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Preliminary Radioisotope Screening for Off-site Consequence Assessment of Advanced Non-LWR Systems

Nathan C. Andrews Michael Higgins Anna Taconi Jennifer Leute

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

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ABSTRACT

Currently a set of 71 radionuclides are accounted for in off-site consequence analysis for LWRs. Radionuclides of dose consequence are expected to change for non-LWRs, with radionuclides of interest being type-specific. This document identifies an expanded set of radionuclides that may need to be accounted for in multiple non-LWR systems:

- high temperature gas reactors (HTGRs)
- fluoride-salt-cooled high-temperature reactors (FHRs)
- thermal-spectrum fluoride-based molten salt reactors (MSRs)
- fast-spectrum chloride-based MSRs
- liquid metal fast reactors with metallic fuel (LMRs)

Specific considerations are provided for each reactor type in Chapter 2 through Chapter 5, and a summary of all recommendations is provided in Chapter 6.

All identified radionuclides are already incorporated within the MACCS software, yet the development of tritium-specific and carbon-specific chemistry models are recommended.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ANL	Argonne National Laboratory
EBR-II	Experimental Breeder Reactor II
FFTF	Fast Flux Test Facility
FHR	Fluoride-Salt-Cooled High-Temperature Reactor
HTGR	High Temperature Gas Reactor
LMR	Liquid Metal Reactor
LWR	Light Water Reactor
MACCS	MELCOR Accident Code Consequence System
MSR	Molten Salt Reactor
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
РуС	Pyrolytic Carbon
SFR	Sodium Fast Reactor
TRISO	Tri-structural ISOtropic

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1. INTRODUCTION

1.1. Background and Scope

The MELCOR Accident Consequence Code System (MACCS) software is currently capable of capturing the impacts of 150 separate radionuclides (isotopes) in off-site consequence assessments. Currently, off-site consequence assessments of light water reactors (LWRs) are performed with a set of 71 isotopes that were identified within NRC's state of the art consequence analyses project [1] and NRC's relative importance of individual elements to reactor accident consequences [2*]. Due to the flexibility of the MACCS software, there is no need to arbitrarily reduce the number of isotopes tracked without a complete knowledge of the inventory, chemistry or system behavior.

This document identifies an expanded set of radionuclides that may need to be accounted for in multiple non-LWR systems:

- high temperature gas reactors (HTGRs)
- fluoride-salt-cooled high-temperature reactors (FHRs)
- thermal-spectrum fluoride-based molten salt reactors (MSRs)
- fast-spectrum chloride-based MSRs
- liquid metal fast reactors with metallic fuel (LMRs)

The readiness of the MACCS software to capture the behavior of each of these radionuclides is also assessed [3]. Of particular importance are appropriate chemical representations, and dose conversion factors for assessing health consequences.

Advanced reactors are still within the design and licensing process, therefore there are multiple gaps within the knowledge of radionuclide inventories, radionuclide transport pathways and associated chemistry. These gaps have been identified within the NRC's non-LWR software development plans [4]. Until these gaps are sufficiently closed, a final set of radionuclides that will need to be included in consequence assessments for each non-LWR type cannot be established. Of particular importance is a representative inventory for each reactor type that has been developed with the SCALE software system; this will provide a full set of radioactivity associated with each individual isotope.

1.2. Radionuclides Identified from Light Water Reactor Fission Product Screening and their Applicability to non-LWRs

The fission product yield from advanced reactors with U-235, U-233, and Pu-239 fuel in both fast spectrum and thermal spectrum systems is similar to that of what is created in existing LWRs. These radionuclides are included in Table 1-1, which includes fission products, implicit daughters, actinides, and activation products.

Chemical Group	Isotope	Half-life	Chemical Group	Isotope	Half-life
	Kr-85	10.72 yr		Co-58	70.8 d
	Kr-85m	4.48 hr		Co-60	5.271 yr
	Kr-87	76.3 min		Nb-95	35.1 d
Noble Gas	Kr-88	2.84 hr	Early Transition	Nb-97	72.1 min
	Xe-133	5.25 d	Liemento	Nb-97m	1.0 min
	Xe-135	9.09 hr		Mo-99	66.0 hr
	Xe-135m	15.3 min		Tc-99m	6.02 hr
	Rb-86	18.7 d		Zr-95	64.0 d
	Rb-88	17.8 min		Zr-97	16.9 hr
Alkali Metals	Cs-134	2.062 yr		Ce-141	32.5 d
	Cs-136	13.1 d		Ce-143	33.0 hr
	Cs-137	30.0 yr	Tatrovalanta	Ce-144	284.3 d
	Sr-89	50.5 d	Tetravalents	Np-239	2.35 d
	Sr-90	29.1 yr		Pu-238	87.74 yr
Alkaline Earths	Sr-91	9.5 hr		Pu-239	2.41E4 yr
	Sr-92	2.71 hr		Pu-240	6.54E3 yr
	Ba-137m	2.55 min		Pu-241	14.4 yr
	Ba-139	82.7 min		Y-90	64.0 d
	Ba-140	12.74 d		Y-91	58.5 d
	I-131	8.04 d		Y-91m	49.7 min
	I-132	2.30 hr		Y-92	3.54 hr
Halogens	I-133	20.8 hr		Y-93	10.1 hr
	I-134	52.6 min		La-140	40.3 hr
	I-135	6.61 hr		La-141	3.9 hr
	Te-127	9.35 hr	Trivalents	La-142	92.5 min
	Te-127m	109 d		Pr-143	13.56 d
	Te-129	69.6 min		Pr-144	17.3 min
Chalcogens	Te-129m	33.6 d		Pr-144m	7.2 min
	Te-131	25.0 min		Nd-147	11.0 d
	Te-131m	30.0 hr		Am-241	432.2 y
	Te-132	78.2 hr		Cm-242	162.8 d
	Ru-103	39.3 d		Cm-244	18.11 yr
	Ru-105	4.44 hr		Sb-127	3.85 d
Distingida	Ru-106	368.2 d		Sb-129	4.32 hr
Flatinoids	Rh-103m	56.1 min			
	Rh-105	35.4 hr]		
	Rh-106	29.9 sec]		

Table 1-1. Radionuclides identified from current LWRs off-site consequence analysis.

For consideration of non-LWRs, additional activation products will need to be accounted for, which will be dependent on coolant chemistry and the materials present in structural materials.

If the system is based on U-235 and U-238 and operates in a thermal spectrum, then the previously identified actinide isotopes of Np, Pu, Am, and Cm would still be applicable. However, if a U-235 or Pu-239 based system was operated in the fast spectrum then additional actinides would likely need to be accounted for because of additional neutron absorption by heavy nuclides.

Furthermore, if a reactor were to operate in a U-233 and Th-232 fuel then the current set of actinides would no longer be applicable. Instead, a new set of actinides would need to be examined. Potential changes to the actinides included in analyses are included in the MSR section of this report.

1.3. Rationale for Inclusion of Additional Radionuclides

For a radionuclide to be included in the subset of radionuclides that are examined for off-site consequence, the radionuclide must be present in sufficient amounts and have the potential to pose a health risk based on radiotoxicity. Furthermore, the half-life of the nuclide must be long enough such that it does not decay away before the time when the radionuclide would reach a site boundary during a release event. The radionuclide's half-life must not be so long that it does not pose a significant health risk. An early assessment of radionuclide inclusion can be found in WASH-1400 in which relative activity and dose contributions are compared in order to determine a list of most important dose contributors for analysis, which are then grouped based on chemical properties. For LWRs, the common radioisotopes of interest for LWRs are grouped into the following chemical group categories:[5]

- Noble Gases
- Alkali Metals
- Alkaline Earths
- Halogens
- Chalcogens
- Platinoids
- Early Transition Elements
- Tetravalents
- Trivalents
- Cadmium Group

Determining exact cutoffs for these three factors is difficult as the amount of activity that is released to the environment is highly dependent on chemistry and system-specific factors. For instance, nearly 100% of noble gasses may be released to the environment during an accident scenario with a LWR. Whereas only a fraction of a percent of many other radionuclides, such as the higher actinides, would be released in the same scenario.

2. HIGH TEMPERATURE GAS REACTORS

HTGRs utilize a Tri-structural ISOtropic (TRISO) fuel which is either compressed into a prismatic compact or pebbles. TRISO fuel is a multilayer fuel form that contains a uranium oxycarbide (UCO) or uranium carbide (UC₂) fuel kernel surrounded by a porous carbon buffer, silicon carbide, and two pyrolytic carbon (PyC) layers. TRISO fuel can then be compacted into any designed shape, with the most common two fuel matrix designs being pebbles and prismatic fuel elements. [6] The coolant of an HTGR is an inert gas, such as helium. This means that chemical reactions with the coolant and other materials would not occur.



Figure 2-1. TRISO fuel layers and final compact form[6].

2.1. Radionuclide Inventory

TRISO fuel utilizes U-235 as the primary fissile material. Given that the reactor operates in a thermal spectrum, all of the radionuclides of importance for LWRs will continue to be of consequence.

As part of an ongoing experimental program at Idaho National Laboratory, significant experimentation has been performed on TRISO particles undergoing failure. Experimental efforts have shown the following fission gas radionuclides are present within the system in significant quantities. Similar to LWRs, these fission gasses are isotopes of krypton and xenon. Radionuclides that are not currently included in off-site consequence analysis but may be of consequence are as follows: [7]

• Xenon: Xe-131m

Additional isotopes of krypton and xenon are present, but associated half-lives are either 15 minutes or less, or they are already included in off-site consequence analysis.

In addition to the fission gasses, additional fission products have been shown to release experimentally. In these experimental examinations, silver, cesium, iodine, strontium, protactinium, antimony, samarium, and europium have all been shown to be release with the rate

being dependent on time and temperature, as well as chemistry. In addition to the radionuclides that are used in LWR consequence assessment, the following fission product elements (as associated isotopes) have been shown to be present through both experimental and computational analysis[8], [9].

- Silver: Ag-110m,
- Antimony: Sb-125,
- Promethium: Pm-147,
- Samarium: Sm-151,
- Europium: Eu-154 and Eu-155.

Ag-110m is of particular interest from a health consequence perspective because it migrates out of the fuel at a high rate compared to other nuclides. So, while the inventory in an absolute sense may not be large in comparison to that of other nuclides, it could be of higher consequence.

Computational studies of interest include those performed by the Oak Ridge National Laboratories' (ORNL) SCALE development groups, which has used the ORIGEN software to model depletion behavior of TRISO particles in representative conditions. Currently, none of these elements are treated within off-site consequence analyses. The ORNL study identified the above nuclides as well as the following actinides that would require additional consideration because of the goal to burn TRISO fuel particles to significantly higher levels than that of LWR fuel. [10]

- Plutonium: Pu-242,
- Curium: Cm-245.

Tritium release in HTGRs is another area of concern. H-3 is a product of nuclear reactions. H-3 is released through ternary fission, neutron activation of impurities (He-3 in coolant; Li in the graphite), and neutron capture in boron control materials. The H-3 accumulates in the primary system helium coolant. Multiple methods for tritium management exist, but the more extensive tritium release models are needed in software such as MACCS, should it be released.

A second activation product that is not currently included in LWRs that will exist in large quantities in HTGRs is C-14, which can be produced from neutron absorption of C-13. Given that C-13 has a natural abundance of 1.1%, a significant amount of C-14 activity may be present in the reactor, particularly at high burnups. This means that the following two activation products would need to be included in off-site consequence analysis: [7]

- Hydrogen: H-3,
- Carbon: C-14.

In summary the radionuclides in Table 2-1 should receive further consideration for inclusion in off-site consequence analysis based on their presence in TRISO fuel particles and within an HTGR system.

Element	Isotope	Half-life	
Н	3	12.3 y	
С	14	5,730 y	
Ag	110m	250 d	
Sb	125	2.8 y	
Pm	147	2.6 y	
Sm	151	88.8 y	
Fu	154	8.6 y	
20	155	4.8 y	
Pu	242 373,300 y		
Cm	245	8,500 y	

Table 2-1. Radionuclides of interest for the HTGR.

2.2. Chemical Forms

Based on experimental efforts and analysis, the following chemical forms and behaviors of major radionuclides are expected, which are shown in Table 2-2.

For HTGRs, the fission products will either react with other fission products, react with oxygen or carbon in the fuel, or remain in their elemental form. Therefore, formation of some compounds depends on the type of fuel, the stoichiometry, and the fuel temperature. For example, for UC₂ fuel, elements with low affinity for oxygen (Sr, Eu, Zr, Ba) exist as carbide compounds. Cs₂O can exist depending on the temperature of the fuel and oxygen potential. MoO₂ could also form but that is dependent on the stoichiometry[11].

Isotope	Forms in the Fuel	Principle In-Core Behavior	Principal Ex-Core Behavior	Chemical Forms and Compounds
H-3	Element (g)	Permeates intact SiC; sorbs on core graphite	Permeates through heat exchangers	Volatile gas. Sorbs on graphite. TH or T2
Sr-90	Oxide- carbide	High matrix/graphite retention	Deposits on metals	Soluble in UO2*. SrO, SrC2t, could solubility in graphite, can form compounds with BaO.
Ag-110m	Element	Permeates intact SiC	Deposits on metals	Primarily mains in elemental form. Metal inclusion/deposit on other metals
Te-132 Complex Retained by PyC/SiC		Deposits on metal/dust	Oxidizes at grain boundaries (TeO2 Metal inclusion, elemental gas, as mentioned above could be as Cs2Te, but that is rare	
I-131	Element (g)	Retained by PyC/SiC	Deposits on colder metals	Fel2(BP: 827C), Nil2(BP: 797C), Crl2(BP: 1248C), Mnl2 (BP: 1033C) gas or solid depending on temperature and pressure. Boiling points given at 1atm. I2 as a gas, Csl
Xe-133	Xe-133 Element (g) Retained by PyC/SiC		Removed by helium purification system	Gas. No compounds. Could be retained in pellet, graphite, or in the purification system
Cs-137 Oxide- element matrix/graph retention		Retained by SiC; some matrix/graphite retention	Deposits on metals/dusts	Cs2O, Cs2Te (rare), Cslt, can form compounds with carbon, but stability at high temperatures are unknown. Mo-Cs compounds possible but not observed at high temps (1673K)
La-140	La-140 Oxide High retention		Deposits on metals/dust	La2O3. Soluble in UO2*. Relatively stable as an oxide. Could form compound with BaO.
Pu-239	Oxide- carbide	Quantitative matrix /graphite retention	Retained in core	PuO2. Stable in kernel.

Table 2-2.	Chemical	forms and	compo	unds for	HTGRs	[11].

*Changes with UC₂/UO₂ ratios. *Assuming the use of UCO or UC₂ fuel

3. FLUORIDE-SALT-COOLED HIGH TEMPERATURE REACTORS

An FHR system is conceptually a cross between an HTGR and an MSR. The fuel of an FHR is contained within a TRISO compact, while being cooled by a fluoride-based coolant such as FLiBe, which is a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF₂). FHRs are a class of reactors that combine the following features [12]:

- Coated-particle fuels
- Fluoride salt coolant
- Low-pressure, high-temperature primary system to delivery heat in the temperature range of 600 700 C.

Although a distinct reactor class, the FHR combines features from other thermal power plants. The FHR uses development from MSR research in the 1950s-1970s on the use of liquid fluoride salts. HTGRs provide experience with coated-particle fuel and graphite components. LWRs show the advantages of transparent, high-heat capacity coolants with low chemical reactivity.[13]

The radionuclide inventory of an FHR is less researched compared to the HTGR. Although due to similarities in the designs, both reactor types using a thermal spectrum, and similar fuel, it is safe to assume that the radionuclide inventory of the FHR will be very similar to the HTGR.

3.1. Radionuclide Inventory

The FHR is proposed to use TRISO-based fuel pebbles within the coolant. The fuel will maintain temperatures similar to the HTGR, so the spectrum presented by the FHR will be very similar to the HTGR. The key radionuclides are similar to the HTGR, with fission product migration into the coolant similar following the same phenomena as in HTGRs.

The circulating activity in an FHR is brought on through neutron activation products and fission products generated from defective fuel particles. Non-noble-gas fission products will have high solubility in the primary coolant, if the fission products form stable fluorides. Noble metals with low solubility will deposit on the intermediate heat exchanger.

The most mobile activation product formed in FHRs is tritium. In comparing the production of tritium in FHRs to other reactors: the production of tritium is an order of magnitude larger than an LWR but an order of magnitude lower than the CANDU reactor. [12] C-14 may also be present because C-13 in fuel pebbles may become activated and end up in the coolant as a result of pebble damage.

Additional radionuclides that may be necessary to include in an off-site consequence analysis will be the same as in an HTGR. See Table 3-1.

Element	Isotope	Half-life	
Н	3	12.3 y	
С	14	5,730 y	
Ag	110m	250 d	
Sb	125	2.8 y	
Pm	147	2.6 y	
Sm	151	88.8 y	
Fu	154	8.6 y	
24	155	4.8 y	
Pu	Pu 242 373,300 y		
Cm	245	8,500 y	

Table 3-1. Radionuclides of interest for FHRs [12].

3.2. Chemical Forms

The main difference between the FHR and the HTGR is the salt. In most scenarios, the fission products should remain inside the TRISO particle. However, if they escape, some can form stable fluorides, go to the off gas, or dissolve into the salt, graphite, or deposit on the metal. Therefore, the chart below shows similar in-core behavior, with the main difference in the chemical compounds being the fluorides formed.

Based on experimental efforts and analysis, the following chemical forms and behaviors of major radionuclides are expected, which are shown in Table 3-2.

Isotope	Forms in the Fuel	Principle In-Core Behavior	Principal Ex-Core Behavior	Chemical Forms and Compounds
H-3	Element (g)	Permeates intact SiC; sorbs on core graphite	Permeates through heat exchangers	Volatile Gas. Sorbs on graphite. TH or T_2 , TF
Sr-90	Oxide- carbide	High matrix/graphite retention	Deposits on metals	Soluble in UO2 [*] . SrO, SrC2 ^t , solubility in graphite, can form compounds with BaO. For Sr-89, if born in graphite, it will stay in graphite and not move into the salt.
Ag-110m	Element	Permeates intact SiC	Deposits on metals, in particulate loop in the salt	Primarily mains in elemental form. Metal inclusion/deposit on other metals. may dissolve into salt if oxidized, but usually a metal in the salt. Could oxidize Cr. (not a form but something to note for corrosion)
Te-132	Comple x	Retained by PyC/SiC	In MSRE, found in salt and graphite with most depositing on metal	Oxidizes at grain boundaries in fuel (TeO_2) , Metal inclusion, elemental gas, as mentioned above could be as Cs_2Te , but that is rare. Te dissolves into the salt as a gas and can form volatile TeF_6 , and can deposit on metal surface and form stable compounds with steel.
I-131	Element (g)	Retained by PyC/SiC	MSRE found in salt. Negligible or low amounts elsewhere	Fel ₂ (BP: 827C), Nil ₂ (BP: 797C), Crl ₂ (BP: 1248C), Mnl ₂ (BP: 1033C). Boiling points given at 1atm. Csl dissolves in salt. lodine can also form volatile fluoride compounds.
Xe-133, Xe-135	Element (g)	Retained by PyC/SiC	Removed by cover gas/ dissolves in graphite	Gas. No compounds.
Cs-137	Oxide- element	Retained by SiC; some matrix/graphite retention	Deposits on metals/ dusts, retained in graphite, stable fluorides in salt	Cs ₂ O, Cs ₂ Te (rare), Csl ^t , CsF, can form compounds with Carbon, but stability at high temperatures are unknown. Mo-Cs compounds possible but unlikely and rarely observed.
La-140, Sm-149	Oxide	High matrix/graphite retention	Deposits on metals/dust	La_2O_3 (dissolves into salt). Soluble in UO_2° . Relatively stable as an oxide. Could form compound with BaO. Forms stable fluorides in salt (SmF ₃ , LaF ₃). Can deposit on metals if oxygen is present
Pu-239	Oxide- carbide	Quantitative matrix /graphite retention	Retained in core	PuO ₂ . Stable in kernel. Forms stable fluoride in salt. Can react with oxides and fluorides that may form compounds that don't dissolve into salt. PuF ₃ PuF ₄ and PuF ₆

Table 3-2. Chemical forms and compounds of FHRs[14].

*Changes with UC₂/UO₂ ratios. *Assuming the use of UCO or UC₂ fuel

4. MOLTEN SALT REACTOR SYSTEMS

MSRs contain a thorium, uranium or plutonium-based fuel dissolved in a fluoride or chloridebased salt. Typically, a fluoride-based salt will operate in a thermal neutron spectrum and a chloride-based salt will operate in a fast neutron spectrum. Fluoride-based systems will be fueled with either a Th-232/U-233 thermal-spectrum breeder salt or a U-235/U-238 thermal-spectrum salt. Chloride-based systems would likely be fueled with a combination of a U-235/U-238/Pu-239 and operate in a fast spectrum.

4.1. Fission Product Inventory

Given that multiple gaps exist in the knowledge of the system itself, the chemistry of the system, and the neutronics of the system; a reactor inventory cannot be developed at this time. Additionally, relatively few radiation experiments have been performed since the Molten Salt Reactor Experiment (MSRE) reactor was operational. However, the cumulative fission yields of U-233, U-235, and Pu-239 can be used to reasonably approximate which fission products would exist in the system. This list of roughly 1250 radionuclides that are generated in fission can be pared down to a significantly smaller list based on cumulative fission yield and associated fission product half-life, filtering out stable nuclides and those with relatively small half-lives (approximately 30 seconds or less). Cumulative fission yields are used because they provide an answer to what is present after decay processes, particularly short time-frame beta decays, have occurred.

Examining cumulative fission yield provides a list of potential fission products that may exist within MSR systems. This list can then be compared against what is already included in off-site consequence analyses for LWRs. Establishing this larger list allows MACCS software developers to ensure that all potential nuclides are appropriately accounted for in the software. This list was developed using the ENDF/B-VIII.0 nuclear data library and the OECD/NEA software JANIS4.0.

All of the fission product isotopes highlighted in the FHR and HTGR analysis are again potentially a contributor to off-site consequences for MSR systems. Eventually, the ability of each of these individual nuclides to migrate to the atmosphere during an accident scenario will need to be assessed. Given the significant differences in system chemistry in MSRs compared to LWR, it is very hard to infer fission product mobility, especially when neither the system nor the inventory are well defined. Additional elements that may need to be included are:

- Arsenic: As-77,
- Selenium: Se-81, Se-81m and Se-83,
- Bromine: Br-83 and Br-84,
- Krypton: Kr-83m,
- Niobium: Nb-93m,
- Palladium: Pd-109 and Pd-112
- Silver: Ag-111,

- Cadmium: Cd-113m and Cd-115m,
- Tin: Sn-117m, Sn-119m, Sn-121m, and Sn-123,
- Antimony: Sb-125, Sb-126, and Sb-128,
- Tellurium: Te-125m, Te-133m, and Te-134,
- Xenon: Xe-131m and Xe-133m,
- Protactinium: Pr-146,
- Promethium: Pm-147, Pm-148m, Pm-149, and Pm-151,
- Samarium: Sm-151 and Sm-153,
- Europium: Eu-154, Eu-155, Eu-156, and Eu-157.

These nuclides are further summarized in Table 4-1; included are cumulative fission product yields based on incident neutron energies for U-233, U-235, and Pu-239, as well as nuclide half-life.

It is also necessary to include tritium as a nuclide that may contribute to off-site consequence for molten salt systems, particularly in those designs which contain a lithium salt that could be activated by neutrons. Some MSR designs use a fluoride-based salt which contains Na, which is Na-23 naturally. It is possible for this nuclide to be activated to form Na-22 and Na-24, both of which may be of health consequence.

Isotope	U-233	U-235	U-235	Pu-239	Pu-239	Pu-239	Half-Life
H-3	-	-	-	-	-	-	12.5 yr
As-77	2.60E-04	7.96E-05	3.18E-04	7.23E-05	1.27E-04	1.62E-04	38.5 hr
Se-81	3.68E-03	3.70E-03	2.04E-03	2.28E-03	1.83E-03	1.42E-03	18.4 m
Se-81m	2.14E-04	3.88E-04	6.93E-05	3.86E-05	2.11E-04	1.14E-04	57.3 m
Se-83	5.75E-03	5.95E-03	2.65E-03	2.95E-03	1.63E-03	1.77E-03	22.3 m
Br-83	1.01E-02	5.36E-03	5.77E-03	2.97E-03	3.15E-03	3.70E-03	2.4 hr
Br-84	1.54E-02	9.85E-03	1.01E-02	4.29E-03	4.16E-03	4.91E-03	31.8 min
Kr-83m	1.01E-02	5.36E-03	5.77E-03	2.97E-03	3.11E-03	3.64E-03	1.83 hr
Nb-93m	6.63E-02	6.03E-02	5.94E-02	3.61E-02	4.79E-10	4.79E-10	16.13 yr
Pd-109	3.94E-04	8.53E-04	3.12E-04	8.15E-04	1.48E-02	1.03E-02	13.7 h
Pd-112	1.33E-04	6.48E-04	1.30E-04	3.77E-04	1.29E-03	1.89E-03	21.0 h
Ag-111	2.15E-04	1.74E-04	4.24E-04	2.95E-03	3.55E-03	3.88E-03	7.45 d
Cd-113m	1.58E-06	1.66E-06	3.82E-06	9.55E-06	1.44E-05	1.67E-05	14.1 yr
Cd-115m	1.25E-05	1.00E-05	2.80E-05	3.52E-05	4.20E-05	5.12E-05	44.5 d
Sn-117m	2.99E-07	2.62E-07	7.51E-07	9.16E-07	9.31E-07	1.17E-06	13.7 d
Sn-119m	5.04E-06	3.44E-06	9.23E-06	8.63E-06	2.81E-06	3.49E-06	293 d
Sn-121m	2.06E-05	7.25E-06	2.09E-05	2.94E-05	4.43E-05	5.34E-05	43.9 yr
Sn-123	1.15E-04	8.04E-06	3.96E-05	1.04E-04	2.28E-04	2.71E-04	129 d
Sb-125	1.17E-03	3.40E-04	6.80E-04	1.12E-03	1.78E-03	2.00E-03	2.75 y
Sb-126	3.22E-04	8.75E-05	1.37E-04	2.95E-04	1.71E-05	1.73E-05	12.3 d
Sb-128	1.05E-03	2.28E-04	2.24E-04	8.63E-04	8.28E-03	8.59E-03	9.01 hr
Te-125m	2.63E-04	7.65E-05	1.53E-04	2.51E-04	4.11E-04	4.64E-04	57.5 d
Te-133m	3.42E-02	3.99E-02	2.75E-02	3.40E-02	3.14E-02	3.08E-02	55.4 min
Te-134	4.04E-02	6.97E-02	6.57E-02	4.81E-02	4.76E-02	4.54E-02	41.8 min
Xe-131m	5.05E-04	4.05E-04	4.51E-04	5.40E-04	4.56E-04	4.49E-04	11.9 d
Xe-133m	2.11E-03	1.95E-03	1.98E-03	2.35E-03	1.18E-03	1.17E-03	2.2 d
Pr-146	2.59E-02	3.00E-02	2.92E-02	2.46E-02	2.46E-02	2.61E-02	24.2 hr
Pm-147	1.74E-02	2.25E-02	2.14E-02	2.00E-02	2.01E-02	2.15E-02	2.6 yr
Pm-148m	9.82E-09	8.10E-11	3.41E-10	4.50E-08	1.12E-07	1.12E-07	41.3 d
Pm-149	7.78E-03	1.08E-02	1.04E-02	1.22E-02	1.24E-02	1.36E-02	53.1 hr
Pm-151	3.16E-03	4.19E-03	4.12E-03	7.38E-03	7.83E-03	8.84E-03	28.4 h
Sm-151	3.16E-03	4.19E-03	4.12E-03	7.38E-03	7.83E-03	8.84E-03	88.8 yr
Sm-153	1.04E-03	1.58E-03	1.67E-03	3.61E-03	4.25E-03	4.92E-03	46.3 hr
Eu-154	2.08E-08	1.94E-09	6.21E-10	2.80E-07	4.72E-07	4.72E-07	8.6 yr
Eu-155	2.14E-04	3.21E-04	3.95E-04	1.66E-03	2.08E-03	2.48E-03	4.76 yr
Eu-156	1.28E-04	1.49E-04	2.03E-04	1.24E-03	1.54E-03	1.86E-03	15.2 d
Eu-157	6.30E-05	6.15E-05	1.06E-04	7.41E-04	1.06E-03	1.29E-03	15.2 h

Table 4-1. Radionuclides of interest for MSRs, showing cumulative fission yield fraction as afunction of fission parent and incident neutron energy and half-life.

4.2. Higher Actinides in U-233 and Pu-239 Based Systems

Within a U-233 and Th-232 based system the following actinides are recommended for inclusion in consequence assessment; see Table 4-2. Nuclides are based on neutron absorption by actinides and subsequence decay through beta and other processes.

Element	Isotope	Half-life
Ra	224	3.66 d
Th	228	1.91 y
U	232	68.9 y
Pa	233	27.0 d

Table 4-2. Actinides based on a U-233 and Th-232 fuel.

Within a Pu-239 and U-238 based system the following actinides are recommended for inclusion in consequence assessment; see Table 4-3. Nuclides are based on neutron absorption by actinides and subsequence decay through beta and other processes.

Element	Isotope	Half-life
U	237	6.75 d
Pa	233	27 d
Pu	242	380,000 y
Cm	243	29 y
	245	5,800 y
	246	4,700 y
Am	242(m)	150 y
	243	7,400 y

Table 4-3. Actinides based on a Pu-239 and U-238 fuel.

4.3. Chemical Forms

4.3.1. Fluoride Based Salts

For the fluoride-salt MSRs, similar ex-core chemical forms to the above section of FHRs can be expected, but in higher quantities, since the fuel is in salt. The results from the Molten Salt Reactor Experiment (MSRE) regarding the general behavior of the fission products in the salt are

given below. Another observation during the MSRE was that metals formed a mobile particulate pool in the salt where metals were lost to a few final repositories.

Radionuclide Grouping	Isotopes	Salt	Metal	Graphite	Off Gas
Stable Salt Seekers	Zr-95, Ce-144, Nd-147	99%	Negligible	<1%	Negligible
Stable Salt Seekers (noble gas precursors)	Sr-89, Cs-137, Ba-140, Y-91	Variable	Negligible	Low	Variable
Noble Gases	Kr-89, Kr-91, Xe- 135, Xe-137	Low	Negligible	Low	High
Noble Metals	Nb-95, Mo-99, Ru-106, Ag-111	1%-20%	5%-30%	5%-30%	Negligible
Chalcogens	Te-129, Te-127	1%-20%	20%-90%	5%-30%	Negligible
Cadmium Group	Sb-125	1%-20%	20%-90%	5%-30%	Negligible
Halogens	I-131, I-135	50%-75%	<1%	<1%	Negligible

Table 4-4. Fission products from the MSRE system.[15]

Table 4-5 below only covers the chemical forms found in fluoride salts that were <u>not</u> covered in the FHR section, see Section 3.2 for other forms. There are also some highly unlikely but possible chemical forms due to the redox potential of the salt. For example, bromine, the tellurium group, and most transition metals will not have stable fluoride forms.

Radionuclide Grouping	Element	Chemical Forms and Compounds
Noble Gases	Kr	Gas. No compounds.
Halogens	Br	Volatile fluorides: BrF, BrF ₃ , BrF ₅ . LiB, KBr, and NaBr possible, but not likely with redox potential of salt; Br_2
Cadmium group	Sb, As	Sb: SbF ₃ , SbF ₅ ; Deposits on metal surface; Metal inclusion. Fluorides are unstable in salt. Deposits on surfaces and in graphite. As: AsF ₃ (b.p. 60.4 C) (stability unclear but likely low) AsF ₅ , volatile and low stability.
Metals	Nb, Cd, Sn	Nb: can form volatile fluorides, NbF ₅ (borderline stable) Cd: CdF ₂ (not stable due to redox) Sn: SnF ₂ , SnF ₄ (sublimes above 700C) (not stable due to redox) Metals deposit heavily on surfaces and can also be found in graphite.
Rare Earths	Pr, Pm, Sm, Eu	All form stable trifluorides in salt, Eu and Sm can form stable difluorides. Can deposit on metals if oxygen is present
Actinides		Form stable fluorides in salt

Table 4-5.	Chemical forms	s found in f	luoride salt	MSRs[15], [16],

4.3.2. Chloride-Based Salts

Most chlorine compounds formed by fission products are unstable due to the redox potential of the salts that are being considered. MgCl₂, for example, would allow for some stable rare earth chlorides to form, but other options, like LiCl, would not. Table 4-6 below shows potential chemical forms and mentions their stability within the salt. It is also worth noting that forming Cl-36 is likely with these reactors, yet this nuclide has a very long half-life and is likely not of significant health consequence.

Table 4-6. Chemica	I forms found	in the chloride-salt M	SRs [16].
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Radionuclide Grouping	Element	Chemical Forms and Compounds
Tritium	Н	HCI
Noble Gases	Kr, Xe	Gas. No compounds.
Halogens	Br, I	Br ₂ , I ₂
Alkali metals	Cs	CsCl
Chalcogens	Te	TeCl _{4.} Likely in metallic form
Cadmium group	Sb, As	SbCl ₃ , AsCl ₃ (Sb and As unstable). Likely in metallic form
Metals	Nb, Cd, Sn	CdCl ₂ , NbCl ₃ , NbCl ₄ , NbCl ₅ , SnCl ₂ , SnCl ₄ but all most likely unstable. Likely in metallic form
Alkaline earths	Sr	SrCl ₂
Noble metals	Ag	AgCI but unstable. Likely in metallic form
Rare Earths	Pr, Pm, Sm, Eu, La, Sm	Can form various chlorides but unstable so likely in metallic form
Actinides		Can form chlorides but usually unstable in salt so likely in metallic form. Soluble in the salt

5. FAST SPECTRUM METALLIC FUEL SYSTEMS

Liquid metal fast reactors have been proposed for both small modular reactor and microreactor designs. Such systems would use metallic fuel and either lead or sodium as a coolant. The coolant is either flowing or contained in heat pipes, in the case of a microreactor. Such systems are fueled with metallic U-Pu-Zr fuel. Fast reactors will use a fast spectrum to generate electricity. There are a few major characteristics that separate fast reactors from LWRs:[17]

- Sodium or lead coolant
- Metallic fuels that, with burnup, form a final equilibrium core with transuranics
- Near-atmospheric pressure

One sodium fast reactor (SFR) design that has been discussed in literature is the Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR). The PGSFR has been in development since the mid 2010s, with the goal of building a PGSFR by 2028 in Korea[17]. The Korean team behind the PGSFR released a preliminary safety plan for the PGSFR in 2016[18]. This study looked at the various accident scenarios proposed for the PGSFR and the development of the source term in case of accidents. Another large source of information is from Argonne who has experience with the Experimental Breeder Reactor (EBR-II) SFR and has started to develop a source term for a generic pool-type SFR[19]–[21]. The studies published by ANL combine models, theories, and experimental information from the EBR-II and the Fast Flux Test Facility (FFTF) reactors.

5.1. Radionuclide Inventory

The radionuclides within the sodium coolant are generated from many sources. Table 5-1 summarizes the common ways radionuclides and activation products appear in the sodium coolant.



Figure 5-1. The potential source of radionuclides in the Na coolant[19].

Natural sodium is composed entirely of Na-23. However, in an SFR, Na-24 is formed from a (n, γ) reaction with the Na-23. In smaller quantities Na-22 is produced by (n, 2n) reactions with Ne-23 which is produced by a (n,p) reaction. Both the Na-24 and Na-22 activated products impact the activity levels of the reactor. Na-24 plays a larger role based on the half-lives of these two products. Impurities in the Na are likely to have a minor impact on activity levels in the fuel. [19]

Tritium is formed by ternary fission in the fuel and reaches the sodium via diffusion through the cladding. Tritium is an area of concern due to tritium's high mobility, and ability to diffuse through the reactor structures. Tritium is less of a concern in LMRs compared to FHRs and MSRs. For a proposed pool-type SFR, tritium may escape the primary circuit transport to the cover gas, through the heat exchangers to the intermediate sodium loop, travel through the vessel, and is removed through cold traps in the reactor[19].

Fission products and fuel may be found in the coolant as a result of the failed fuel pins. The fission products of concern are Ce and I, as they are highly soluble in the sodium. Figure 5-2 shows the maximum activation measured in the primary sodium for both the EBR-II and FFTF[19].

From Figure 5-2 the activity of Na-24 is the largest contributor during operation. However, due to the short half-life of Na-24 (~15 hours), it quickly diminishes during shutdown. The other radionuclides are comparable in their contribution to maximum activity. The activity of corrosion products and sodium impurities have been shown to be below the minimum level shown in Figure 5-2. [19]



Figure 5-2. Activation of fission products measured in the primary sodium of the EBR-II and the FFTF[19].

There are two primary sodium decay products that impact the activity of the cover gas. The first is through the production of Ne-23, based on the (n,p) reaction with Na-23. The half-life of Ne-23 is only 38 seconds, so this activity will quickly decay during shutdown [19]. The other reaction of interest produces Ar-41. Ar-41 is primarily formed through (n, gamma) reactions but can also be formed with K-41, as an impurity in the sodium.

Noble gases and tritium may also travel to the cover gas. However, the activity level of Ne-23 and Ar-41 tends to be the primary source of activity in the cover gas. In the case of the noble gases, the activity is correlated with the number of damaged fuel rods. Figure 5-3 shows the maximum activity levels calculated for the FFTF reactor.



Figure 5-3. The maximum activity level of the cover gas for the FFTF reactor. [19].

Analysis of sodium fast reactor systems has identified several activation products that would need to be included in consequence analysis. The first of these is Ar-41, which is a product of the activation of Ar-40 cover gas that is used over the top of sodium pools. Sodium itself may also activate from Na-23 to Na-22 or Na-24. Given that sodium is volatile when exposed to the atmosphere, both would need to be taken into account. In core components, sodium fast reactors generally use austenitic steels with high amounts of nickel and chromium. Accordingly, it is possible for Cr-51, Mn-54, Fe-69, Co-58, Co-60, and Ta-182 to exist as activation products. Tritium may also be created from B-10 in absorbers. A summary of activation products that may be necessary to include in off-site analysis is shown in Table 5-1. [22]

Element	Isotope	Half-life
н	3	12.3 y
Na	22	2.6 y
	24	15 h
Ar	41	110 m
Cr	51	27.7 d
Mn	54	312.3 d
Fe	59	44.5 d
Та	182	114.4 d

Table 5-1. Activation product nuclides of interest for the SFR system[19].

Fission product radionuclides that may need to be considered in consequence analysis will be the same as those identified for MSRs; however, additional inventory calculations will need to be performed to verify this for any reactor design. The inclusion of additional elements is supported by mechanistic source term characterization efforts performed by Argonne National Laboratory (ANL), who identified Br, Se, Pd, and Sm as additional elements of source term significance. [19] These elements overlap directly with the previously identifies list of MSR fission products. As with MSRs (Tables 4-1 and 4-4), the list of fission product nuclides identified would likely need to be addressed because of the significantly different chemistry of liquid metal systems and the differences in inventories that result when moving from thermal to fast systems. They are not repeated for the sake of brevity.

5.2. Higher Actinides in Fast Systems

Higher actinides of interest in LMR systems will need to be taken into account similarly to fast, breeder MSR systems. Therefor the following nuclides need to be included.

Element	Isotope	Half-life
U	237	6.75 d
Pa	233	27 d
Pu	242	380,000 y
Cm	243	29 y
	245	5,800 y
	246	4,700 y
Am	242(m)	150 y
	243	7,400 y

Table 5-2. Higher actinides of interest in LMR systems

5.3. Chemical Forms

As shown in Table 5-3 below, rare earths and noble metals are unlikely to leak from the fuel as well as zirconium. However, they are suspected to stay in their metal form in the event they do. The noble metals could form metal inclusions within the walls. Rare earths and actinides can oxide if they are exposed to air or if oxide fuel is chosen.

The primary products likely to be in the cover gas are the noble gasses, tritium, halides, and alkali metals. Iodine also forms NaI and will be in the fuel. CsI has the potential to form but readily decomposes at high temperatures in the presence of sodium. Cs and Rb will weakly absorb onto the stainless steel and have minor solubility in sodium. [23]–[25]

The alkaline earth metals are less volatile and can form oxides if in the presence of oxygen. They have some solubility in sodium.

There is currently not enough data on antimony and selenium to determine their behavior, so it is assumed they behave similar to Tellurium. Most works agree that tellurium will form Na_2Te , but there is still some uncertainty.

Radionuclide Grouping	Element	Origin	Primary Location if leaked from fuel	Chemical Forms
Transition Metals	Mn, Zr	Stainless Steel Cladding	Cladding	Metal
Noble Metals	Ru, Rh, Pd, Mo, Tc, Co	Fission Product and Cladding	Not likely to leak	Elemental/metal inclusions
Tritium	Н	Ternary Fission	Cover Gas	Gas
Noble Gas	Xe, Kr	Fission Product	Cover Gas	Element, gas
Halides	I, Br	Fission Product	Coolant and cover gas	Nal (in fuel), l₂ (g), Csl (see below)
Alkali Metals	Cs, Rb	Fission Product	Cover gas.	Element. Volatile. Weakly absorbed on SS. Minor amounts dissolve in sodium.
Chalcogens	Te, Sb, Se	Fission Product		Gas. Na ₂ Te
Alkaline Earth Metals	Sr, Ba	Fission Product	Largely absorbed on piping in the primary system. Some in coolant	Elemental form, BaO and SrO if in the presence of oxygen.
Rare Earth	La, Nd, Eu, Nb, Pm, Pr, Sm, Cm, Y	Fission Product/fuel	Not likely to leak from fuel	Metal. Oxide form if exposed to air or oxygen from oxide fuel.
Actinides	Ce, Pu, Np, U	Fuel/fission product	Coolant	Metal. Oxide form if exposed to air or oxygen from oxide fuel. Ce soluble in sodium

Table 5-3. Chemical forms for the radionuclides in the SFR [23]–[25].

6. RADIONUCLIDE INCLUSION RECOMMENDATIONS

This chapter provides recommendations for additional radionuclides that may need to be accounted for in the offsite-consequence analysis of non-LWR systems. These radionuclides are *additional* to those contained in Table 1-1. Table 6-1 shows the chemical groups that are used to model the behaviors of the elements that are used in LWR off-site consequence analysis (groups 1-9, and 11). Groups 10, and 12-13 are additional groups that could be included for non-LWR off-site consequence analysis. No appropriate chemical treatment currently exists for tritium, particularly in a TF or water-based form; additional software model development will be required to address this.

Group #	Group Name	Corresponding Elements
1	Noble Gasses	He, Ne, Ar, Xe, Kr, Rn, H, N
2	Alkali Metals	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkaline Earths	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	F, Cl, Br, I, At
5	Chalcogens	O, S, Se, Te, Po
6	Platinoids	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalents	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalents	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm. Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10	Uranium Group	U
11	Cadmium Group	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12	Tin Group	Ga, Ge, In, Sn, Ag
13	Boron Group	B, Si, P

Table 6-1. Chemical groups currently used in MACCS

It is to be noted that the recommendations provided in this chapter are all preliminary. The next step will necessarily be to look at realistic inventories for each non-LWR type at varying stages

of burn-up and then determine if each of the nuclides are of health consequence, should they be released.

6.1. High Temperature Gas Reactors and Fluoride-Salt-Cooled High-Temperature Reactors

Recommendations for additional radionuclides to be included in HTGR and FHR off-site consequence analysis are shown in Table 6-2. The radionuclide list is the same for HTGR and FHR due to the same fuel form, TRISO, and a similar thermal spectrum.

Table 6-2. Recommended additional radionuclides for inclusion in off-site consequence analysis for HTGRs and FHRs, showing corresponding chemical group in MACCS.

Nuclide	Corresponding Chemical Group
H-3	Proposed New Group
C-14	Proposed New Group
Ag-110m	Tin Group
Sb-125	Cadmium Group
Pm-147	Trivalents
Sm-151	Trivalents
Eu-154	Trivalents
Eu-155	Trivalents
Pu-242	Tetravalents
Cm-244	Trivalents
Cm-245	Trivalents

6.2. Molten Salt Reactors

6.2.1. Fluoride Salt Systems with a Thermal Spectrum

Recommendations for additional radionuclides to be included in fluoride salt based MSRs offsite consequence analysis are shown in Table 6-3. The additional actinides included in the table are only recommended if a thoria-based fuel cycle is used. Na-22 and Na-24 are recommended for inclusion only if a salt with Na is present in the reactor.

Nuclide	Corresponding Chemical Group	Nuclide	Corresponding Chemical Group
H-3	Proposed New Group	Sb-128	Cadmium Group
Na-22	Alkali Metal	Te-125m	Chalcogens
Na-24	Alkali Metal	Te-133m	Chalcogens
As-77	Cadmium Group	Te-134	Chalcogens
Se-81	Chalcogens	Xe-131m	Noble Gas
Se-81m	Chalcogens	Xe-133m	Noble Gas
Se-83	Chalcogens	Pr-146	Trivalents
Br-83	Halogen	Pm-147	Trivalents
Br-84	Halogen	Pm-148m	Trivalents
Kr-83m	Noble Gas	Pm-149	Trivalents
Nb-93m	Trivalents	Pm-151	Trivalents
Pd-109	Platinoids	Sm-151	Trivalents
Pd-112	Platinoids	Sm-153	Trivalents
Ag-111	Tin Group	Eu-154	Trivalents
Cd-113m	Cadmium Group	Eu-155	Trivalents
Cd-115m	Cadmium Group	Eu-156	Trivalents
Sn-117m	Tin Group	Eu-157	Trivalents
Sn-119m	Tin Group	Ra-224	Noble Gas
Sn-121m	Tin Group	Th-228	Tetravalents
Sn-123	Tin Group	U-232	Uranium Group
Sb-125	Cadmium Group	Pa-233	Tetravalents
Sb-126	Cadmium Group		·

Table 6-3. Recommended additional nuclides for inclusion in off-site consequence analysis for fluoride salt MSRs, showing corresponding chemical group in MACCS.

6.2.2. Chloride Salt Systems with a Fast Spectrum

Recommendations for additional nuclides to be included in chloride salt based MSRs off-site consequence analysis are shown in Table 6-4.

Nuclide	Corresponding Chemical Group	Nuclide	Corresponding Chemical Group	
H-3	New Proposed Group	Te-125m	Chalcogens	
As-77	Cadmium Group	Te-133m	Chalcogens	
Se-81	Chalcogens	Te-134	Chalcogens	
Se-81m	Chalcogens	Xe-131m	Noble Gas	
Se-83	Chalcogens	Xe-133m	Noble Gas	
Br-83	Halogen	Pr-146	Trivalents	
Br-84	Halogen	Pm-147	Trivalents	
Kr-83m	Noble Gas	Pm-148m	Trivalents	
Nb-93m	Trivalents	Pm-149	Trivalents	
Pd-109	Platinoids	Pm-151	Trivalents	
Pd-112	Platinoids	Sm-151	Trivalents	
Ag-111	Tin Group	Sm-153	Trivalents	
Cd-113m	Cadmium Group	Eu-154	Trivalents	
Cd-115m	Cadmium Group	Eu-155	Trivalents	
Sn-117m	Tin Group	Eu-156	Trivalents	
Sn-119m	Tin Group	Eu-157	Trivalents	
Sn-121m	Tin Group	U-237	Uranium Group	
Sn-123	Tin Group	Pa-233	Tetravalents	
Sb-125	Cadmium Group	Pu-242	Tetravalents	
Sb-126	Cadmium Group	Cm-243	Trivalents	
Sb-128	Cadmium Group	Cm-245	Trivalents	
		Cm-246	Trivalents	
		Am-242m	Trivalents	
		Am-243	Trivalents	

Table 6-4. Recommended additional nuclides for inclusion in off-site consequence analysis for chloride salt MSRs, showing corresponding chemical group in MACCS.

6.3. Metallic-Fueled Fast Reactors

Recommendations for additional nuclides to be included in a metallic-fueled liquid metal cooled fast reactor off-site consequence analysis are shown in Table 6-5. The Na nuclides are to be included only if the reactor is an SFR.

Nuclide	Corresponding Chemical Group	Nuclide	Corresponding Chemical Group	
H-3	New Proposed Group	Te-125m	Chalcogens	
Na-22	Alkali Metal	Te-133m	Chalcogens	
Na-24	Alkali Metal	Te-134	Chalcogens	
Ar-41	Noble Gas	Xe-131m	Noble Gas	
Cr-51	Early Transition Elements	Xe-133m	Noble Gas	
Mn-54	Early Transition Elements	Pr-146	Trivalents	
Fe-59	Early Transition Elements	Pm-147	Trivalents	
As-77	Cadmium Group	Pm-148m	Trivalents	
Se-81	Chalcogens	Pm-149	Trivalents	
Se-81m	Chalcogens	Pm-151	Trivalents	
Se-83	Chalcogens	Sm-151	Trivalents	
Br-83	Halogen	Sm-153	Trivalents	
Br-84	Halogen	Eu-154	Trivalents	
Kr-83m	Noble Gas	Eu-155	Trivalents	
Nb-93m	Trivalents	Eu-156	Trivalents	
Pd-109	Platinoids	Eu-157	Trivalents	
Pd-112	Platinoids	Ta-182	Early Transition Elements	
Ag-111	Tin Group	U-237	Uranium Group	
Cd-113m	Cadmium Group	Pa-233	Tetravalents	
Cd-115m	Cadmium Group	Pu-242	Tetravalents	
Sn-117m	Tin Group	Cm-243	Trivalents	
Sn-119m	Tin Group	Cm-245	Trivalents	
Sn-121m	Tin Group	Cm-246	Trivalents	
Sn-123	Tin Group	Am-242m	Trivalents	
Sb-125	Cadmium Group	Am-243	Trivalents	
Sb-126	Cadmium Group			
Sb-128	Cadmium Group			

Table 6-5. Recommended additional nuclides for inclusion in off-site consequence analysis for metallic-fueled, metallic-cooled fast reactors, showing corresponding chemical group in MACCS.

7. ADDITIONAL CONSIDERATIONS

7.1. System Design, Inventories and Release Fractions

This document provides a recommended list of radionuclides for inclusion in off-site consequence analysis. However, it is acknowledged that this result is tentative. Advanced reactors are still within the design and licensing process, therefore there are multiple gaps within the knowledge of radionuclide inventories, radionuclide transport pathways and associated chemistry. These gaps have been identified by the NRC, among others, and are being addressed. Although the set of radionuclides identified in this document provides a basis for expanding the nuclides to be considered for advanced non-LWRs, ongoing work to address these gaps should be included in determining whether further expansion is needed for future analyses. Of particular importance is a representative inventory for each reactor type that has been developed with the SCALE software system; this will provide a full set of radioactivity associated with each individual isotope. Additionally, determining realistic release fractions to the environment using a code such as MELCOR will allow analysts to ensure that included radionuclides are actually the ones with the highest consequence.

7.2. Chemical Hazards

Along with radiation hazards in severe accidents, it is also important to note the chemical hazards that may be present as well. This is particularly important in systems that have toxic elements in their cooling system, like beryllium. Future efforts should be made to understand and identify the potential of a chemical hazard. It has been noted that some compounds that can form in beryllium and chloride salt species could be hazardous depending on the conditions. Beryllium itself is considered a hazardous chemical and chlorine gas is a hazardous reactive chemical and these chemicals can pose significant hazards.

7.3. MACCS Capability

The capability of MACCS 4.0 (released in June 2020) is well-suited for performing consequence analysis for non-LWRs. There are a total of 825 radionuclides that can be currently selected in MACCS, with 150 selectable at a time, which includes all the radionuclide recommendations in this study. This list of 825 is dependent on the dose coefficient file supplied with MACCS, which is currently based on Federal Guidance Report 13 [27]. However, it is further recommended that a dedicated tritium model and carbon model be developed and integrated into MACCS to best account for the unique behaviors and characteristics of tritium and carbon in a release environment. The decades of research and development in MACCS for performing LWRs analyses has created a robust tool well suited for non-LWR analyses.

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