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Chapter 13

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NORTHWEST MEDICAL ISOTOPES

Chapter 13.0 – Accident Analysis

Construction Permit Application for Radioisotope Production Facility

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FIGURES

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TERMS

Acronyms and Abbreviations

^{99}Mo	molybdenum-99
^{99m}Tc	technetium-99m
^{235}U	uranium-235
^{241}Am	americium-241
AAC	augmented administrative control
AC	administrative control
ACI	American Concrete Institute
AEC	active engineered control
AEGL	Acute Exposure Guideline Level
AISC	American Institute of Steel Construction
ALARA	as low as reasonably achievable
ALOHA	areal locations of hazardous atmospheres
ARF	airborne release fraction
ASCE	American Society of Civil Engineers
CDE	committed dose equivalent
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulations
DAC	derived air concentration
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DR	damage ratio
EDE	effective dose equivalent
EOI	end of irradiation
ETA	event tree analysis
FEMA	Federal Emergency Management Agency
FMEA	failure modes and effects analysis
FTA	fault tree analysis
HAZOP	hazards and operability
HEGA	high-efficiency gas adsorption
HEPA	high-efficiency particulate air
HIC	high-integrity canister
HNO_3	nitric acid
HVAC	heating, ventilation, and air conditioning
IBC	International Building Code
IROFS	items relied on for safety
IRU	iodine removal unit
ISA	integrated safety analysis
ISG	Interim Staff Guidance
IX	ion exchange
LEU	low enriched uranium
LPF	leak path factor
MAR	material at risk
MHA	maximum hypothetical accident
Mo	molybdenum
MURR	University of Missouri Research Reactor
NaOH	sodium hydroxide

NDA	nondestructive assay
NIOSH	National Institute for Occupational Safety and Health
NO_x	nitrogen oxide
NOAA	National Oceanic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission
NWMI	Northwest Medical Isotopes, LLC
NWS	National Weather Service
OSTR	Oregon State University TRIGA Reactor
OSU	Oregon State University
P&ID	piping and instrumentation drawing
PEC	passive engineered control
PFD	process flow diagram
PHA	preliminary hazards analysis
PMP	probable maximum precipitation
QRA	quantitative risk assessment
RASCAL	Radiological Assessment System for Consequence Analysis
RF	respirable fraction
RPF	Radioisotope Production Facility
RSAC	Radiological Safety Analysis Code
SNM	special nuclear material
SSC	structures, systems, and components
ST	source term
TCE	trichloroethylene
TEDE	total effective dose equivalent
U	uranium
U.S.	United States
UN	uranyl nitrate

Units

°C	degrees Celsius
°F	degrees Fahrenheit
Ci	curie
Cm	centimeter
ft	feet
ft^3	cubic feet
g	gram
hr	hour
$in.^2$	square inch
kg	kilogram
km	kilometer
km^2	square kilometer
L	liter
lb	pound
m	meter
M	molar
m^3	cubic meter
mg	milligram
mi	mile
mi^2	square mile
mil	thousandth of an inch
min	minute
mrem	millirem
oz	ounce
ppm	parts per million
rem	roentgen equivalent man
sec	second
Sv	sievert
wk	week
wt%	weight percent
yr	year

13.0 RADIOISOTOPE PRODUCTION FACILITY ACCIDENT ANALYSIS

The proposed action is the issuance of a U.S. Nuclear Regulatory Commission (NRC) Construction Permit and Operating License under Title 10, *Code of Federal Regulations*, Part 50 (10 CFR 50) "Domestic Licensing of Production and Utilization Facilities," and provisions of 10 CFR 70, "Domestic Licensing of Special Nuclear Material," and 10 CFR 30, "Rules of General Applicability to Domestic Licensing of Byproduct Material," that would authorize Northwest Medical Isotopes, LLC (NWMI) to construct and operate a molybdenum-99 (^{99}Mo) Radioisotope Production Facility (RPF) at a site located in Columbia, Missouri. The RPF is being designed to have a nominal operational processing capability of one batch per week of up [Proprietary Information].

The primary mission of the RPF will be to recover and purify radioactive ^{99}Mo generated via irradiation of low-enriched uranium (LEU) targets in off-site non-power reactors. The purified ^{99}Mo will be packaged and transported to medical industry users where the radioactive decay product, technetium-99m (^{99m}Tc), can be employed as a valuable resource for medical imaging.

This section analyzes potential hazards and accidents that could be encountered in the RPF during operations involving special nuclear material (SNM) (irradiated and unirradiated), radioisotope recovery and purification, and the use of hazardous chemicals relative to these radiochemical processes. Irradiation services and transportation activities are not analyzed in this chapter.

This chapter evaluates the various processing and operational activities at the RPF, including:

- Receiving LEU from U.S. Department of Energy (DOE)
- Producing LEU target materials and fabrication of targets
- Packaging and shipping LEU targets to the university reactor network for irradiation
- Returning irradiated LEU targets for dissolution, recovery, and purification of ^{99}Mo
- Recovering and recycling LEU to minimize radioactive, mixed, and hazardous waste generation
- Treating/packaging wastes generated by RPF process steps to enable transport to a disposal site

Chapter Organization

Section 13.1 describes hazard and accident analysis methodologies applied to the RPF integrated safety analysis (ISA) (Section 13.1.1). Section 13.1.2 identifies the accident initiating events, and Section 13.1.3 summarizes the results of the RPF preliminary hazards analysis (PHA) (NWMI-2015-SAFETY-001, *NWMI Radioisotope Production Facility Preliminary Hazards Analysis*). The PHA discussion in Section 13.1.3 identifies the accident scenarios that required further evaluation.

Section 13.2 presents analyses of radiological and criticality accidents. Section 13.2.1 evaluates a non-credible maximum hypothetical accident (MHA) whose dose consequences bound all other potential accidents. Subsequent subsections under Section 13.2 present analyses of the radiological or criticality-related accidents evaluated, as follows:

- Section 13.2.2 discusses spills and spray accidents
- Section 13.2.3 discusses dissolver offgas accidents
- Section 13.2.4 discusses leaks into auxiliary systems accidents
- Section 13.2.5 discusses loss of electrical power
- Section 13.2.6 discusses natural phenomena accidents

- Section 13.2.7 identifies the additional accident sequences evaluated and associated items relied on for safety (IROFS)

Section 13.3 presents bounding accidents involving hazardous chemicals.

The data presented in the following subsections are based on a comprehensive PHA, conservative assumptions, the MHA results, draft quantitative risk assessments (QRA), and scoping calculations. These items provide an adequate basis for the construction application.

13.1 ACCIDENT ANALYSIS METHODOLOGY AND PRELIMINARY HAZARDS ANALYSIS

13.1.1 Methodologies Applied to the Radioisotope Production Facility Integrated Safety Analysis Process

This section describes methodologies applied to the RPF ISA. The ISA process comprises the PHA and the follow-on development and completion of QRAs to address events and hazards identified in the PHA as requiring further evaluation.

The ISA process flow diagram is provided Figure 13-1. The ISA process (being adapted for this application) consists of conducting a PHA of a system using a combination of written process descriptions, process flow diagrams (PFD), process and instrument drawings (P&ID), and supporting calculations to identify events that could lead to adverse consequences. Those adverse consequences are evaluated qualitatively by the ISA team members to identify the likelihood and severity of consequences using guidance on event frequencies and consequence categories consistent with the regulatory guidelines.

Each event with an adverse consequence that involves licensed material or its byproducts is evaluated for risk using a risk matrix that enables the user to identify unacceptable intermediate- and high-consequence risks. For the unacceptable intermediate- and high-consequence risks events, the IROFS developed to prevent or mitigate the consequences of the events and an event tree analysis are used to demonstrate that the risk can be reduced to acceptable frequencies through preventative or mitigative IROFS.

Fault trees and failure mode and effects analysis can be used to (1) provide quantitative failure analysis data (failure frequencies) for use in the event tree analysis of the IROFS, as necessary, or (2) quantitatively analyze an event from its basic initiators to demonstrate that the quantitative failure frequency is already highly unlikely under normal standard industrial conditions, thus not needing the application of IROFS. Once the IROFS are developed, management measures are identified to ensure that the IROFS failure frequency used in the analysis is preserved and the IROFS are able to perform their intended function when needed.

The following subsections summarize the RPF ISA methodologies.

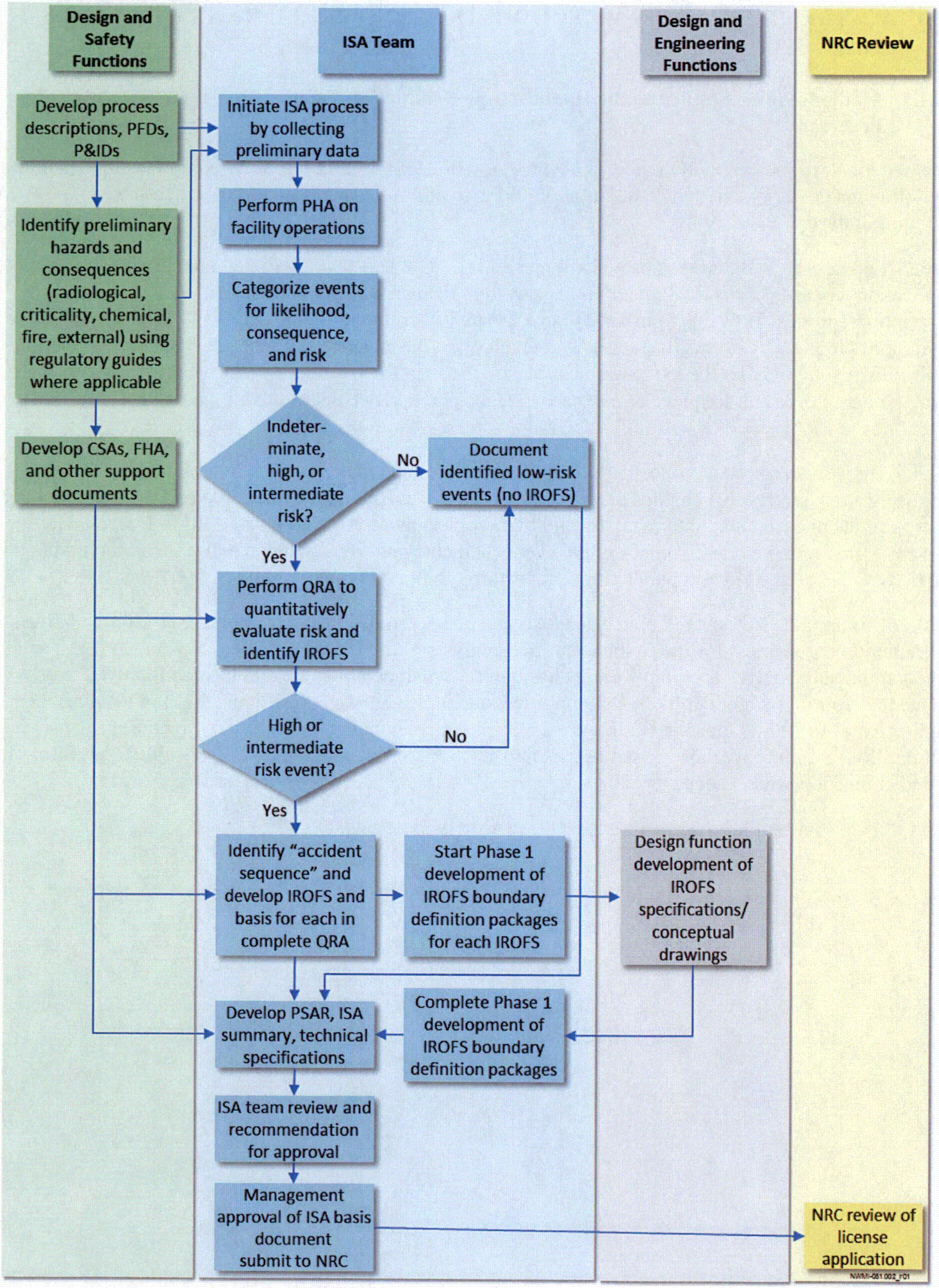

Figure 13-1. Integrated Safety Analysis Process Flow Diagram

13.1.1.1 Accident Likelihood Categories, Consequence Severity Categories, and Risk Matrix

Table 13-1 shows the accident likelihood categories applied to the RPF ISA process. Table 13-2 shows qualitative guidelines for applying the likelihood categories from Table 13-1. Table 13-3 shows accident consequence severity categories from 10 CFR 70.61, "Performance Requirements." Table 13-4 shows the RPF risk matrix, which is a product of the likelihood and consequence severity categories from Table 13-1 and Table 13-3, respectively.

Table 13-1. Likelihood Categories

	Likelihood category	Event frequency limit
Not unlikely	3	More than 10^{-3} events per year
Unlikely	2	Between 10^{-3} and 10^{-5} events per year
Highly unlikely	1	Less than 10^{-5} per events per year

Table 13-2. Qualitative Likelihood Category Guidelines

Likelihood category	Initiator
3	An event initiated by a human error
3	An event initiated by failure of a process system processing corrosive materials
3	An event initiated by a fire or explosion in areas where combustibles or flammable materials are present
3	An event initiated by failure of an active control system
3	A damaging seismic event
3	A damaging high wind event
3	A spill of material
3	A failure of a process variable monitored or unmonitored by a control system
3	A valve out of position or a valve that fails to seat and isolate
3	Most standard industrial component failures (valves, sensors, safety devices, gauges, etc.)
3	An adverse chemical reaction caused by improper quantities of reactants, out-of-date reactants, out-of-specification reaction environment, or the wrong reactants are used
3	Most external man-made events (until confirmed using an approved method)
2	An event initiated by the failure of a robust passive design feature with no significant internal or external challenges applied (e.g., spontaneous rupture of an all-welded dry nitrogen system pipe operating at or below design pressure in a clean, vibration-free environment)
1-2	An adverse chemical reaction when proper quantities of in-date chemicals are reacted in the proper environment
1	Natural phenomenon such as tsunami, volcanos, and asteroids for the Missouri facility site

Table 13-3. Radioisotope Production Facility Consequence Severity Categories Derived from 10 CFR 70.61

Category description	Consequence category	Workers	Off-site public	Environment
High consequence	3	• Radiological dose[a] > 1 Sv (100 rem) • Airborne, radiologically contaminated nitric acid >170 ppm nitric acid (AEGL-3, 10-min exposure limit) • Unshielded nuclear criticality	• Radiological dose[a] > 0.25 Sv (25 rem) • Toxic intake > 30 mg soluble U • Airborne, contaminated nitric acid > 24 ppm nitric acid (AEGL-2, 60-min exposure limit)	
Intermediate consequence	2	• Radiological dose[a] between 0.25 Sv (25 rem) and 1 Sv (100 rem) • Airborne, radiologically contaminated nitric acid > 43 ppm nitric acid (AEGL-2, 10-min exposure limit)	• Radiological dose[a] between 0.05 Sv (5 rem) and 0.25 Sv (25 rem) • Airborne, contaminated nitric acid > 0.16 ppm nitric acid (AEGL-1, 60-min exposure limit)	24-hr radioactive release > 5,000 × Table 2 of 10 CFR 20,[b] Appendix B
Low consequence	1	Accidents with lower radiological, chemical, and/or toxicological exposures than those above from licensed material and byproducts of licensed material	Accidents with lower radiological, chemical, and/or toxicological exposures than those above from licensed material and byproducts of licensed material	Radiological releases producing lower effects than those listed above from licensed material

Source: 10 CFR 70.61, "Performance Requirements," *Code of Federal Regulations*, Office of the Federal Register, as amended.

[a] As total effective dose equivalent.

[b] 10 CFR 20, "Standards for Protection Against Radiation," *Code of Federal Regulations*, Office of the Federal Register, as amended.

AEGL = Acute Exposure Guideline Level. U = uranium.

Table 13-4. Radioisotope Production Facility Risk Matrix

Severity of consequences	Likelihood of occurrence		
	Highly unlikely (Likelihood category 1)	Unlikely (Likelihood category 2)	Not unlikely (Likelihood Category 3)
High consequence (Consequence category 3)	Risk index = 3 Acceptable risk	Risk index = 6 Unacceptable risk	Risk index = 9 Unacceptable risk
Intermediate consequence (Consequence category 2)	Risk index = 2 Acceptable risk	Risk index = 4 Acceptable risk	Risk index = 6 Unacceptable risk
Low consequence (Consequence category 1)	Risk index = 1 Acceptable risk	Risk index = 2 Acceptable risk	Risk index = 3 Acceptable risk

13.1.1.2 Accident Consequence Analysis

The ISA process requires an understanding of the source terms and consequences of an adverse event to determine if the event is low, intermediate, or high consequence, as compared with the hazard criteria identified in Table 13-4. NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook*, offers methodologies to calculate the quantitative consequences of events. For simplicity and prudent expenditure of resources, the RPF ISA assumes a worst-case approach using a few bounding evaluations of events that are identified through either:

- Calculations (e.g., the source term and radiation doses caused by contained material in the system)
- Studies of representative accidents (e.g., comparison of accidental criticalities in industry with processes similar to those at the RPF)
- Bounding release calculations using approved methods (e.g., using RASCAL [Radiological Assessment System for Consequence Analysis] to model bounding facility releases that affect the public)
- Reference to nationally recognized safety organizations (e.g., use of Acute Exposure Guideline Levels [AEGL] from the U.S. Environmental Protection Agency to identify chemical exposure limits for each consequence category)
- Approved methods for evaluation of natural and man-made phenomenon and comparison to the design basis (e.g., calculation of explosive damage potential from the nearest railroad line on the facility)

Accident consequence analysis results are identified before or during the ISA process following preliminary reviews of the processes, and as the process hazard identification phase identifies new potential hazards.

Initial hazards identified by the preliminary reviews include:

- High radiation dose to workers and the public from irradiated target material during processing
- High radiation dose due to accidental nuclear criticality
- Toxic uptake of licensed material by workers or the public during processing or accidents
- Fires and explosions associated with chemical reactions and use of combustible materials and flammable gases
- Chemical exposures associated with chemicals used in processing the irradiated target material
- External events (both natural and man-made) that impact the facility operations

13.1.1.3 What-If and Structured What-If

RPF activities that will be mainly conducted by personnel using a sequence of actions to affect a process were evaluated using what-if or structured-what-if techniques to identify process hazards that can lead to unacceptable risk. These methods allow free-form evaluation of the activity by ISA team members, which can be enhanced by using a list of key guidewords addressing the specific hazards identified in the facility (e.g., the deviations to normal condition criticality safety controls like spacing, mass, moderation; material spills; wrong materials, place, or time for activities; etc.). The key words for each structured what-if evaluation are documented in the PHA.

13.1.1.4 Hazards and Operability Study Method

For processes that are part of a processing system and have well-defined PFDs and/or P&IDs, the more structured hazards and operability (HAZOP) approach was used. This method systematically evaluates each node of a process using a set of key words that enables the team to systematically identify adverse changes in the process and evaluate those changes for adverse consequences. The key words for each evaluation are documented in the PHA.

13.1.1.5 Event Tree Analysis

An event tree analysis (ETA) is a bottoms-up, logical modeling technique for both success and failure that explores responses through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis. ETA uses a modeling technique referred to as an event tree, which branches events from one single event using Boolean logic.

The ISA uses ETA in two primary ways. For those initiating events where the ISA team is uncertain of the likelihood of reaching the adverse consequence, the method can be used during the QRA to follow the sequence of events leading to an adverse consequence and thus quantify the adverse event's frequency given the initiator. ETA is also used in the QRA process to demonstrate that the IROFS, selected to prevent an adverse event, reduce the failure frequency to a level that satisfies the performance requirements (e.g., the frequency of a high-consequence event is reduced to highly unlikely).

13.1.1.6 Fault Tree Analysis

Fault tree analysis (FTA) is a top-down, deductive failure analysis in which an undesirable system state is analyzed with Boolean logic to combine a series of lower-level initiating events. The process enables the user to understand how systems can fail, identify the best ways to reduce risk, and/or determine event rates of an accident or a particular system-level functional failure. This analysis method is mainly used in QRAs when a failure frequency or probability is needed for a specific component, an IROFS, or some other complex process.

13.1.1.7 Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is an inductive reasoning (forward logic) single point of failure analysis that is also quantitative in nature. FMEA involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, along with associated causes and effects. For each component, the failure modes and associated effects on the rest of the system are recorded in a FMEA worksheet. This is an exhaustive analysis technique that can be used to evaluate the reliability of a complex, active engineered control (AEC) type of IROFS.

13.1.2 Accident-Initiating Events

Each of the following accident initiating events were included in the PHA. Loss of power as an accident event is discussed further in Section 13.2.5.

- Criticality accident
- Loss of electrical power
- External events (meteorological, seismic, fire, flood)
- Critical equipment malfunction
- Operator error
- Facility fire (explosion is included in this category)
- Any other event potentially related to unique facility operations

The PHA (NWMI-2015-SAFETY-001) identifies and categorizes accident sequences that require further evaluation. Table 13-5 defines the top-level accident sequence notation used in the RPF PHA.

Table 13-5. Radioisotope Production Facility Preliminary Hazard Analysis Accident Sequence Category Designator Definitions

PHA top-level accident sequence category[a]	Definition
S.C.	Criticality
S.F.	Fire or explosion
S.R.	Radiological
S.M.	Man-made
S.N.	Natural phenomena
S.CS.	Chemical safety

[a] The alpha category designator is followed in the PHA by a two-digit number "XX" that refers to the specific accident sequence (e.g., S.C.01, S.F.07, etc.). Specific accident sequences are discussed in Sections 13.1.3 and 13.3.

PHA = preliminary hazard analysis.

Table 13-6 provides a crosswalk between the PHA top-level accident sequence categories and the NUREG-1537, *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors – Format and Content*, Part 1 Interim Staff Guidance (ISG) accident initiating events listed above. As noted at the bottom of Table 13-6, PHA accident sequences involve one or more of the NUREG-1537 Part 1 ISG accident initiating event categories, as noted by ✓ in the corresponding table cell, but the PHA accident sequences themselves are not necessarily initiated by the ISG accident initiating event. Table 13-6 shows how PHA accident sequences correspond with ISG accident initiating events, and demonstrates that the PHA considers the full range of accident events identified in the ISG.

Table 13-6. Crosswalk of NUREG-1537 Part 1 Interim Staff Guidance Accident Initiating Events versus Radioisotope Production Facility Preliminary Hazards Analysis Top-Level Accident Sequence Categories

NUREG-1537[a] Part 1 ISG accident initiating event category	PHA Top-Level Accident Sequence Category[b]					
	S.C.	S.F.	S.R.	S.M.	S.N.	S.CS.
Criticality accident	✓	✓			✓	
Loss of electrical power			✓		✓	
External events (meteorological, seismic, fire, flood)	✓	✓		✓	✓	✓
Critical equipment malfunction	✓	✓	✓	✓		✓
Operator error	✓		✓	✓		✓
Facility fire (explosion is included in this category)		✓	✓			
Any other event potentially related to unique facility operations	✓		✓	✓		

[a] NUREG-1537, *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors – Format and Content*, Part 1, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Washington, D.C., February 1996.

[b] PHA accident sequences involve one or more of the NUREG-1537 Part 1 ISG accident initiating event categories, as noted by an ✓ in the corresponding table cell, but the PHA sequences themselves are not necessarily initiated by the ISG accident initiating event.

ISG = Interim Staff Guidance. PHA = preliminary hazard analysis.

The RPF PHA subdivides the RPF process into eight primary nodes based on facility design documentation. Table 13-7 lists the RPF primary nodes and corresponding subprocesses, as identified in the PHA.

Table 13-7. Radioisotope Production Facility Preliminary Hazards Analysis Primary Process Nodes and Subprocesses (2 pages)

Node no.	Node name	Subprocesses encompassed in node
1.0.0	Target fabrication process	• Fresh uranium receipt and storage • Fresh uranium dissolution • Uranyl nitrate blending and feed preparation • Nitrate extraction • Recycled uranyl nitrate concentration • [Proprietary Information] • [Proprietary Information] • [Proprietary Information] • [Proprietary Information] • [Proprietary Information] • [Proprietary Information] • Uranium scrap recovery • Target assembly, loading, inspection, quality checking, verification, packaging and storage
2.0.0	Target dissolution process	• [Proprietary Information] • [Proprietary Information] • Primary process offgas treatment • Fission gas retention
3.0.0	Molybdenum recovery and purification process	• Feed preparation • First stage recovery • First stage purification preparation • First stage purification • Second stage purification preparation • Second stage purification • Final purification adjustment • ^{99}Mo preparation for shipping]
4.0.0	Uranium recovery and recycle process	• Impure uranium lag storage • First-cycle uranium recovery • Second-cycle uranium purification • Product uranium lag storage • Other support (storage vessels, transfer lines, solid waste handling for resin bed replacement)

Table 13-7. Radioisotope Production Facility Preliminary Hazards Analysis Primary Process Nodes and Subprocesses (2 pages)

Node no.	Node name	Subprocesses encompassed in node
5.0.0	Waste handling system process	• Liquid waste storage • High dose liquid waste volume reduction • Condensate storage and recycling • Concentrated high dose liquid waste storage/preparation • Low dose liquid waste volume reduction and storage • Liquid waste solidification • Solid waste handling • Waste encapsulation • TCE solvent reclamation • Mixed waste accumulation
6.0.0	Target receipt and disassembly process	• Cask receipt and target unloading • Target Inspection • Target disassembly • [Proprietary Information] • Target disassembly stations • Gaseous fission product control • [Proprietary Information] • Empty target hardware handling
7.0.0	Ventilation system	• (No subprocesses identified in PHA. Ventilation system provides cascading pressure zones, a common air supply system with makeup air as necessary, heat recovery for preconditioning incoming air, and HEPA filtration.)
8.0.0	Natural phenomena, man-made external events, and other facility operations	• Natural phenomena • Man-made external events • Chemical storage and preparation areas • On-site vehicle operation • General storage, utilities, and maintenance activities • Laboratory operations • Hot cell support activities • Waste storage operations including packaging and shipment

^{99}Mo = molybdenum-99
HEPA = high-efficiency particulate air.
PHA = preliminary hazards analysis.
TCE = trichloroethylene.

Table 13-8 shows a crosswalk that identifies the applicability of RPF PHA top-level accident sequence categories to the primary process nodes. The information in this table is referenceable to Table 13-6 and ultimately shows the relationship between the PHA process nodes and the NUREG-1537 Part 1 ISG accident initiating event categories via the PHA top-level accident scenario categories.

Table 13-8. Crosswalk of Radioisotope Production Facility Preliminary Hazards Analysis Process Nodes and Top-Level Accident Sequence Categories

Primary process node	PHA Top-Level Accident Sequence Category					
	S.C. (criticality)	S.F. (fire)	S.R. (radiological)	S.M. (man-made)	S.N. (natural phenomena)	S.CS. (chemical safety)
Target fabrication (Node 1.0.0)	✓	✓	✓			
Target dissolution (Node 2.0.0)	✓	✓	✓			
Molybdenum recovery and purification (Node 3.0.0)	✓	✓	✓			
Uranium recovery and recycle (Node 4.0.0)	✓	✓	✓			
Waste handling system (Node 5.0.0)	✓	✓	✓			
Target receipt and disassembly (Node 6.0.0)	✓		✓			
Ventilation system (Node 7.0.0)	✓	✓	✓			
Natural phenomena, man-made external events, and other facility operations (Node 8.0.0)	✓	✓	✓	✓	✓	✓

Note: The ✓ in a table cell indicates that the accident sequence category applies to the process node. If it does not, the cell is blank.

PHA = preliminary hazards analysis.

13.1.3 Preliminary Hazards Analysis Results

This section presents the radiological, criticality, and chemical hazards that could result in high or intermediate consequences.

13.1.3.1 Hazard Criteria

Methodologies and hazard criteria are identified in Section 13.1.1. Numerous hazards are present during the handling and processing the materials in the RPF. The target material is fissile LEU consisting of uranium enriched up to 19.95 weight percent (wt%) uranium-235 (^{235}U). This material presents a criticality accident hazard in the processes that involve high concentrations of uranium. Both 10 CFR 50 and 10 CFR 70 require that accidental nuclear criticalities be prevented using the double-contingency principle, as defined in ANSI/ANS-8.1, *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors*. The RPF separates ^{99}Mo from among the fission products in the irradiated LEU target material. The fission products, including ^{99}Mo, present a high-dose hazard that must be properly contained and shielded to protect workers and the public. Radiation protection standards are given in 10 CFR 20, "Standards for Protection Against Radiation," and its appendices.

The RPF also uses high concentrations of acids, caustics, and oxidizers, both separate from and mixed with licensed material, that present chemical hazards to workers. The National Institute for Occupational Safety and Health (NIOSH) provides acute exposure guidelines (CDC, 2010) that evaluate chemical exposure hazards to workers and the public from chemicals and toxic licensed material.

The facility can also be impacted by various internal and external man-made and natural phenomena events that have the potential to damage structures, systems, and components (SSC) that control the licensed material, thereby leading to intermediate- and high-consequence events.

Known and credited safety features for normal operations include:

- The hot cell shielding boundary, credited for shielding workers and the public from direct exposure to radiation (an expected operational hazard)
- The hot cell confinement boundaries, credited with confining fissile and high-dose solids, liquids, and gases, and controlling gaseous releases to the environment

Administrative and passive engineered design features that control uranium batch size, volume, geometry and interaction are credited for maintaining critically safe (i.e., subcritical) configurations during normal operations with fissile material. The RPF PHA identifies abnormal operation event initiators that require further evaluation for IROFS to ensure that the double-contingency principle is satisfied.

13.1.3.2 Radioisotope Production Facility Accident Sequence Evaluation

A structured what-if analysis was used to evaluate RPF system nodes where operators are primarily involved with licensed material manipulations. All process system nodes were analyzed using a HAZOP approach with special emphasis on criticality, radiological, and chemical safety hazards. Fire safety issues are addressed in every node and addressed generally in Node 8.0.0. Fire safety issues include the explosive hazard associated with hydrogen gas generation via radiolytic decomposition of water in process solutions and due to certain chemical reactions encountered during dissolution processes. Most hot cell processing areas contain very few combustible materials, either transient or fixed.

The RPF PHA has identified adverse events listed in Table 13-9 through Table 13-16. Adverse events are identified as:

- Standard industrial events that do not involve licensed material
- Acceptable accident sequences that satisfy performance criteria by being low consequence and/or low frequency
- Unacceptable accident sequences that require further evaluation via the QRA process

An accident sequence number was assigned to each accident initiator that results in the same, or similar, bounding accident sequence result and consequence. The same accident sequence designator can appear in multiple nodes. (Table 13-5 provides definitions of accident sequence category designators.)

Table 13-9. Adverse Event Summary for Target Fabrication and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
1.1.1.1, 1.1.1.2, 1.6.1.1, 1.8.1.1, 1.8.2.1, and 1.8.3.1	Operator double batches allotted amount of material (fresh U, scrap U, [Proprietary Information], target batch) into one location or container during handling	Accidental criticality issue – Too much fissile mass in one location may become critical	S.C.02, Failure of administrative control on mass (batch limit) during handling of fresh U, scrap U, [Proprietary Information], and targets
1.1.1.3	Supplier ships greater than 20 wt% ^{235}U to site	Accidental criticality issue – Too much ^{235}U put into a container or solution vessel, exceeding assumed amounts	S.C.01, Failure of site enrichment limit
1.1.1.6, 1.1.1.7, 1.6.1.2, 1.6.1.4, 1.8.1.2, 1.8.1.3, 1.8.1.6, 1.8.2.2, 1.8.2.3, 1.8.3.2, 1.8.3.3, 1.8.3.4, and 1.8.3.5	Operator handling various containers of uranium or batches of uranium components brings two containers or batches closer together than the approved interaction control distance	Accidental criticality issue – Too much uranium mass in one location	S.C.03, Failure of administrative control on interaction limit during handling of fresh U, scrap U, [Proprietary Information], and targets
1.2.1.1, 1.2.1.11, 1.2.1.14, 1.2.1.25, 1.3.1.1, 1.3.1.6, 1.3.1.11, 1.3.1.17, 1.4.1.19, 1.4.1.20, 1.4.1.21, 1.4.1.23, 1.4.2.6, 1.4.2.10, 1.4.2.15, 1.4.3.14, 1.4.3.26, 1.4.3.31, 1.4.4.1, 1.4.4.6, 1.4.4.10, 1.4.4.15, 1.5.1.21, 1.5.1.23, 1.5.1.26, 1.5.2.16, 1.7.1.1, 1.7.1.11, 1.7.1.14, 1.7.1.25, 1.9.1.1, 1.9.1.6, 1.9.1.10, and 1.9.1.15	Failure of safe geometry confinement	Accidental criticality from fissile solution not confined in safe geometry	S.C.04, Spill of fissile material from safe geometry system confinement
1.2.1.2 and 1.7.1.2	Uranium-containing solution leaks out of safe geometry confinement into the heating/cooling jacketed space	Accidental criticality from fissile solution not confined in safe geometry	S.C.05, Leak of fissile solution into heating/ cooling jacket on vessel
1.2.1.3, 1.4.3.33, 1.4.3.34, and 1.7.1.3	Uranium solution is transferred via a leak between the process system and the heater/cooling jackets or coils on a tank or in an exchanger	Accidental criticality from fissile solution not confined in safe geometry	S.C.07, Leak of fissile solution across auxiliary system boundary (chilled water or steam)

Table 13-9. Adverse Event Summary for Target Fabrication and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
1.2.1.8, 1.3.1.4, 1.4.1.15, 1.4.2.4, 1.4.3.18, 1.4.4.4, 1.5.1.20, 1.5.2.11, 1.7.1.8, and 1.9.1.4	Failure of safe geometry dimension caused by configuration management (installation, maintenance), internal or external event	Accidental criticality from fissile solution not confined in safe geometry	S.C.19, Failure of passive design feature – Component safe geometry dimension
1.2.1.12, 1.3.1.9, 1.4.2.8, 1.4.4.8, 1.4.5.4, 1.7.1.12, and 1.9.1.8	Tank overflow into process ventilation system	Accidental criticality issue – Fissile solution entering a system not necessarily designed for fissile solutions	S.C.06, Overfill of a tank or component causing fissile solution entering the process vessel ventilation system
1.3.1.2, 1.4.2.2, 1.4.4.2, and 1.9.1.20	Uranium precipitate or other high uranium solids accumulate in safe geometry vessel	Accidental criticality from fissile solution not confined to safe geometry and interaction controls within allowable concentrations	S.C.20, Failure of concentration limits – Precipitation of uranium in safe geometry tank
1.2.1.26, 1.3.1.7, 1.5.1.3, and 1.5.2.5	Uranium solution backflows into an auxiliary support system (water line, purge line, chemical addition line) due to various causes	Accidental criticality issue – Fissile solution entering a system not necessarily designed for fissile solutions	S.C.08, Fissile solution backflow into an auxiliary system at a fill point boundary
1.4.1.6, 1.4.1.12, and 1.4.1.16	Failure of safe geometry confinement due to inadvertent transfer to U-bearing solution across a boundary into non-favorable geometry	Accidental criticality from fissile solution not confined in safe geometry	S.C.11, Fissile material contamination of contactor regeneration aqueous waste stream - boundary to unsafe geometry system
1.4.3.1, 1.4.3.9, 1.4.3.19, 1.4.3.21, 1.4.5.9, and 1.4.5.11	Failure of safe geometry confinement due to inadvertent transfer to U-bearing solution across a boundary into non-favorable geometry	Accidental criticality from fissile solution not confined in safe geometry	S.C.09, Fissile material contamination of evaporator condensate - boundary to unsafe geometry system
1.6.1.3	Failure of safe geometry confinement due to inadvertent transfer to U-bearing solution across a boundary into non-favorable geometry	Accidental criticality from fissile solution not confined in safe geometry	S.C.12, Wash of [Proprietary Information] with wrong reagent contaminating wash solution with fissile U; boundary to unsafe geometry system
1.1.1.11	Dusty surface generated during shipping on uranium pieces spontaneously ignites due to pyrophoric nature of uranium	Potential exposure to workers due to airborne uranium generation	S.F.01, Pyrophoric fire in uranium metal

Table 13-9. Adverse Event Summary for Target Fabrication and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
1.2.1.6, 1.2.1.11, 1.7.1.6, and 1.7.1.11	Hydrogen buildup in tanks or system, leading to explosive concentrations	Explosion leading to radiological and criticality concerns	S.F.02, Accumulation of flammable gas in tanks or systems
1.4.1.17, 1.4.1.21, and 1.4.1.23	Fire in process system containing high concentration uranium spreads the uranium	Radiological and criticality issue – Radiological airborne release of uranium and uncontrolled spread of uranium outside safe geometry confinement	S.F.07, Fire in nitrate extraction system - flammable solvent with uranium
1.6.1.6, 1.6.1.9, and 1.6.1.12	Air inleakage into the reduction furnace during H_2 purge cycle or H_2 inleakage into reduction furnace before inerting with nitrogen can lead to an explosive mixture in the presence of an ignition source	Accidental criticality issue – Uncontrolled spread of uranium outside safe geometry confinement	S.F.03, Hydrogen detonation in reduction furnace
1.6.1.8	Loss of cooling of exhaust or fire in the reduction furnace leads to high temperatures in downstream ventilation component and accelerated release of adsorb radionuclides	Radiological issue – Potential accelerated release of high-dose radionuclides to the stack (worker and public exposure)	S.F.04, High temperature damage to process ventilation system due to loss of cooling in reduction furnace exhaust or fire in reduction furnace
1.2.1.11, 1.2.1.14, 1.4.1.17, 1.4.1.19, 1.4.1.20, 1.4.1.21, 1.4.1.23, 1.4.2.6, 1.4.3.14, 1.4.3.26, 1.4.3.31, 1.4.3.32, 1.7.1.11, 1.7.1.14, and 1.9.1.6	High concentration uranium solution is sprayed from the system, causing high airborne radioactivity	Radiological release of uranium solution spray that remains suspended in the air, exposing workers or the public	S.R.03, Solution spray release potentially creating airborne uranium above DAC limits
1.2.1.11, 1.2.1.12, 1.2.1.14, 1.2.1.25, 1.3.1.1, 1.3.1.6, 1.3.1.11, 1.3.1.17, 1.4.1.17, 1.4.1.18, 1.4.1.19, 1.4.1.21, 1.4.2.1, 1.4.2.6, 1.4.2.8, 1.4.2.10, 1.4.2.15, 1.4.3.14, 1.4.3.26, 1.4.3.31, 1.4.4.6, 1.4.4.10, 1.4.4.15, 1.5.1.21, 1.7.1.11, 1.7.1.14, 1.7.1.25, 1.9.1.1, 1.9.1.6, 1.9.1.8, 1.9.1.10, and 1.9.1.15	High concentration uranium solution is spilled from the system	Potential radiological exposure to workers from uranium-contaminated solution	S.R.01, Uranium-contaminated solution spill

Table 13-9. Adverse Event Summary for Target Fabrication and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
1.2.1.21, 1.2.1.22, 1.4.5.13, 1.7.1.21, and 1.7.1.22	Boiling or carryover of steam or high concentration water vapor into the primary ventilation system, affecting retention beds from partial or complete loss of cooling system capabilities	Radiological release from retention beds	S.R.04, Liquid enters process vessel ventilation system damaging IRU or retention beds releasing retained radionuclides
1.3.1.16 and 1.4.1.24	High-dose solution (failure of the uranium recovery process) results in high-dose radionuclides entering the first stage of processing uranium [Proprietary Information] (eventually handled by the worker)	Potentially high radiological exposure to workers	S.R.05, High-dose solution enters the UN blending and storage tank
1.8.3.7	Loading limits are not adhered to by the operators or the closure requirements are not satisfied, and the cask does not provide the containment or shielding function that it is designed to perform	High-dose to workers or the public from improperly shielded cask	S.R.28, Target or waste shipping cask not loaded or secured according to procedure, leading to personnel exposure

^{235}U = uranium-235.
DAC = derived air concentration.
H_2 = hydrogen gas.
IRU = iodine removal unit.
PHA = process hazards analysis.
U = uranium.
UN = uranyl nitrate.

Table 13-10. Adverse Event Summary for Target Dissolution and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
2.1.1.1, 2.1.1.11, 2.1.1.13, 2.1.1.17, 2.2.1.5, 2.2.1.12, 2.2.1.15, 2.3.6.5, 2.3.6.12, and 2.3.6.13	Failure of safe geometry confinement	Accidental criticality from fissile solution not confined in safe geometry	S.C.04, Failure of confinement in safe geometry; spill of fissile material solution
2.1.1.2	Uranium-containing solution leaks out of safe geometry confinement into the heating/cooling jacketed space	Accidental criticality from fissile solution not confined in safe geometry	S.C.05, Leak of fissile solution in to heating/cooling jacket on vessel
2.1.1.3	Uranium solution is transferred via a leak between the process system and the heater/cooling jackets or coils on a tank or in an exchanger	Accidental criticality from fissile solution not confined in safe geometry	S.C.07, Leak of fissile solution across auxiliary system boundary (chilled water or steam)
2.1.1.8, 2.2.1.11, and 2.3.6.11	Failure of safe geometry dimension	Accidental criticality from fissile solution not confined in safe geometry	S.C.19, Failure of passive design feature; component safe-geometry dimension
2.1.1.12, 2.1.1.15, and 2.3.1.4	Failure of safe-geometry confinement	Accidental criticality from fissile solution not confined in safe geometry	S.C.13, Fissile solution enters the NO_x scrubber where high uranium solution is not intended
2.1.1.14 and 2.3.4.14	Tank overflow into process ventilation system	Accidental criticality issue – Fissile solution entering a system not necessarily designed for fissile solutions	S.C.06, System overflow to process ventilation involving fissile material
2.3.4.11	Uranium enters carbon retention bed dryer where it can mix with condensate to form a fissile solution	Accidental criticality from fissile material or solution not confined in safe geometry	S.C.24, Build-up of high uranium particulate in the carbon retention bed dryer system
2.1.1.33 and 2.1.1.34	Uranium solution backflows into an auxiliary support system (water line, purge line, chemical addition line) due to various causes	Accidental criticality and high radiological dose – High-dose and fissile solution entering a system not necessarily designed for fissile solutions that exist outside of hot cell walls	S.C.08, System backflow into auxiliary support system

Table 13-10. Adverse Event Summary for Target Dissolution and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
2.1.1.18, 2.3.1.21, 2.3.2.21, 2.3.3.24, 2.3.4.3, and 2.3.5.5	Hydrogen build-up in tanks or system leading to explosive concentrations	Explosion leading to radiological and criticality concerns	S.F.02, Accumulation of flammable gas in tanks or systems
2.3.4.20, 2.3.5.2, 2.3.5.6, 2.3.5.10, and 2.3.5.13	A fire develops through exothermic reaction to contaminants in the carbon retention bed and rapidly releases accumulated gaseous high-dose radionuclides	Radiological issue – Potential accelerated release of high-dose radionuclides to the stack (worker and public exposure)	S.F.05, Fire in a carbon retention bed
2.1.1.1, 2.1.1.2, 2.1.1.11, 2.1.1.13, 2.1.1.17, 2.2.1.5, 2.2.1.12, 2.2.1.15, 2.3.6.5, 2.3.6.12, and 2.3.6.13	High-dose and/or high-concentration uranium solution is spilled from the system	Potential radiological exposure to workers from high-dose and/or high uranium-contaminated solution	S.R.01, Radiological release in the form of a liquid spill of high-dose and/or high uranium concentration solution
2.1.1.3	High-dose solution is transferred via a leak between the process system and the heater/cooling jackets or coils on a tank or in an exchanger	Radiological exposure to workers and the public from high-radiological dose not contained in the hot cell containment or confinement boundary	S.R.13, High-dose solution leaks to chilled water or steam condensate system
2.1.1.11, 2.1.1.17, 2.2.1.15, and 2.3.6.13	Spill leading to spray-type release, causing airborne radioactivity above DAC limits for exposure	Radiological dose from airborne spray of product solution from systems	S.R.03, Spray of product solution in hot cell area
2.1.1.23, 2.1.1.26, 2.1.1.27, 2.3.4.1, 2.3.4.12, and 2.3.4.17	Carryover of high vapor content gases or entrance of solutions into the process ventilation header can cause poor performance of the retention bed materials and release radionuclides	High airborne radionuclide release, affecting workers and the public	S.R.04, Carryover of heavy vapor or solution into the process ventilation header causes downstream failure of retention bed, releasing radionuclides

Table 13-10. Adverse Event Summary for Target Dissolution and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
2.3.1.17, 2.3.1.22, 2.3.1.24, 2.3.2.17, 2.3.2.22, 2.3.2.24, 2.3.3.8, 2.3.3.20, 2.3.3.27, 2.3.4.3, 2.3.4.5, 2.3.4.6, and 2.3.4.8	A spill of low-dose condensate occurs for a variety of reasons from the confinement tanks or vessels	Potential radiological dose to workers and the public from spilled liquid	S.R.02, Spill of low-dose condensate
2.3.3.1, 2.3.3.2, 2.3.3.3, 2.3.3.6, 2.3.3.12, 2.3.3.13, 2.3.3.16, 2.3.3.17, 2.3.3.23, 2.3.4.13, 2,3.5.1, 2.3.5.6, 2.3.5.8, and 2.3.5.10	High flows through the IRU increases the release of the retained iodine and increases the high-dose concentration of this gas in the stack	Potential radiological dose to workers and the public from iodine above regulatory limits	S.R.06, High flow through IRU causes premature release of high-dose iodine gas
2.3.3.15 and 2.3.5.8	Low temperatures in the IRU inlet gas stream drives release of iodine from the unit	Potential radiological dose to workers and the public from iodine above regulatory limits	S.R.07, Loss of temperature control on the IRU leads to premature release of high-dose iodine
2.3.3.22 and 2.3.5.8	Liquid and water vapor in the IRU inlet gas stream drives release of iodine from the unit	Potential radiological dose to workers and the public from iodine above regulatory limits	S.R.04, Liquid/high vapor in the IRU leads to premature release of high-dose iodine
2.3.4.4, 2.3.4.5, and 2.3.4.6	Loss of vacuum pumps in the dissolver offgas treatment system leads to pressure buildup inside the process and potential release of radionuclides from the system upstream	Potential radiological dose to workers and the public from spilled liquid	S.R.08, Loss of vacuum pumps
2.3.4.11	Uncontrolled loss of media and contact with a liquid with potential for premature release of the adsorbed iodine	Potential radiological dose to workers and the public from iodine above regulatory limits	S.R.09, Loss of IRU media to downstream dryer

Table 13-10. Adverse Event Summary for Target Dissolution and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
2.3.3.28, 2.3.4.19, 2.3.5.9, 2.3.4.15, and 2.3.5.11	Using the wrong retention media (IRU or carbon beds) or using saturated media with potential for ineffective adsorption of high-dose gaseous radionuclides	Potential radiological dose to workers and the public from radionuclides above regulatory limits	S.R.10, Wrong retention media added to bed or saturated retention media
2.3.4.16, 2.3.5.5, and 2.3.5.12	An event causes damage to the structure holding the retention media, and retention media is released to an uncontrolled environment	Potential radiological dose to workers and the public from radionuclides above regulatory limits	S.R.09, Breach of an IRU or retention bed resulting in release of the media
2.1.1.33 and 2.1.1.34	High-dose process solution backflows into an auxiliary support system (water line, purge line, chemical addition line) due to various causes	High radiological dose – High dose process solution enters a system that exits outside of the hot cell walls	S.R.11, System backflow of high-dose solution into an auxiliary support system and outside the hot cell boundary

DAC = derived air concentration.
IRU = iodine removal unit.
NO_x = nitrogen oxide.
PHA = process hazards analysis.

Table 13-11. Adverse Event Summary for Molybdenum Recovery and Identification of Accident Sequences Needing Further Evaluation (3 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
3.3.1.24	Higher radiation dose due to hold-up accumulation or transient batch differences	Higher localized dose in hot cell boundary (unoccupied by workers)	N/A
3.2.3.7, 3.2.4.7, 3.4.3.7, 3.4.4.7, 3.6.3.7, and 3.6.4.7	Chemical spills of nonradiologically contaminated bulk chemicals	Standard industrial accident – Chemical exposure (not involving licensed material) to workers	N/A
3.7.4.5 and 3.7.4.6	Dropped cask or cask component during loading or handling	Standard industrial accident – Worker injury	N/A
3.7.4.2, 3.7.5.2, and 3.7.5.3	Mo product is exposed with no shielding as the result of an accident, shipment mishap, or shipment mishandling after leaving the site	Potential dose to the public and/or environment due to release or mishandling of Mo product during transit	N/A – Addressed by DOT packaging and transportation regulations (10 CFR 71[a])
3.1.1.9, 3.1.1.14, 3.1.1.23, 3.1.2.4, 3.1.2.7, 3.1.2.13, 3.1.2.16, 3.1.2.17, 3.2.1.6, 3.2.1.10, 3.2.1.20, 3.2.1.22, 3.2.1.23, 3.2.2.9, 3.2.2.13, 3.2.3.6, 3.2.3.8, 3.2.5.9, 3.2.5.14, 3.2.5.23, 3.8.1.9, 3.8.1.13, and 3.8.1.22	Failure of safe-geometry confinement	Accidental criticality from fissile solution not confined in safe geometry	S.C.04, Failure of confinement in safe geometry; spill of fissile material solution
3.1.1.4, 3.1.1.16, 3.2.5.4, 3.2.5.16, and 3.8.1.4	Tank overflow into process ventilation system	Accidental criticality issue – Fissile solution entering a system not necessarily designed for fissile solutions	S.C.06, System overflow to process ventilation involving fissile material
3.1.1.23, 3.2.1.23, 3.2.5.23, and 3.8.1.22	Uranium solution is transferred via a leak between the process system and the heater/cooling jackets or coils on a tank or in an exchanger	Accidental criticality from fissile solution not confined in safe geometry	S.C.07, Leak of fissile solution across auxiliary system boundary (chilled water or steam)
3.2.1.4, 3.2.1.5, 3.2.2.3, 3.2.2.4, 3.2.2.5, 3.2.3.6, and 3.2.4.6	Fissile product solution transferred to a system not designed for safe-geometry confinement	Criticality safety issue – Fissile solution directed to a system not intended for fissile solution	S.C.10, Inadvertent transfer of solution to a system not designed for fissile solutions

Table 13-11. Adverse Event Summary for Molybdenum Recovery and Identification of Accident Sequences Needing Further Evaluation (3 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
3.1.1.13, 3.1.2.9, 3.2.1.15, 3.2.5.13, and 3.8.1.12	Failure of safe-geometry dimension	Accidental criticality from fissile solution not confined in safe geometry	S.C.19, Failure of passive design feature; component safe-geometry dimension
3.1.1.25, 3.2.5.25, 3.3.1.25, 3.5.1.25, and 3.8.1.24	Hydrogen buildup in tanks or system, leading to explosive concentrations	Explosion leading to radiological and criticality concerns	S.F.02, Accumulation of flammable gas in tanks or systems
3.7.1.1, 3.7.1.2, 3.7.2.1, 3.7.3.1, 3.7.3.2, and 3.7.4.1	Operator spills Mo product solution during remote handling operations	Radiological spill of high-dose Mo solution	S.R.01, Radiological spill of Mo product during remote handling
3.1.1.9, 3.1.1.14, 3.1.1.23, 3.1.2.7, 3.1.2.13, 3.1.2.16, 3.1.2.17, 3.2.1.6, 3.2.1.20, 3.2.1.22, 3.2.1.23, 3.2.2.7, 3.2.2.9, 3.2.2.13, 3.2.3.6, 3.2.3.8, 3.2.3.10, 3.2.4.10, 3.2.5.9, 3.2.5.14, 3.2.5.23, 3.3.1.9, 3.3.1.14, 3.3.1.18, 3.3.1.22, 3.3.1.23, 3.3.2.4, 3.3.2.7, 3.3.2.13, 3.3.2.16, 3.3.2.17, 3.4.1.5, 3.4.1.9, 3.4.1.19, 3.4.1.21, 3.4.1.22, 3.4.2.6, 3.4.2.7, 3.4.2.12, 3.4.3.6, 3.4.3.8, 3.4.3.10, 3.4.3.14, 3.4.4.6, 3.4.4.10, 3.4.4.14, 3.5.1.9, 3.5.1.14, 3.5.1.16, 3.5.1.23, 3.5.2.4, 3.5.2.7, 3.5.2.13, 3.5.2.16, 3.5.2.17, 3.6.1.5, 3.6.1.6, 3.6.1.10, 3.6.1.20, 3.6.1.20, 3.6.1.23, 3.6.2.7, 3.6.2.9, 3.6.2.13, 3.6.3.8, 3.6.3.10, 3.6.3.14, 3.6.4.10, 3.6.4.14, 3.8.1.9, 3.8.1.13, and 3.8.1.22	Spill of product solution in the hot cell area	Radiological dose from spill of product solution from systems	S.R.01, Spill of product solution in hot cell area

Table 13-11. Adverse Event Summary for Molybdenum Recovery and Identification of Accident Sequences Needing Further Evaluation (3 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
3.1.1.9, 3.2.1.10, 3.2.1.22, 3.2.2.7, 3.2.2.9, 3.2.3.8, 3.2.3.10, 3.2.4.10, 3.2.5.9, 3.3.1.9, 3.3.1.18, 3.3.1.22, 3.3.2.7, 3.4.1.10, 3.4.1.22, 3.4.2.7, 3.4.3.8, 3.5.1.9, 3.5.1.23, 3.6.1.10, 3.6.2.7, 3.6.3.8, and 3.8.1.9	Spill leading to spray-type release, causing airborne radioactivity above DAC limits for exposure	Radiological dose from airborne spray of product solution from systems	S.R.03, Spray of product solution in hot cell area
3.1.1.7, 3.1.1.22, 3.2.5.7, 3.2.5.22, 3.3.1.4, 3.3.1.7, 3.3.1.16, 3.5.1.4, 3.5.1.7, 3.5.1.16, 3.5.1.22, 3.8.1.7, and 3.8.1.13	Boiling or carryover of steam or high-concentration water vapor into the primary process offgas ventilation system affecting retention beds with partial or complete loss of cooling system capabilities	Radiological release from retention beds	S.R.04, Loss of cooling, leading to liquid or steam carryover into the primary offgas treatment train
3.7.4.3	A Mo product cask is removed from the hot cell boundary with improper shield plug installation	Potential dose to workers, the public, and/or environment due to release or mishandling of Mo product during transit	S.R.12, Mo product is released during shipment
3.3.1.23, 3.3.2.16, 3.4.1.22, 3.5.1.23, and 3.6.1.23	High-dose radionuclide solution leaks through an interface between the process system and a heating/cooling jacket coil into a secondary system (e.g., chilled water or steam condensate) releasing radionuclides to workers, the public, and environment	High-dose radionuclide solution that leaks to the environment through another system to expose workers or the public	S.R.13, High dose radionuclide containing solution leaks to chilled water or steam condensate system

[a] 10 CFR 71, "Packaging and Transportation of Radioactive Material," *Code of Federal Regulations*, Office of the Federal Register, as amended.

DAC = derived air concentration.
DOT = U.S. Department of Transportation.
Mo = molybdenum.
N/A = not applicable.
PHA = process hazards analysis.

Table 13-12. Adverse Event Summary for Uranium Recovery and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
4.1.1.4, 4.1.1.18, 4.2.1.4, 4.2.1.6, 4.2.1.17, 4.2.1.18, 4.2.3.6, 4.2.8.4, 4.2.8.18, 4.2.10.4, 4.3.1.4, 4.3.1.6, 4.3.1.18, 4.3.1.19, 4.3.3.6, 4.3.8.4, 4.3.8.18, 4.3.10.4, 4.4.1.4, 4.4.1.17, 4.5.1.4, 4.5.1.17, 4.5.2.4, 4.5.2.17, 4.5.3.4, and 4.5.3.14	Tank overflow into process ventilation system	Accidental criticality issue – Fissile solution enters a system not necessarily designed for fissile solutions	S.C.06, System overflow to process ventilation involving fissile material
4.1.1.6, 4.2.1.7, 4.2.2.4, 4.2.3.4, 4.2.3.7, 4.2.3.8, 4.2.8.7, 4.3.1.7, 4.3.2.4, 4.3.3.4, 4.3.3.7, 4.3.3.8, 4.3.8.7, 4.4.1.6, 4.5.2.6, and 4.5.3.6	Uranium solution backflows into an auxiliary support system (water line, purge line, chemical addition line) due to various causes	Accidental criticality issue – Fissile solution enters a system not necessarily designed for fissile solutions	S.C.08, System backflow into auxiliary support system
4.1.1.14, 4.2.1.14, 4.2.3.16, 4.2.8.15, 4.3.1.15, 4.3.3.16, 4.3.8.15, 4.3.9.20, 4.4.1.14, 4.5.1.14, 4.5.2.14, and 4.5.3.11	Failure of safe geometry dimension caused by configuration management (installation, maintenance) or external event	Accidental criticality from fissile solution not confined in safe geometry	S.C.19, Failure of passive design feature; component safe-geometry dimension
4.1.1.8, 4.1.1.9, 4.1.1.12, 4.1.1.13, 4.1.1.16, 4.2.1.9, 4.2.1.13, 4.2.5.11, 4.2.8.10, 4.2.8.13, 4.2.8.14, 4.2.8.17, 4.2.9.18, 4.3.1.10, 4.3.1.11, 4.3.1.14, 4.3.1.17, 4.3.1.18, 4.3.5.11, 4.2.8.10, 4.3.8.13, 4.3.8.14, 4.3.8.17, 4.3.9.18, 4.4.1.8, 4.4.1.9, 4.4.1.12, 4.4.1.13, 4.4.1.16, 4.5.1.16, 4.5.2.8, 4.5.2.9, 4.5.2.12, 4.5.2.13, and 4.5.2.16	Uranium precipitate or other high uranium solids accumulate in safe-geometry vessel	Accidental criticality from fissile solution not confined to safe geometry and interaction controls within allowable concentrations	S.C.20, Failure of concentration limits
4.1.1.10, 4.1.1.15, 4.1.1.23, 4.2.1.11, 4.2.1.15, 4.2.1.24, 4.2.2.1, 4.2.3.11, 4.2.3.13, 4.2.3.18, 4.2.3.22, 4.2.3.23, 4.2.3.24, 4.2.4.10, 4.2.5.10, 4.2.7.8, 4.2.8.11, 4.2.8.16, 4.2.8.23, 4.2.9.16, 4.2.9.29, 4.2.9.34, 4.3.1.12, 4.3.1.16, 4.3.1.25, 4.3.2.1, 4.3.3.11, 4.3.3.13, 4.3.3.18, 4.3.3.22, 4.3.3.23, 4.3.3.24, 4.3.4.10, 4.3.5.10, 4.3.7.8, 4.3.8.11, 4.3.8.16, 4.3.8.23, 4.3.9.16, 4.3.9.28, 4.3.9.34, 4.4.1.10, 4.4.1.15, 4.4.1.23, 4.5.1.23, 4.5.2.10, 4.5.2.15, 4.5.2.23, 4.5.3.8, 4.5.3.12, and 4.5.3.19	Failure of safe-geometry confinement due to spill of uranium solution from the system	Accidental criticality from fissile solution not confined in safe geometry	S.C.04, Failure of confinement in safe geometry; spill of fissile material solution

Table 13-12. Adverse Event Summary for Uranium Recovery and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
4.2.3.21, 4.2.4.11, 4.2.6.12, 4.3.3.21, 4.3.4.11,and 4.3.6.12	Failure of safe-geometry confinement due to inadvertent transfer to U-bearing resin to the U IX waste collection tanks through a broken retention element	Accidental criticality from fissile solution not confined in safe geometry	S.C.14, Failure of confinement in safe geometry; transfer of U-bearing resin to U IX waste collection tanks
4.2.5.5, 4.3.1.9, 4.3.5.5, and 4.5.1.5	Failure of safe-geometry confinement due to inadvertent transfer to U-bearing solution to the U IX waste collection tanks	Accidental criticality from fissile solution not confined in safe geometry	S.C.14, Failure of confinement in safe geometry; transfer of U-bearing solution to U IX waste collection tanks
4.2.7.7, 4.3.7.7, and 4.5.3.10	Inadvertent transfer of high uranium-concentration solution or resins to spent resin tanks	Accidental criticality too high of uranium mass in waste stream	S.C.15, Too high of uranium mass in spent resin waste stream
4.2.9.10, 4.2.9.19, 4.2.9.21, 4.2.9.23, 4.2.10.10, 4.2.10.12, 4.3.9.10, 4.3.9.19, 4.3.9.21, 4.3.9.23, 4.3.10.10, and 4.3.10.12	Uranium is inadvertently carried over from the concentrator (1 or 2) to the condenser and subsequently, the condenser condensate collection tanks	Accidental criticality from fissile solution not confined in safe geometry	S.C.09, Carryover of uranium to the condenser or condensate tanks
4.2.9.36 and 4.3.9.36	Uranium solution is transferred via a leak between the process system and heater/cooling jackets or coils on a tank or in an exchanger	Accidental criticality from fissile solution not confined in safe geometry	S.C.07, Uranium-containing solution leaks to chilled water or steam condensate system
4.1.1.8, 4.1.1.22, 4.2.1.9, 4.2.1.17, 4.2.1.23, 4.2.9.11, 4.2.9.14, 4.2.9.17, 4.2.9.23, 4.2.9.30, 4.2.9.32, 4.2.10.14, 4.3.1.10, 4.3.1.18, 4.3.1.24, 4.3.9.11, 4.3.9.14, 4.3.9.17, 4.3.9.23, 4.3.9.30, 4.3.9.32, 4.3.10.14, 4.4.1.8, 4.4.1.22, 4.5.1.9, 4.5.1.22, and 4.5.2.8	Carryover of high-vapor content gases or entrance of solutions into the process ventilation header can cause poor performance of the retention bed materials and release radionuclides	High airborne radionuclide release, affecting workers and the public	S.R.04, Carryover of heavy vapor or solution into the process ventilation header causes downstream failure of retention bed, releasing radionuclides

Table 13-12. Adverse Event Summary for Uranium Recovery and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
4.1.1.10, 4.1.1.15, 4.1.1.23, 4.2.1.11, 4.2.1.15, 4.2.1.24, 4.2.2.1, 4.2.2.4, 4.2.3.11, 4.2.3.13, 4.2.3.18, 4.2.3.22, 4.2.3.23, 4.2.3.24, 4.2.4.10, 4.2.5.10, 4.2.6.11, 4.2.7.8, 4.2.8.11, 4.2.8.16, 4.2.8.23, 4.2.9.16, 4.2.9.28, 4.2.9.34, 4.3.1.12, 4.3.1.16, 4.3.1.25, 4.3.2.1, 4.3.2.4, 4.3.3.11, 4.3.3.13, 4.3.3.18, 4.3.3.22, 4.3.3.23, 4.3.3.24, 4.3.4.10, 4.3.5.10, 4.3.6.11, 4.3.7.8, 4.3.8.11, 4.3.8.16, 4.3.8.23, 4.3.9.16, 4.3.9.28, 4.3.9.34, 4.4.1.10, 4.4.1.15, 4.4.1.23, 4.5.1.11, 4.5.1.15, 4.5.1.23, 4.5.2.10, 4.5.2.15, 4.5.2.23, 4.5.3.8, 4.5.3.12, and 4.5.3.19	High-dose radionuclide solution is spilled from the system	Radiological release of high-dose solution with potential to impact workers, the public, or environment	S.R.01, Spill of product solution in hot cell area
4.2.1.12, 4.2.1.24, 4.2.2.1, 4.2.3.11, 4.2.3.13, 4.2.3.18, 4.2.3.22, 4.2.3.23, 4.2.4.10, 4.2.5.10, 4.2.6.11, 4.2.8.11, 4.2.8.16, 4.2.8.23, 4.2.9.16, 4.2.9.28, 4.2.9.34, 4.2.9.35, 4.3.1.12, 4.3.1.16, 4.3.1.12, 4.3.1.25, 4.3.2.1, 4.3.3.11, 4.3.3.13, 4.3.3.18, 4.3.3.22, 4.3.3.23, 4.3.4.10, 4.3.5.10, 4.3.6.11, 4.3.8.11, 4.3.8.16, 4.3.8.23, 4.3.9.16, 4.3.9.28, 4.3.9.34, 4.3.9.35, 4.4.1.10, 4.4.1.15, 4.4.1.23, 4.5.1.11, 4.5.1.23, 4.5.2.10, 4.5.2.15, 4.5.2.23, and 4.5.3.19	High-dose radionuclide solution is sprayed from the system, causing high airborne radioactivity	Radiological release of high-dose spray that remains suspended in the air, giving high dose to workers or the public	S.R.03, Spray of product solution in hot cell area
4.2.9.37, 4.2.9.36, 4.3.9.36, and 4.3.9.37	High-dose radionuclide solution leaks through an interface between the process system and a heating/cooling jacket coil into a secondary system (e.g., chilled water or steam condensate), releasing radionuclides to workers, the public, and environment	High-dose radionuclide solution that leaks to the environment through another system to expose workers or the public	S.R.13, High-dose, radionuclide-containing solution leaks to chilled water or steam condensate system

Table 13-12. Adverse Event Summary for Uranium Recovery and Identification of Accident Sequences Needing Further Evaluation (4 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
4.1.1.25, 4.2.1.26, 4.2.8.25, 4.3.1.27, 4.3.8.25, 4.4.1.25, 4.5.1.25, 4.5.2.25, and 4.5.3.21	Hydrogen buildup in tanks or system, leading to explosive concentrations	Explosion leading to radiological and criticality concerns	S.F.02, Accumulation of flammable gas in tanks or systems
4.1.1.24, 4.2.1.25, 4.2.8.24, 4.2.10.18, 4.3.1.26, 4.3.8.24, 4.3.10.18, 4.4.1.24, 4.5.1.24, 4.5.2.24, and 4.5.3.20	Higher dose than normal due to double-batching an activity or due to buildup of radionuclides in the system over time	Radiation dose is elevated over normal operational levels, but does not exceed low consequence values for exposure to workers due to shielding	Hot cell shielding is credited as the normal condition, mitigating safety feature for this hazard (adverse condition does not represent failure of the safety function of the IROFS)
4.2.4.8 and 4.3.4.8	High temperature pre-elution or regeneration reagent causes unknown impact on IX resin	Consequence is not fully understood	Tentatively S.R.14
4.2.10.6 and 4.3.10.6	Same as S.C.08 except with low-dose solution from condenser condensate	Low consequence resulting in contaminated system	N/A
4.2.10.8, 4.2.10.11, 4.2.10.17, 4.3.10.8, 4.3.10.11, and 4.3.10.17	Spill or spray of low-dose condensate	Low consequence resulting in contaminated surfaces and dose to worker below intermediate consequence dose levels	N/A

IROFS = items relied on for safety.
IX = ion exchange.
N/A = not applicable.
PHA = process hazards analysis.
U = uranium.

Uranium Recovery Open Item

The following adverse event needs to be further researched.

PHA items 4.2.4.8 and 4.3.4.8 postulate high-temperature 2 molar (M) nitric acid (HNO_3) solution being used on the uranium purification ion-exchange (IX) media as a pre-elution rinse. The consequence of the bounding accident was not fully understood and needs to be further researched. The likelihood was identified as low, as there are no good causes of the high temperature from the supply tank other than an improper mixing sequence. This upset would not cause extremely elevated temperatures nor go undetected.

Table 13-13. Adverse Event Summary for Waste Handling and Identification of Accident Sequences Needing Further Evaluation (2 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
5.1.1.13	High uranium content product solution is directed to the high-dose waste collection tanks by accident	Solution from this tank is solidified in a non-favorable geometry process with potential to result in accident nuclear criticality at the high uranium concentration	S.C.10, Fissile solution in high-dose waste collection tanks (a non-fissile solution boundary)
5.2.1.13 and 5.2.2.13	High uranium content product solution enters the low-dose waste collection tanks by accident	Solution from this tank is solidified in a non-favorable geometry process with potential to result in accidental nuclear criticality at the high uranium concentration	S.C.10, Fissile solution is directed to the low-dose waste collection tank
5.4.1.1	High uranium content accumulates in the TCE reclamation evaporator	The mass of uranium may exceed a safe mass and result in an accidental nuclear criticality without monitoring and controls	S.C.22, High concentration of uranium in the TCE evaporator residue
5.4.2.1	Dissolved uranium products may accumulate in the silicone oil waste stream	The mass of uranium may exceed a safe mass and result in an accidental nuclear criticality without monitoring and controls	S.C.23, High concentration in the spent silicone oil waste
5.1.1.24 and 5.1.4.23	Hydrogen buildup in tanks or system leads to explosive concentrations	Explosion leads to radiological and criticality concern	S.F.02, Accumulation of flammable gas in tanks or systems
5.1.1.4, 5.1.1.16, 5.1.4.4, 5.1.4.15, and 5.1.4.17	Several tank or components vented to the process vessel ventilation system overflow and send high-dose solution into process ventilation system components that exit the hot cell boundary	Radiological release may cause a high-dose exposure to workers and the public	S.R.04, High-dose solution from a tank or component overflows into the process ventilation system, compromising the retention beds
5.1.1.6 and 5.1.4.6	The purge air system (an auxiliary system that originates outside the hot cell boundary) allows high-dose radionuclides to exit the boundary in an uncontrolled manner	Radiological release may cause a high-dose exposure to workers and the public	S.R.16, High-dose solution backflows into the purge air system
5.1.1.10, 5.1.1.14, 5.1.1.22, 5.1.2.26, 5.1.2.31, 5.1.4.10, 5.1.4.13, 5.1.4.21, 5.1.5.16, 5.1.5.19, 5.1.5.20, 5.3.1.14, 5.3.1.17, and 5.3.1.18	Spills from multiple sources; materials originating from high-dose process solutions are spilled from the system or process that normally confines them	Radiological release may cause a high-dose exposure to workers and the public	S.R.01, High-dose solution spill in the hot cell waste handling area

Table 13-13. Adverse Event Summary for Waste Handling and Identification of Accident Sequences Needing Further Evaluation (2 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
5.1.1.21, 5.1.2.28, and 5.1.4.20	Several tanks or components vented to the process vessel ventilation system evolve high liquid vapor concentrations, resulting in accelerated high-dose radionuclide release to the stack from wetted retention beds	Radiological release may cause a high-dose exposure to workers and the public	S.R.04, High-dose radionuclide release due to high vapor content in exhaust
5.1.1.22, 5.1.2.26, 5.1.2.31, 5.1.2.32, 5.1.4.10, and 5.1.4.21	Catastrophic failure of a component (high pressure or detonation) leads to rapid release of solution and higher airborne levels	Radiological release may cause a high-dose exposure to workers and the public	S.R.03, High-dose solution spray events from equipment upsets may cause high airborne radioactivity
5.1.2.9, 5.1.2.18, 5.1.2.19, and 5.1.2.21	Adverse events in the concentrator or evaporator systems lead to carryover of high-dose solution into the condenser, resulting in high-dose radionuclides in the low-dose waste collection tanks	Radiological exposure levels on the low-dose encapsulated waste may exceed intermediate or high consequence levels	S.R.17, Carryover of high-dose solution into condensate (a low-dose waste stream)
5.1.2.33	Normally low-dose vapor in the condenser leaks through the boundary into the chilled water system	Radiological release may cause a high-dose exposure to workers and the public	S.R.13, Process vapor from the evaporator leaks across the condenser cooling coils into the chilled water system
5.1.5.8	High-dose solution is inadvertently misfed into the solidification hopper	Radiological release may cause a high-dose exposure to workers and the public	S.R.18, High-dose solution flows into the solidification hopper
5.5.1.1	Due to several potential initiators, the payload container or the shipping cask of high-dose encapsulated waste is dropped during transfer from the storage location to the conveyance	Radiological issue – Depending on damage from the drop, workers could receive high-dose radiation exposure. Unshielded package may impact dose rates at the controlled area boundary.	S.R.32, Container or cask dropped during transfer

PHA = process hazards analysis.
TCE = trichloroethylene.

Table 13-14. Adverse Event Summary for Target Receipt and Identification of Accident Sequences Needing Further Evaluation (2 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
6.1.2.4, 6.1.2.8, 6.1.2.9, 6.1.2.11, 6.1.2.14, and 6.1.2.15	Handling damage to the target basket fixed-interaction passive design feature leads to accidental nuclear criticality	Accidental nuclear criticality leads to high dose to workers and potential dose to the public	S.C.21, Target basket passive design control failure on fixed interaction spacing
6.1.2.7, 6.1.2.10, 6.2.1.1, 6.2.1.5, 6.2.2.1, 6.2.2.2, 6.2.2.4, 6.2.2.5, 6.2.3.3, 6.2.4.1, 6.2.4.2, 6.2.4.4, 6.2.6.1, 6.2.6.3, and 6.2.6.4	Too much uranium mass is handled at once either through operator error or inattention to housekeeping	Accidental nuclear criticality leads to high dose to workers and potential dose to the public	S.C.02, Operator exceeds batch handling limits during target disassembly operations in the hot cell
6.2.1.6, 6.2.2.9, 6.2.3.4, and 6.2.6.6	Operator accumulates more targets or [Proprietary Information] containers into specific room than allowed and violates interaction control	Accidental nuclear criticality leads to high dose to workers and potential dose to the public	S.C.03, Failure of administrative control on interaction limit during handling of targets and irradiated [Proprietary Information]
6.2.1.3, 6.2.1.4, 6.2.1.5, 6.2.2.2, 6.2.2.4, 6.2.2.6, 6.2.3.1, 6.2.3.2, 6.2.3.3, 6.2.5.1, 6.2.5.3, 6.2.5.4, 6.2.5.8, 6.2.6.1, 6.2.6.2, 6.2.6.3, and 6.2.6.5	Too much uranium in the solid waste container (that is not safe-geometry) entering the solid waste encapsulation process (where moderator will be added in the form of water)	Accidental nuclear criticality leads to high dose to workers and potential dose to the public	S.C.17, [Proprietary Information] residual determination fails, and used target housings have too much uranium in solid waste encapsulation waste stream
6.1.1.5, and 6.1.1.9	Cask involved in an in-transit accident or improperly closed prior to shipment, leading to streaming radiation	High dose to workers during receipt inspection and opening activities	S.R.28, High dose to workers during shipment receipt inspection and cask preparation activities due to damaged irradiated target cask
6.1.1.10	Cask involved in in-transit accident or targets failed during irradiation, leading to excessive offgasing from damaged targets	High dose to workers during receipt inspection and opening activities	S.R.29, High dose to workers from release of gaseous radionuclides during cask receipt inspection and preparation for target basket removal
6.1.1.11, 6.1.1.12, 6.1.2.1, 6.1.2.13, and 6.1.2.16	Seal between cask and hot cell docking port fails from a number of causes	High dose to workers from streaming radiation and/or high airborne radioactivity	S.R.30, Cask docking port failures lead to high dose to workers due to streaming radiation and/or high airborne radioactivity

Table 13-14. Adverse Event Summary for Target Receipt and Identification of Accident Sequences Needing Further Evaluation (2 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
6.1.1.1	Cask involved in a crane movement incident, leading to streaming radiation	High dose to workers during receipt inspection and opening activities	S.R.32, High dose to workers during shipment receipt inspection and cask preparation activities due to damaged cask in crane movement incident
6.1.2.3 and 6.1.2.5	Improper handling activities result in high external dose rates through the hot cell wall when removing the target basket and setting it in the target basket carousel shielded well	High external dose to workers	S.R.19, High target basket retrieval dose rate
6.1.2.10, 6.1.2.15, 6.2.1.5, 6.2.2.2, 6.2.2.4, 6.2.3.3, 6.2.4.2, 6.2.5.4, 6.2.6.1, and 6.2.6.3	[Proprietary Information] spilled or ejected in an uncontrolled manner during various target and container-handling activities or during target-cutting activities	High dose to workers or the public may result from uncontrolled accumulation of irradiated [Proprietary Information]	S.R.20, Radiological spill of irradiated targets in the hot cell area
6.1.2.15	Operations removing the target basket (potentially in a heavy shielding housing) with a hoist leads to striking the wall and damaging the hot cell wall shielding function	High dose to workers due to degraded shielding	S.R.21, Damage to the hot cell wall providing shielding
6.2.4.5	Delays in processing a batch of removed [Proprietary Information] results in long-term heating outside of target housing	High dose to workers from high airborne radioactivity	S.R.22, Decay heat buildup in unprocessed [Proprietary Information] removed from targets leads to higher high dose radionuclide offgasing
6.2.4.6 and 6.2.4.7	Improper venting of the chamber or premature opening of the valve during processing of a previously added batch results in release of high-dose radionuclides to the hot cell space	High dose to workers from high airborne radioactivity	S.R.23, Offgasing from irradiated target dissolution tank occurs when the upper valve is opened
6.2.5.5, 6.2.5.6, and 6.2.5.7	The seal on the bagless transport door fails and leads to high dose radionuclides escaping the hot cell containment or confinement boundary	High dose to workers from high airborne radioactivity	S.R.24, Bagless transport door failure

PHA = process hazards analysis.

Table 13-15. Adverse Event Summary for Ventilation System and Identification of Accident Sequences Needing Further Evaluation

PHA item numbers	Bounding accident description	Consequence	Accident sequence
7.1.1.7 and 7.1.1.8	Too much uranium accumulated on the HEPA filter allows an accidental criticality when left in the wrong configuration	Accidental nuclear criticality leads to high dose to workers and potential dose to the public	S.C.24, High uranium content on HEPA filters
7.1.1.2, 7.1.1.3, and 7.1.1.6	Hydrogen buildup in the ventilation system, due to insufficient flow to sweep it away, leads to fire in the HEPA filters or carbon beds	A detonation or deflagration event in the ventilation system rapidly releases retained high-dose radionuclides, causing high airborne radioactivity	S.F.06, Accumulation of flammable gas in ventilation system components
7.1.1.10 and 7.2.1.19	Ignition source causes fire in the carbon bed	Fire event in the ventilation system rapidly releases retained high-dose radionuclides, causing high airborne radioactivity	S.F.05, Fire in the carbon bed
7.1.1.11 and 7.2.1.20	Overloading of HEPA filter leads to failure and release of accumulated radionuclide particulate	High dose to workers from high airborne radioactivity	S.R.25, HEPA filter failure
7.1.1.12, 7.1.1.14, and 7.2.1.21	The accumulated high-dose (and low-dose) radionuclides retained in the carbon bed are released through a flow, heat, or chemical reaction from the media (or the media is released)	High dose to workers from high airborne radioactivity	S.R.04, Carbon bed radionuclide retention failure
7.2.1.4, 7.2.1.7, 7.2.1.8, 7.2.1.9, 7.2.1.13, 7.2.1.14, 7.2.1.17, and 7.2.1.22	Loss of the negative air balance between zones (a confinement feature that prevents migration of radionuclides from areas of high dose and high concentration to areas of low concentration)	High dose to workers from high airborne radioactivity	S.R.26, Failed negative air balance from zone to zone or failure to exhaust a radionuclide buildup in an area
7.2.1.12 and 7.2.1.17	During an extended power outage, some solution systems freeze and cause failure of the piping system, leading to radiological spills	High dose to workers from high airborne radioactivity	S.R.27, Extended outage of heat, leading to freezing, pipe failure, and release of radionuclides from liquid process systems

HEPA = high-efficiency particulate air. PHA = process hazards analysis.

Table 13-16. Adverse Event Summary for Node 8.0 and Identification of Accident Sequences Needing Further Evaluation (5 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
8.2.1.5	Large leak leads to localized low oxygen levels that adversely impact worker performance and may lead to death	Standard industrial hazard – Localized asphyxiant	Nitrogen storage or distribution system leak
8.5.1.1 and 8.5.1.5	Operator double-batches allotted amount of material (fresh U, scrap U, [Proprietary Information], target batch) into one location or container during handling	Accidental criticality issue – Too much fissile mass in one location may become critical	S.C.02, Failure of AC on mass (batch limit) during handling of fresh U, scrap U, [Proprietary Information], and targets
8.5.1.3 and 8.5.1.5	Operator handling various containers of uranium or batches of uranium components brings two containers or batches closer together than the approved interaction control distance	Accidental criticality issue – Too much uranium mass in one location	S.C.03, Failure of AC on interaction limit during handling of fresh U, scrap U, [Proprietary Information], and targets
8.6.1.7	A liquid spill of recycle uranium or target dissolution solution occurs within the hot cell boundary	Criticality issue – Fissile solution may collect in unsafe geometry	S.C.04, A liquid spill of fissile solution occurs
8.6.1.9	Process solutions backflow through chemical addition lines to locations outside the hot cell boundary	Criticality issue – Fissile solution may collect in unsafe geometry	S.C.08, Fissile process solutions backflow through chemical addition lines
8.6.1.13	Improper installation of HEPA filters (and prefilters) leads to transfer of fissile uranium particulate into downstream sections of the ventilation system with uncontrolled geometries	Accidental nuclear criticality leads to high dose to worker and potential dose to public	S.C.24, High uranium content on HEPA filters
8.5.1.2 and 8.5.1.5	Operator handling enriched solutions pours solution into an unapproved container	Criticality hazard – Too much uranium mass in one place can lead to accidental nuclear criticality	S.C.27, Failure of AC on volume limit during sampling
8.4.1.8 and 8.6.1.12	Drop of a hot cell cover block or other heavy object damages SSCs relied on for safety	Criticality issue – Structural damage could adversely damage SSCs relied on for safety, leading to accidents with intermediate or high consequence	S.C.28, Crane drop accident over hot cell or other area with SSCs relied on for safety

Table 13-16. Adverse Event Summary for Node 8.0 and Identification of Accident Sequences Needing Further Evaluation (5 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
8.1.2.7 and 8.1.2.12	A general facility fire (caused by vehicle accident inside or outside of the facility, wildfire, combustible fire in non-industrial areas, or fire in non-licensed material processing areas) spreads to areas in the building that contain licensed material	Uncontrolled fire can lead to damage to SSCs relied on for safety, resulting in chemical, radiological, or criticality hazards that represent intermediate to high consequence to workers, the public, and environment	S.F.08, General facility fire
8.2.1.7	Leak of hydrogen in the facility attains an explosive mixture and finds an ignition source, leading to detonation or deflagration of the mixture	May lead to an explosion (detonation or deflagration), depending on the location in the facility where the hydrogen leaks from. Explosion may compromise SSCs to various degrees and may lead to intermediate or high consequence events.	S.F.09, Hydrogen explosion in the facility due to a leak from the hydrogen storage or distribution system
8.6.1.11	Electrical fire sparks larger combustible fire in one of the hot cells	Radiological and criticality issue – Depending on the location and quantity of combustibles or flammables left in the area, a fire in the hot cell area could rupture systems with high-dose fission products and/or high uranium content, leading to spills and airborne releases	S.F.10, Combustible fire occurs in hot cell area
8.1.2.9 and 8.4.1.9	A natural gas leak develops in the steam generator room and finds an ignition source, resulting in a detonation or deflagration that damages SSCs	Potential explosion that could catastrophically damage nearby SSCs. Depending on the extent of the damage to SSCs, an accidental nuclear criticality or an intermediate or high consequence exposure to workers could occur.	S.F.11, Detonation or deflagration of natural gas leak in steam generator room
8.1.2.7, 8.3.1.2, and 8.6.1.5	Vehicle inside building strikes fresh uranium dissolution system component, leading to a spill or accidental criticality due to disruption of geometry and/or interaction	Accidental nuclear criticality leads to high dose to workers and potential dose to public	S.M.01, Vehicle strikes SSC relied on for safety and causes damage or leads to an accident sequence of intermediate or high consequence
8.4.1.6	TBD (impact must be evaluated after determining all IROFS that rely on personnel action)	TBD (impact must be evaluated after determining all IROFS that rely on personnel action)	S.M.02, Facility evacuation impacts on operation

Table 13-16. Adverse Event Summary for Node 8.0 and Identification of Accident Sequences Needing Further Evaluation (5 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
8.1.2.13	Flooding from external events and internal events compromises the safe geometry slab area under certain tanks. Depending on the liquid level, interspersed moderation of components may be impacted. Floor storage arrays are subject to stored containers floating (loss of interaction control).	Criticality issue – Water accumulation under safe geometry storage vessels or in safe interaction storage arrays, causing interspersed moderation. Flooding could compromise safe-geometry storage capacity for subsequent spills of fissile solution. Either event could compromise criticality safety.	S.M.03. Flooding occurs in building due to internal system leak or fire suppression system activation (likely)
8.1.1.1	Large tornado strikes the facility	Radiological, chemical, and criticality issue – Structural damage could adversely damage SSCs relied on for safety. Facility could lose all electrical distribution. Facility could lose chilled water system function (cooling tower outside of building).	S.N.01, Tornado impact on facility and SSCs
8.1.1.2	Straight-line winds strike the facility	Radiological, chemical, and criticality issue – Structural damage could adversely damage SSCs relied on for safety. Facility could lose all electrical distribution. Facility could lose chilled water system function (cooling tower outside of building).	S.N.02, High straight-line wind impact on facility and SSCs
8.1.1.3	A 48-hr probable maximum precipitation event strikes the facility	Radiological, chemical, and criticality issue – Structural damage from roof collapse could adversely damage SSCs relied on for safety	S.N.03, Heavy rain impact on facility and SSCs
8.1.1.4	Flooding occurs in the area in excess of 500-year return frequency	Radiological issue – Minor structural damage is not anticipated to impact SSCs relied on for safety except that the facility could lose all electrical distribution and/or chilled water system function (cooling tower outside of building)	S.N.04, Flooding impact on facility and SSCs
8.1.1.6	Safe shutdown earthquake strikes – Seismic shaking can lead to damage of the facility and partial to complete collapse. This damage impacts SSCs inside and outside the hot cell boundary. Leaks of fissile solution, compromise of safe-geometry, and safe interaction storage in solid material storage arrays and pencil tanks or vessels containing enriched uranium solutions.	Radiological, chemical, and criticality issue – Structural damage could adversely damage SSCs relied on for safety. Facility could lose all electrical distribution. Facility could lose chilled water system function (cooling tower outside of building).	S.N.05, Seismic impact on facility and SSCs

Table 13-16. Adverse Event Summary for Node 8.0 and Identification of Accident Sequences Needing Further Evaluation (5 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
8.1.1.9, 8.1.1.10	Heavy snowfall or ice buildup exceeds design loading of the roof, resulting in collapse of the roof and damage to SSCs (e.g., those outside of the hot cells)	Radiological, chemical, and criticality issue – Structural damage from roof collapse could adversely damage SSCs relied on for safety. Loss of site electrical power is highly likely in heavy ice storm event.	S.N.06, Heavy snowfall or ice buildup on facility and SSCs
8.6.1.8	Any stored high-dose product solution spills within the hot cell boundary	Radiological issue – High-dose solution is unconfined or uncontrolled and can cause exposures to workers, the public, and environment	S.R.01, A liquid spill of high-dose fission product solution occurs
8.5.1.5	Operator spills diluted sample outside of the hot cell area	Radiological issue – Potential spray or vaporization of radionuclide containing vapor-causing adverse worker exposure (based on typical low quantities handled in the laboratory, this is postulated to be an intermediate consequence event)	S.R.01, Spill of product solution in laboratory
8.6.1.10	Recycle uranium transferred out before lag storage decay complete or with significant high-dose radionuclide contaminants	Radiological issue – High radiation may occur in non-hot cell areas, impacting workers with higher than normal external doses	S.R.05, High-dose solution exits hot cell shielding boundary (destined for UN blending and storage tank)
8.6.1.9	Process solutions backflow through chemical addition lines to locations outside the hot cell boundary	Radiological issue – High radiation may occur in non-hot cell areas, impacting workers with higher than normal external doses	S.R.16, High-dose process solutions backflow through chemical addition lines
8.6.1.2 and 8.6.1.3	An improperly sealed cover block or transport door (e.g., for cask transfers) offer large opening potentials for radiation streaming	Radiological issue – Depending on location of damage, some streaming of high radiation may occur, impacting workers with higher than normal external doses	S.R.21, Damage to the hot cell wall penetration, compromising shielding
8.6.1.1	The seal on the bagless transport door fails and leads to high-dose radionuclides escaping the hot cell confinement boundary	Radiological issue – Degraded or loss of cascading negative air pressure between zones may allow high radiological airborne contamination to release without proper filtration and adsorption, leading to higher than allowed exposure rates to workers and the public	S.R.24, Bagless transport door failure
8.6.1.13	Following process upsets and over long periods of operation, contamination levels in downstream components leads to high dose during maintenance and to uncontrolled accumulation of fissile material	Radiological and criticality issue – Following process upsets and over long periods of operation, contamination levels in downstream components can lead to high dose during maintenance and to uncontrolled accumulation of fissile material	S.R.25, HEPA filter failure

Table 13-16. Adverse Event Summary for Node 8.0 and Identification of Accident Sequences Needing Further Evaluation (5 pages)

PHA item numbers	Bounding accident description	Consequence	Accident sequence
8.6.1.2, 8.6.1.3, and 8.6.1.6	An improperly sealed cover block or transport door (e.g., for cask transfers) compromises negative air pressure balance	Radiological issue – Degraded or loss of cascading negative air pressure between zones may allow high radiological airborne contamination to release without proper filtration and adsorption, leading to higher than allowed exposure rates to workers and the public	S.R.26, Failed negative air balance from zone to zone or failure to exhaust a radionuclide buildup in an area
8.5.1.7 and 8.5.1.8	Laboratory technician is burned by solutions containing radiological isotopes during sample analysis activities	Radiological issue – Burns may lead to intermediate consequence events if eyes are involved	S.R.31, Chemical burns from contaminated solutions during sample analysis
8.4.1.8, 8.6.1.4, and 8.6.1.12	Drop of a hot cell cover block or other heavy object damages SSCs relied on for safety	Radiological and criticality issue – Structural damage could adversely damage SSCs relied on for safety, leading to accidents with intermediate or high consequence	S.R.32, Crane drop accident over hot cell or other area with SSCs relied on for safety
8.2.1.1	All nitric acid from a nitric acid storage tank is released in 1 hr from the chemical preparation and storage room	Standard industrial accident with potential to impact SSCs or cause additional accidents of concern	S.CS.01, Nitric acid fume release

AC = administrative control.
HEPA = high efficiency particulate air.
IROFS = items relied on for safety.
PHA = process hazards analysis.
SSC = structures, systems, and components.
TBD = to be determined.
U = uranium.
UN = uranyl nitrate.

The identified accident sequences are further evaluated in QRAs to continue the accident analysis and to identify IROFS for those accident sequences that exceed the performance criteria as specified in NWMI-2014-051, *Integrated Safety Analysis Plan for the Radioisotope Production Facility*.