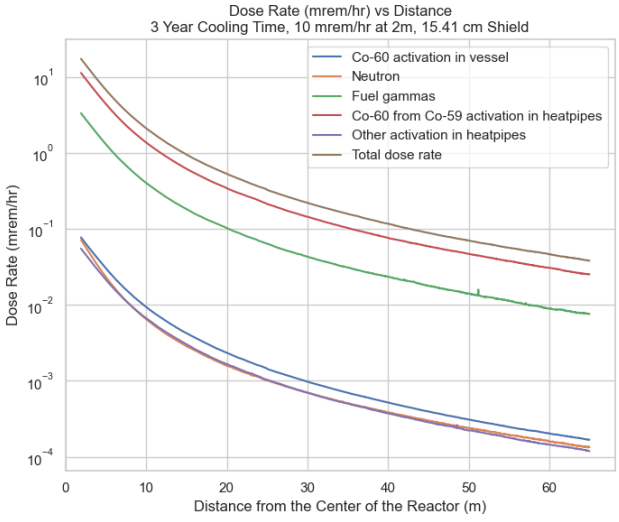

Relative Uncertainty vs Distance
1 Year Cooling Time, 50 mrem/hr at 2m, 12.71 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

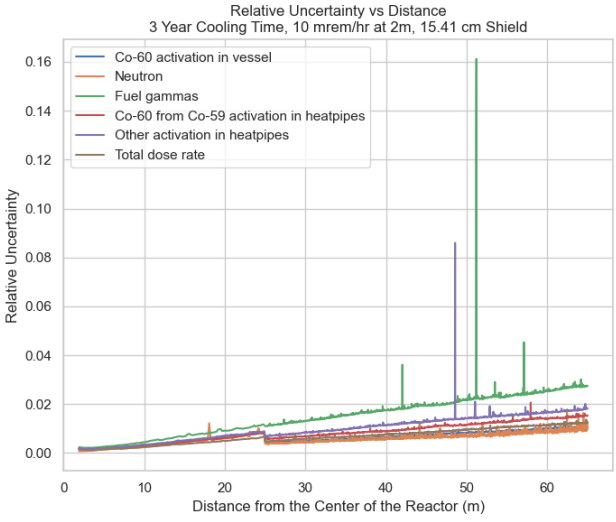

Dose Rate (mrem/hr) vs Distance
1 Year Cooling Time, 100 mrem/hr at 2m, 10.79 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)

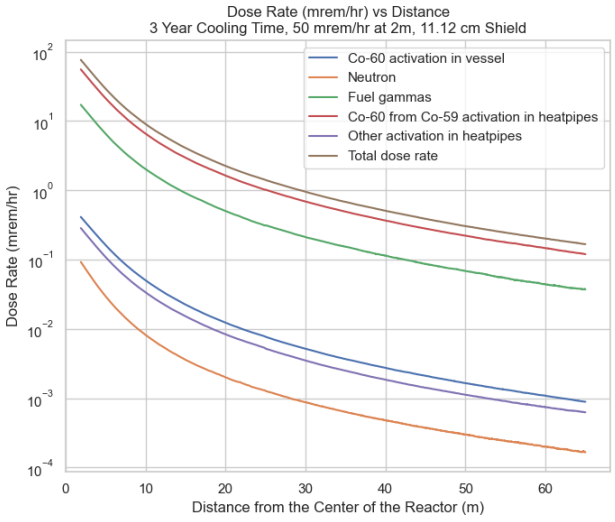

Relative Uncertainty vs Distance
1 Year Cooling Time, 100 mrem/hr at 2m, 10.79 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

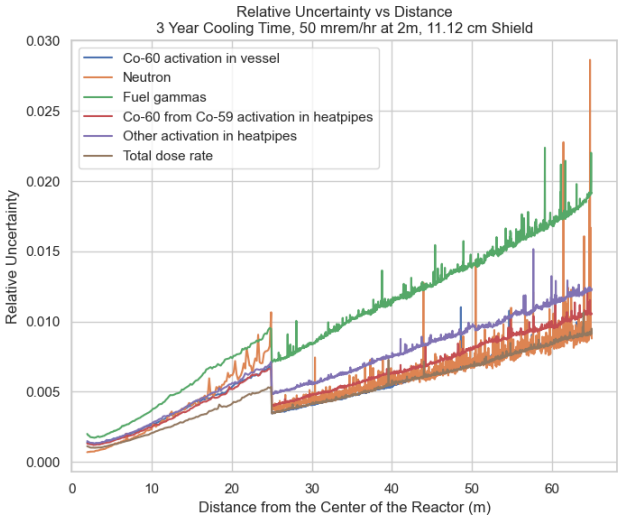

Dose Rate (mrem/hr) vs Distance
1 Year Cooling Time, 200 mrem/hr at 2m, 8.95 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)

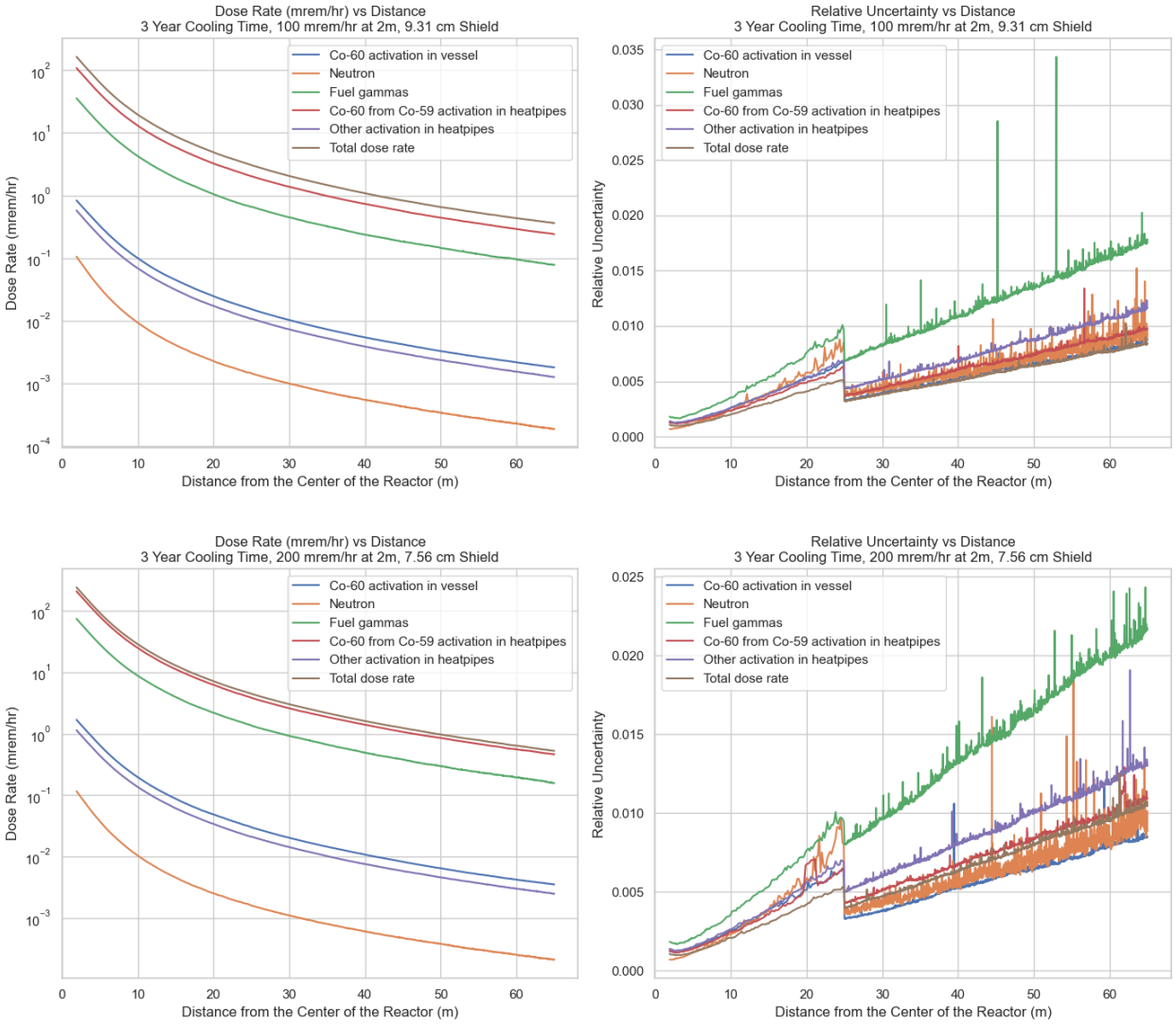

Relative Uncertainty vs Distance
1 Year Cooling Time, 200 mrem/hr at 2m, 8.95 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)


Dose Rate (mrem/hr) vs Distance
3 Year Cooling Time, 10 mrem/hr at 2m, 15.41 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)


Relative Uncertainty vs Distance
3 Year Cooling Time, 10 mrem/hr at 2m, 15.41 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

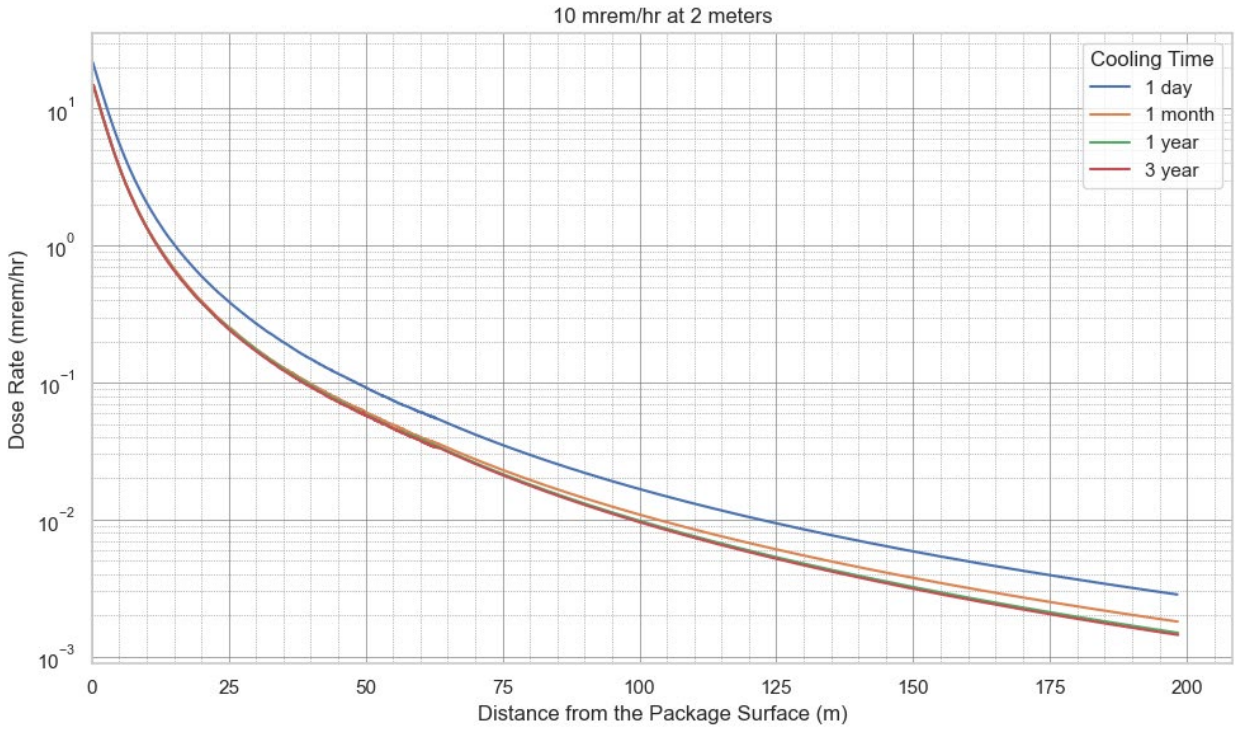

Dose Rate (mrem/hr) vs Distance
3 Year Cooling Time, 50 mrem/hr at 2m, 11.12 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Dose Rate (mrem/hr)
Distance from the Center of the Reactor (m)

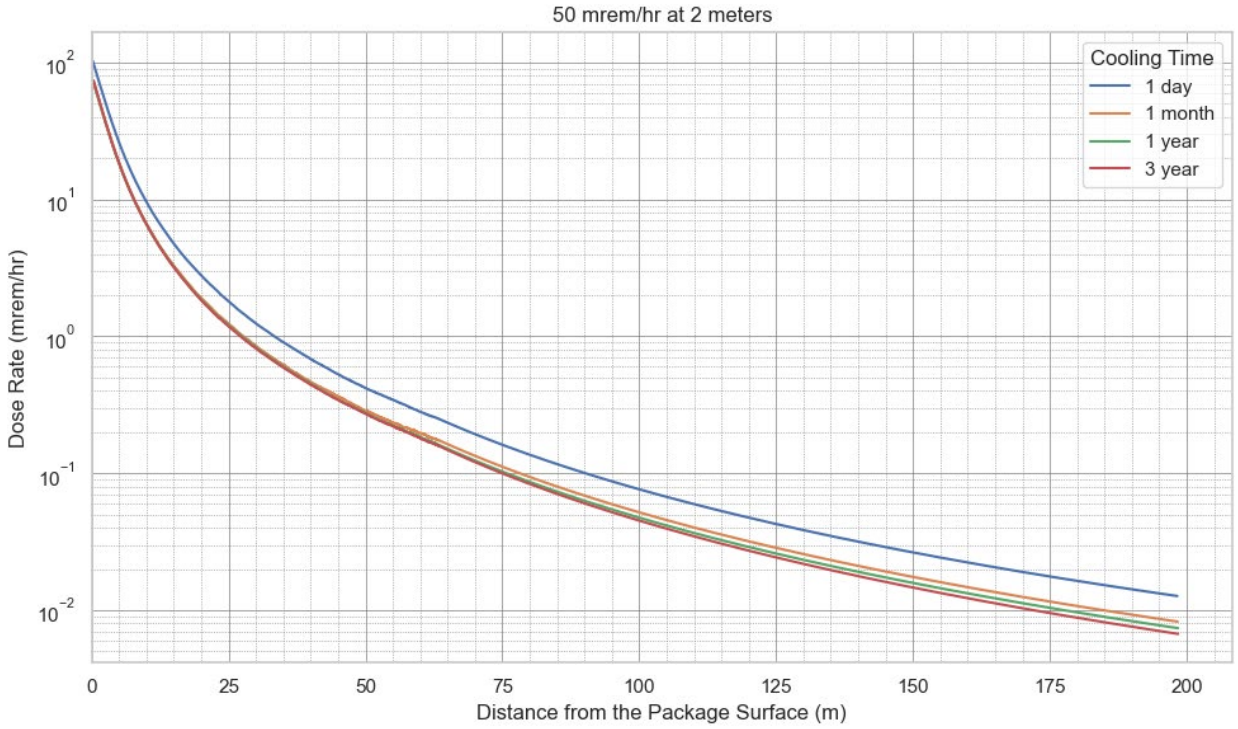

Relative Uncertainty vs Distance
3 Year Cooling Time, 50 mrem/hr at 2m, 11.12 cm Shield
Co-60 activation in vessel
Neutron
Fuel gammas
Co-60 from Co-59 activation in heatpipes
Other activation in heatpipes
Total dose rate
Relative Uncertainty
Distance from the Center of the Reactor (m)

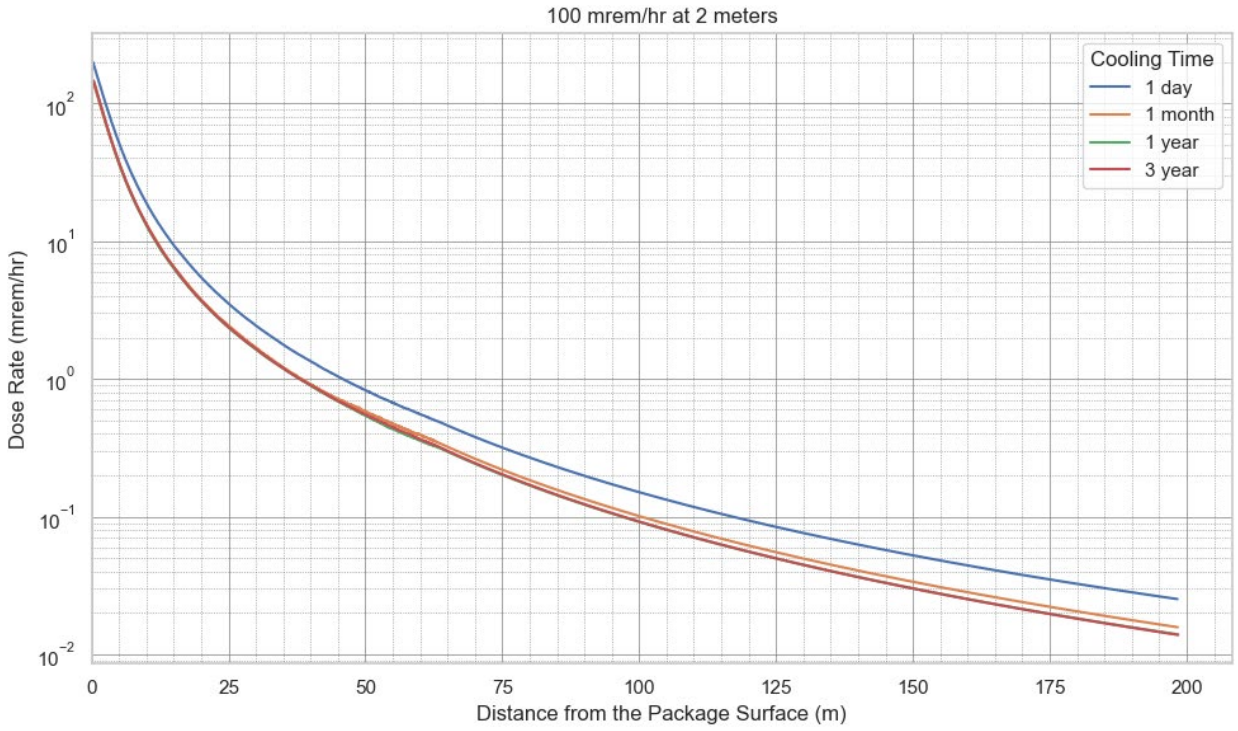


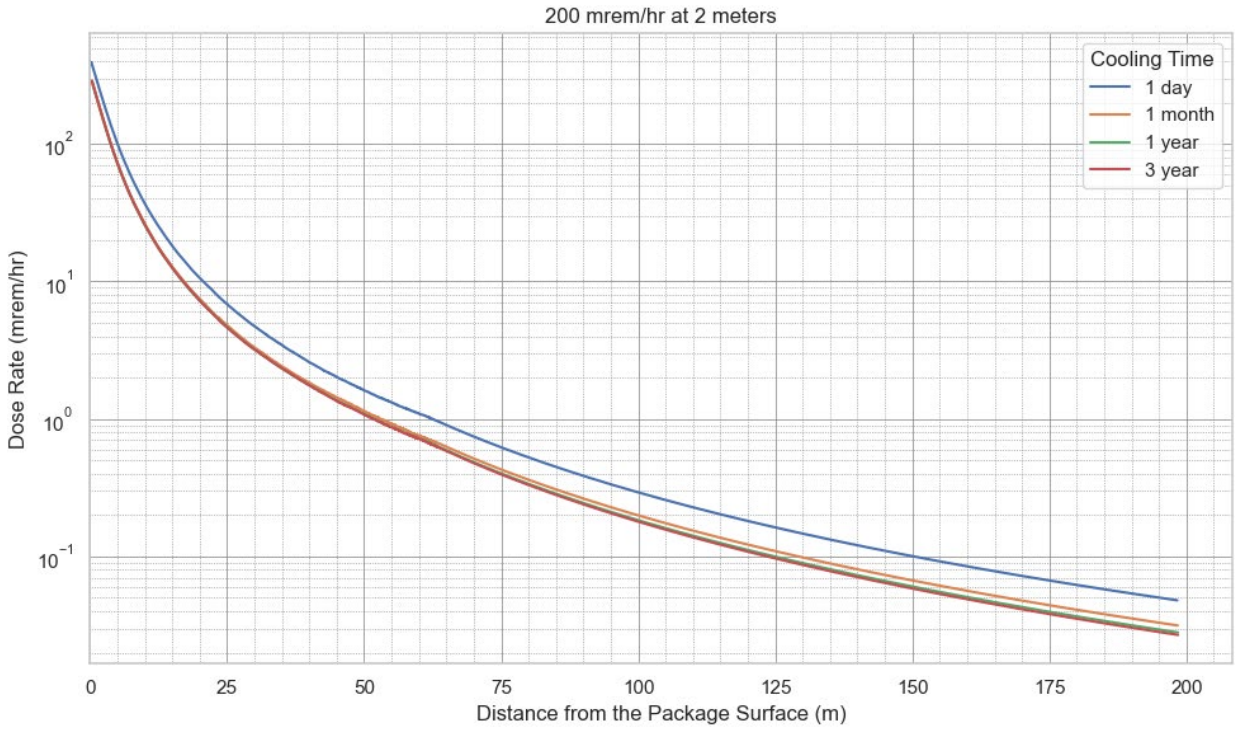
A.2 Dose Versus Distance Data at Each Target Radiation Dose Rate Level

The following figures show the combined radiation dose rate versus distance data, including all source term components up to 200 meters (656.2 feet). The distance in these plots is from the package surface. For each curve, the shield thicknesses were adjusted to achieve the target radiation dose rate at 2 meters (6.6 feet). The shield thicknesses are defined in Table 4.


10 mrem/hr at 2 meters
Cooling Time
1 day
1 month
1 year
3 year
Dose Rate (mrem/hr)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
25
50
75
100
125
150
175
200
Distance from the Package Surface (m)


50 mrem/hr at 2 meters
Cooling Time
1 day
1 month
1 year
3 year
Dose Rate (mrem/hr)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
200
Distance from the Package Surface (m)


100 mrem/hr at 2 meters
Cooling Time
1 day
1 month
1 year
3 year
Dose Rate (mrem/hr)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
200
Distance from the Package Surface (m)


200 mrem/hr at 2 meters
Cooling Time
1 day
1 month
1 year
3 year
Dose Rate (mrem/hr)
10^{2}
10^{1}
10^{0}
10^{-1}
0
25
50
75
100
125
150
175
200
Distance from the Package Surface (m)

A.3 Radiation Dose Rate Calculation Results in mrem/hr for the 200 m (656.2 ft) Region Tally

Case	Vessel Cobalt	Vessel Cobalt Uncertainty	Neutron	Neutron Uncertainty	Fuel Photon	Fuel Photon Uncertainty	Cobalt in Heatpipes	Cobalt in Heatpipes Uncertainty	Other Activation Products	Other Activation Uncertainty	Total Dose Rate	Total Dose Rate Uncertainty	Total Dose Rate Relative Uncertainty
1 day cooling 19.82cm shield	1.96×10^{-6}	4.68×10^{-8}	2.88×10^{-5}	3.43×10^{-7}	2.13×10^{-2}	5.92×10^{-4}	1.36×10^{-2}	2.24×10^{-4}	1.31×10^{-2}	2.10×10^{-4}	4.80×10^{-2}	6.67×10^{-4}	1%
1 day cooling 22.06cm shield	7.88×10^{-7}	1.95×10^{-8}	2.53×10^{-5}	3.04×10^{-7}	1.09×10^{-2}	2.62×10^{-4}	7.22×10^{-3}	1.12×10^{-4}	7.11×10^{-3}	1.07×10^{-4}	2.53×10^{-2}	3.04×10^{-4}	1%
1 day cooling 24.31cm shield	3.53×10^{-7}	9.45×10^{-9}	2.24×10^{-5}	2.78×10^{-7}	5.28×10^{-3}	1.31×10^{-4}	3.72×10^{-3}	5.91×10^{-5}	3.64×10^{-3}	5.63×10^{-5}	1.27×10^{-2}	1.55×10^{-4}	1%
1 day cooling 29.53cm shield	4.48×10^{-8}	1.61×10^{-9}	1.52×10^{-5}	1.82×10^{-7}	1.08×10^{-3}	3.79×10^{-5}	8.75×10^{-4}	1.75×10^{-5}	8.73×10^{-4}	1.69×10^{-5}	2.84×10^{-3}	4.50×10^{-5}	2%
1 month cooling 14.12cm shield	1.72×10^{-5}	3.28×10^{-7}	3.87×10^{-5}	4.60×10^{-7}	2.87×10^{-2}	5.73×10^{-4}	2.62×10^{-3}	5.33×10^{-5}	8.82×10^{-5}	2.61×10^{-6}	3.15×10^{-2}	5.76×10^{-4}	2%
1 month cooling 16.16cm shield	7.77×10^{-6}	1.53×10^{-7}	3.28×10^{-5}	3.80×10^{-7}	1.44×10^{-2}	3.66×10^{-4}	1.26×10^{-3}	3.06×10^{-5}	3.65×10^{-5}	1.41×10^{-6}	1.58×10^{-2}	3.67×10^{-4}	2%
1 month cooling 18.2cm shield	3.67×10^{-6}	8.05×10^{-8}	2.95×10^{-5}	3.49×10^{-7}	7.64×10^{-3}	1.93×10^{-4}	5.65×10^{-4}	1.54×10^{-5}	1.74×10^{-5}	7.69×10^{-7}	8.26×10^{-3}	1.93×10^{-4}	2%
1 month cooling 23.19cm shield	5.34×10^{-7}	1.36×10^{-8}	2.18×10^{-5}	2.63×10^{-7}	1.68×10^{-3}	3.94×10^{-5}	9.47×10^{-5}	2.72×10^{-6}	2.22×10^{-6}	1.04×10^{-7}	1.80×10^{-3}	3.95×10^{-5}	2%
1 year cooling 10.79cm shield	5.53×10^{-5}	9.05×10^{-7}	1.47×10^{-5}	1.67×10^{-7}	6.28×10^{-3}	1.31×10^{-4}	7.62×10^{-3}	1.25×10^{-4}	6.00×10^{-5}	1.30×10^{-6}	1.40×10^{-2}	1.81×10^{-4}	1%
1 year cooling 12.71cm shield	2.65×10^{-5}	4.70×10^{-7}	1.30×10^{-5}	1.49×10^{-7}	3.43×10^{-3}	8.42×10^{-5}	3.90×10^{-3}	7.39×10^{-5}	2.69×10^{-5}	7.18×10^{-7}	7.40×10^{-3}	1.12×10^{-4}	2%
1 year cooling 17.18cm shield	4.67×10^{-6}	9.78×10^{-8}	9.51×10^{-6}	1.16×10^{-7}	7.76×10^{-4}	2.47×10^{-5}	6.96×10^{-4}	1.90×10^{-5}	4.50×10^{-6}	1.74×10^{-7}	1.49×10^{-3}	3.12×10^{-5}	2%
1 year cooling 8.95cm shield	1.19×10^{-4}	2.29×10^{-6}	1.70×10^{-5}	1.92×10^{-7}	1.22×10^{-2}	2.65×10^{-4}	1.55×10^{-2}	2.49×10^{-4}	1.26×10^{-4}	2.55×10^{-6}	2.80×10^{-2}	3.63×10^{-4}	1%
3 year cooling 11.12cm shield	3.71×10^{-5}	6.36×10^{-7}	5.03×10^{-6}	5.95×10^{-8}	1.50×10^{-3}	4.17×10^{-5}	5.16×10^{-3}	8.77×10^{-5}	2.55×10^{-5}	4.87×10^{-7}	6.72×10^{-3}	9.71×10^{-5}	1%
3 year cooling 15.41cm shield	7.27×10^{-6}	1.41×10^{-7}	3.76×10^{-6}	4.35×10^{-8}	3.31×10^{-4}	1.21×10^{-5}	1.09×10^{-3}	2.38×10^{-5}	5.18×10^{-6}	1.35×10^{-7}	1.44×10^{-3}	2.67×10^{-5}	2%
3 year cooling 7.56cm shield	1.49×10^{-4}	2.33×10^{-6}	6.57×10^{-6}	7.19×10^{-8}	6.82×10^{-3}	2.08×10^{-4}	1.99×10^{-2}	3.34×10^{-4}	1.06×10^{-4}	2.03×10^{-6}	2.69×10^{-2}	3.94×10^{-4}	1%
3 year cooling 9.31cm shield	7.78×10^{-5}	2.45×10^{-6}	5.69×10^{-6}	6.32×10^{-8}	3.09×10^{-3}	8.14×10^{-5}	1.07×10^{-2}	1.66×10^{-4}	5.33×10^{-5}	9.59×10^{-7}	1.39×10^{-2}	1.85×10^{-4}	1%

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