Pacific Northwest
NATIONAL LABORATORY

PNNL-29367 Rev. 1

Non-LWR Fuel Cycle Environmental Data

March 2020

Bruce A. Napier

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-29367 Rev. 1

Non-LWR Fuel Cycle Environmental Data

March 2020

Bruce A. Napier

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

The U.S. Nuclear Regulatory Commission (NRC) has generically evaluated the environmental effects of the nuclear fuel cycle other than from operation of light water reactors (LWR) in 10 CFR 51.51 Table S-3 Table of Uranium Fuel Cycle Environmental Data. However, Section 51.51 only applies to LWRs.. However, 10 CFR 51.50 requires the environmental report (ER) to contain the basis for evaluating the contribution of the environmental effects for the fuel cycle activities for the nuclear power reactor. The NRC must still evaluate fuel cycle impacts to meet its obligations under the National Environmental Policy Act (NEPA) and, as such the relevant basis needs to be provided in an applicant's Environmental Report. This document provides the methodology to determine the environmental data for non-light-water reactors (non-LWRs). Therefore, the applicant's Environmental Report should contain a full description and detailed analysis of the environmental data for the fuel cycle and wastes before operation and after operation ceases. Section 6.1.in NRC Regulatory Guide 4.2 provides guidance for estimating impacts from the fuel cycle for LWRs.

For LWRs, environmental data for the nuclear fuel cycle other than the operation of the reactor in question may be addressed by scaling from 10 CFR 51.51 Table S-3 as the basis for evaluating the contribution of the environmental effects of uranium mining and milling, the production of uranium hexafluoride, isotopic enrichment, fuel fabrication, reprocessing of irradiated fuel, transportation of radioactive materials and management of low-level wastes and high-level wastes related to uranium fuel cycle activities to the environmental costs of licensing the nuclear power reactor. For other than light-water-cooled nuclear power reactors, the environmental report shall contain the basis for evaluating the contribution of the environmental effects of fuel cycle activities for the nuclear power reactor (10 CFR 51.50).

This report provides an approach to determining environmental data for the fuel and required other material mining and preparation, fuel and other required material enrichment, fuel and other required material fabrication, and waste management for non-light-water reactors. Because reprocessing of irradiated fuels is not currently performed in the United States (U.S.), the environmental effects of reprocessing fuel are not addressed herein; the environmental impact of long-term fuel storage is assumed to be similar to the impacts describe in NUREG-2157, Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel. Other waste management disposal activities are assumed to comply with the applicable regulations. Transportation of fuel and waste is addressed in a separate document.

Environmental impacts are given in terms of natural resource use (e.g., land commitments, water consumption, fossil fuel use), gaseous and particulate effluent emissions to the atmosphere, liquid effluent releases, and thermal effluents.

Acronyms and Abbreviations

HALEU	High assay low enriched uranium (<20% U^{235})
UC/UCO	Uranium carbide/uranium oxycarbide
TRISO	Tri-structural isotopic (graphite & silicon carbide coated fuel spheres)
MW	Megawatt
kW	Kilowatt
SWU	Separative Work Unit
ISL	In situ leach recovery
LIS/AVLIS	Laser isotopic separation/advanced vapor laser isotopic separation
Colex	Column Exchange isotopic separation process
LLW	Low Level radioactive Waste
LWR	Light water reactor
MSR	Molten salt cooled reactor
SAFSTOR	Safe Storage
IAEA	International Atomic Energy Agency
NRC	Nuclear Regulatory Commission
NEPA	National Environmental Policy Act of 1969, as amended
EA	environmental assessment
EIS	environmental impact statement
USGS	United States Geological Survey
U.S.	United States
PBMR	Pebble Bed Modular Reactor

Contents

Abstract ii
Acronyms and Abbreviations iii
Contents iv
1.0 Introduction 1
  1.1 The Uranium Fuel Cycle 2
  1.2 Other Fuel Cycles 4
2.0 Methodology 5
3.0 Information Required 7
4.0 Examples 12
  4.1 Example 1: Helium Cooled PBMR 12
  4.2 Example 2: Molten Salt Reactor 22
  4.3 Example 3: Thorium-Fueled reactor (various types possible) 26
  4.4 Example 4: High-Assay Low-Enriched Uranium (HALEU) Metallic Fuel Fast Reactor 30
  4.5 Example 5: Liquid Metal Cooled Fast Reactor 33
5.0 Summary 36
6.0 References 37

Figures

Figure 1. The conventional uranium fuel cycle. 3

Tables

Table 1. Fuel Cycle Data Summary for Example 1 20
Table 2. Fuel Cycle Data Summary for Example 2 24
Table 3. Fuel Cycle Data Summary for Example 3 29
Table 4. Fuel Cycle Data Summary for Example 4 32
Table 5. Fuel Cycle Data Summary for Example 5 35

1.0 Introduction

U.S. Code of Federal Regulations, Title 10, Part 51 contains environmental protection regulations applicable to the Nuclear Regulatory Commission's (NRC's) domestic licensing and related regulatory functions under the National Environmental Policy Act of 1969, as amended (NEPA). These pertain to each of:

- Environmental Reports – documents submitted to the Commission by an applicant for a permit, license, or other form of permission, or an amendment to or renewal of a permit, license or other form of permission, or by a petitioner for rulemaking, in order to aid the Commission in complying with section 102(2) of NEPA,

- Environmental Assessments – documents prepared to determine whether or not an action is a "major federal action significantly affecting the quality of the human environment," and

- Environmental Impact Statements - detailed written statements as required by section 102(2)(C) of NEPA.

The NRC has generically evaluated the environmental effects of the nuclear fuel cycle other than from operation of light water reactors (LWRs) in 10 CFR 51.51 Table S-3 Table of Uranium Fuel Cycle Environmental Data. However, Section 51.51 only applies to LWRs and does not mention non-LWR license applicants when discussing the requirement to provide information on the environmental effects of the nuclear fuel cycle in an applicant's Environmental Report. However, the NRC must still evaluate fuel cycle impacts to meet its obligations under the National Environmental Policy Act (NEPA) and, as such, requires the relevant information be provided in an applicant's Environmental Report. Therefore, the applicant's Environmental Report should contain a full description and detailed analysis of the environmental effects of the fuel cycle and wastes before operation and after operation ceases, through decommissioning. Section 6.1.in NRC Regulatory Guide 4.2 (NRC 2018) provides detailed guidance for LWR applicants on estimating environmental impacts from the fuel cycle for LWRs.

For LWRs, environmental effects of the nuclear fuel cycle other than the operation of the reactor in question may be addressed by scaling from 10 CFR 51.51 Table S-3 as the basis for evaluating the contribution of the environmental effects of uranium mining and milling, the production of uranium hexafluoride, isotopic enrichment, fuel fabrication, reprocessing of irradiated fuel, transportation of radioactive materials and management of low-level wastes and high-level wastes related to uranium fuel cycle activities to the environmental costs of licensing the nuclear power reactor. For other than light-water-cooled nuclear power reactors, the environmental report shall contain the basis for evaluating the contribution of the environmental effects of fuel cycle activities for the nuclear power reactor (10 CFR 51.50).

This report provides an approach to determining effects of fuel and required other material mining and preparation, fuel and other required material enrichment, fuel and other required material fabrication, and waste management for non-light-water reactors. Because reprocessing of irradiated fuels is not currently performed in the U.S., the environmental effects of reprocessing fuel are not addressed herein; the environmental impact of long-term fuel storage is assumed to be similar to the impacts describe in NUREG-2157, Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel. Other waste management disposal activities are assumed to comply with the applicable regulations. Transportation of fuel and waste is dealt with in a separate document.

Environmental impacts are given in terms of natural resource use (e.g., land commitments, water consumption, fossil fuel use), gaseous and particulate effluent emissions to the atmosphere, liquid effluent releases, and thermal effluents.

1.1 The Uranium Fuel Cycle

The typical nuclear fuel cycle uses uranium in different chemical and physical forms. Figure 1 illustrates the stages, which include uranium recovery, conversion, enrichment, and fabrication, to produce fuel for nuclear reactors. Uranium is recovered or extracted from ore, converted, and enriched. Then the enriched uranium is manufactured into fuel pellets. These fuel pellets are placed into fuel assemblies to power nuclear reactors.

The fuel cycle starts with recovery of uranium from the environment, usually by way of conventional or solution mining.

The mined uranium ore is processed, in a step known as milling. A conventional uranium mill is a chemical plant that extracts uranium from ore. In a conventional mill, the process of uranium extraction from ore begins when ore is hauled to the mill and crushed. Sulfuric acid dissolves and removes 90 to 95 percent of the uranium from the ore. The uranium is then separated from the solution, concentrated, and dried to form yellowcake. This processing can be done at three types of uranium recovery facilities: conventional mills, in situ recovery facilities, and heap leach facilities. Once this processing is done, the uranium is in a powder form known as yellowcake, which is packed into 55-gallon (208-liter) drums and transported to a fuel cycle facility for further processing.

Heap leach facilities also extract uranium from ore. At these facilities, the ore is placed in piles or heaps on top of liners. The liners prevent uranium and other chemicals from moving into the ground. Sulfuric acid is dripped onto the heap and dissolves uranium as it moves through the ore. Uranium solution drains into collection basins, where it is piped to a processing plant. At the plant, uranium is extracted, concentrated, and dried to form yellowcake. There are currently no heap leach facilities in operation in the U.S.

In situ recovery is another way to extract uranium—in this case, directly from underground ore. In this process, a solution of native ground water, typically mixed with oxygen or hydrogen peroxide and sodium bicarbonate or carbon dioxide, is injected into the ore to dissolve the uranium. The solution is then pumped out of the rock and the uranium separated to form yellowcake. Currently, all uranium mining in the U.S. is accomplished with in situ recovery.

For the current generation of light water reactors, the yellowcake is converted into uranium hexafluoride (UF_6) gas at a conversion facility. While at the conversion facility, the gaseous UF_6 is cooled to form solid UF_6 in NRC-certified shipping containers for transportation to an enrichment facility. Next, an enrichment facility heats the solid UF_6 enough to turn it into a gas, which is “enriched,” or processed to increase the isotropic concentration of uranium-235. The enriched uranium UF_6 is again cooled to a solid form and shipped to a fuel fabrication facility.

The fuel fabrication facility takes the enriched uranium gas where it is mechanically and chemically processed back into a solid UO_2 powder. The powder is blended, milled, pressed, and fused into ceramic fuel pellets about the size of a fingertip. The pellets are stacked into tubes or rods that are approximately 14 feet (4.3 meters) long and made of material such as zirconium alloys; this material is referred to as cladding. These fuel rods are made to maintain both their chemical and physical properties under the extreme conditions of heat and radiation present inside an operating reactor. The fuel rods are bundled into fuel assemblies for use in reactors. The assemblies are washed, inspected, and stored in a special rack until ready for shipment to a nuclear power plant. Once shipped to a nuclear power plant, the fuel assemblies are eventually loaded into the reactor core, as is appropriate, where they undergo fission and produce heat that is later converted into electricity.

After use in the nuclear power plant, the used fuel is generally stored for final disposal – what is called the "open' fuel cycle. In what is called a "closed" fuel cycle, the used fuel may be recycled – the residual uranium and perhaps also plutonium ("mixed oxide" or MOX) is recovered and reused in newly- made fuel.

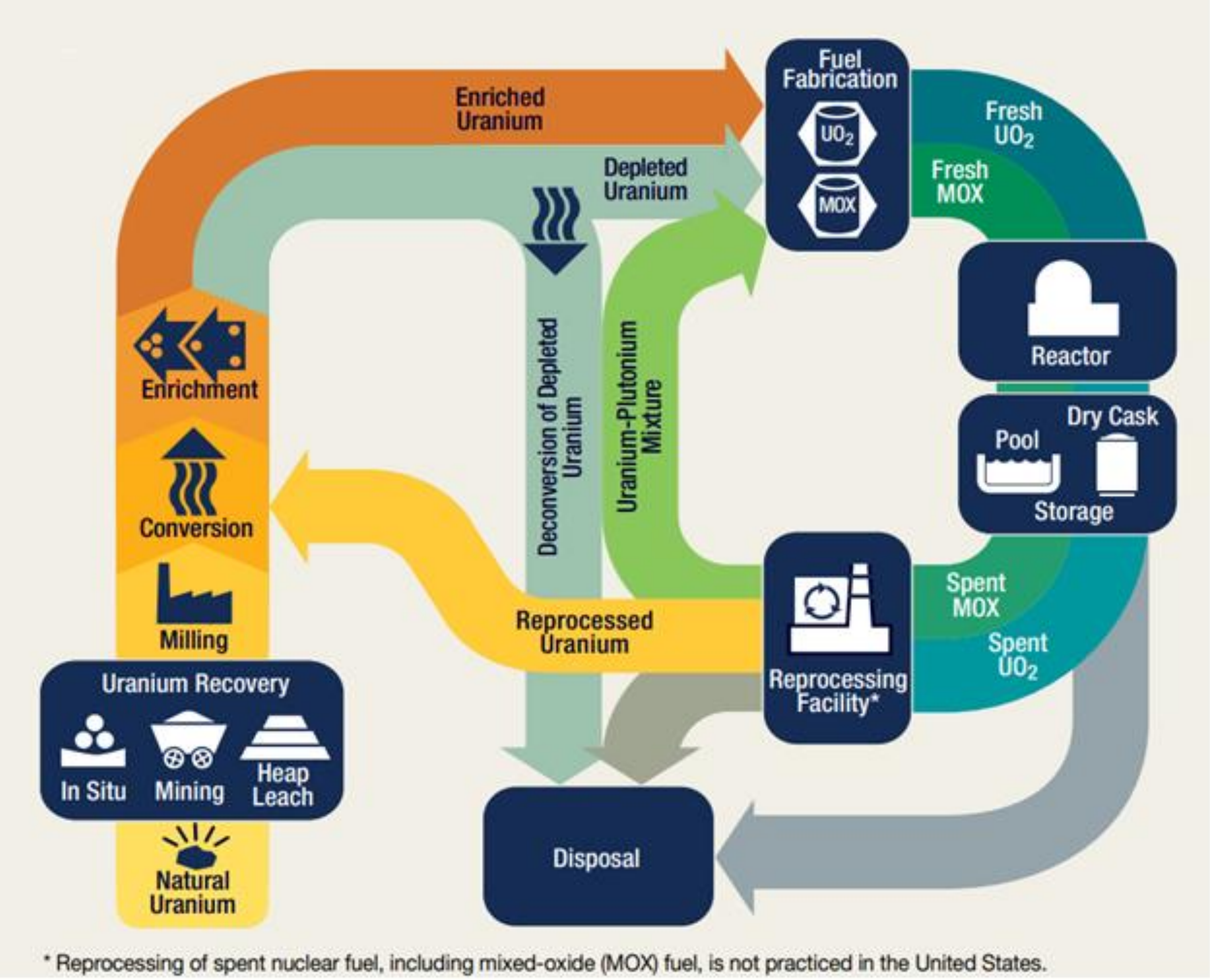

Figure 1. The conventional uranium fuel cycle (NRC 2019)

1.2 Other Fuel Cycles

Fuel cycles based on fissile or fertile materials other than uranium are possible. For example, thorium may be irradiated to create ^{233}U, which is fissile. The fuel cycle thus would start with mining of thorium, rather than uranium. Because this fuel cycle requires some initial fissile material to start it (typically considered to be ^{235}U), it can be considered to be partially the uranium cycle of Figure 1 and partially a separate cycle with mining, milling, fuel fabrication, reactor use, storage, reprocessing and waste disposal steps similar to, but distinct from, those for uranium. Enrichment of thorium is unnecessary, and the cycle differs in that conversion and enrichment are omitted.

2.0 Methodology

A nuclear energy system (fuel cycle) comprises the complete spectrum of nuclear facilities and institutional measures associated with the provision, use and ultimate disposition of fuel for nuclear power reactors. Nuclear facilities include infrastructure for mining and milling, processing and enrichment of uranium and/or thorium, manufacturing of nuclear fuel, production (of electricity or other energy supply), reprocessing of nuclear fuel, and facilities for management activities of related materials, including transportation and waste management. The total amount of waste generated from the operation of a nuclear power reactor consists not only of the operational reactor waste, but of waste from the front end nuclear fuel cycle generated at all stages of fuel manufacture, waste arising from its decommissioning, and waste from the back end nuclear fuel cycle, which may include spent fuel encapsulated for direct disposal or waste arising from the reprocessing of spent fuel if the closed fuel cycle option is chosen. The chemical-physical composition of the waste determines the selection of technology for its processing. The activities of all steps of the fuel cycle have an impact on human health and the environment.

The final estimate of environmental impact is based upon projections of land use, natural resources committed, and air, water, and thermal effluents generated by the fuel cycle for the specific type of non-light-water reactor envisioned. These projections are developed for the applicable activities of the specific fuel cycle – starting with mining and preparation of fuel and special materials needed for the reactor, fuel and special materials enrichment activities, fuel and special materials fabrication, emissions related to fuel use, and wastes generated.

In order to define each of the steps in the fuel cycle, a list of information needs – structured as questions to the applicant – is provided. Depending upon the reactor and fuel cycle type under consideration, not all of the information is required, so the flow of questions is structured to allow deviations.

When the information is gathered, a generic method for estimating the impacts (land use, natural resources committed, and air, water, and thermal effluents generated) is provided. This is based on available literature, primarily existing NRC and other government agency documents where available. The basic method is predicated upon existing environmental assessments (EAs), environmental impact statements (EISs), and other supporting documentation. For example, a generic EIS on in-situ leach (ISL) recovery of uranium (https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1910/) and several EAs for individual mining sites are available. These provide insight to the impacts of uranium recovery in the U.S. There are also EAs for the relicensing of the sole operating conversion facility and an EIS for operation of the sole operating U.S. enrichment facility (https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1790/v1/). Impacts are scaled to the proposed project from existing analyses.

In some instances, an applicant may wish to use pre-existing resources. In this case, the analysis would enter the fuel cycle at an appropriate point. For example, a proposed reactor might use depleted uranium, in which case the US stockpile of depleted uranium exists and mining, milling, and enrichment are not required; the analysis would begin at fuel fabrication. The analysis of fuel cycle impacts should be focused on those parts of the fuel cycle that occur within the United States.

Finally, if the project is not covered by the fuel cycle using these sources, then the applicant would use other applicable information to determine the fuel cycle Impacts. In some instances, a new EA or EIS might be required before the project could move forward.

3.0 Information Required

The following logic tree outlines a high-level approach for obtaining the data necessary for estimating the fuel cycle environmental impacts. The general outline has been adapted from INEEL (2003). The intent is to estimate land, water, and energy use and to project radiological and non-radiological emissions. Where possible, information is provided about where the analyst can obtain current data on specific subjects. The logic tree may be entered at various points as appropriate. For example, fuel could be provided from a source other than mining, such as down-blending of highly enriched uranium, in which case mining aspects would not be evaluated.

The logic tree is structured as a series of questions, the answers to which determine the next set of questions. Responses to the questions should be as detailed and specific as possible so that the appropriate information can be extracted and evaluated.

Notes and references are provided to show the use of the answers to the questions in the assessment methodology. Examples of responses and the process for evaluating the fuel cycle impacts are provided in Section 4.

1. What is the technical configuration of the proposed reactor?
    a. Reactor power ($MW_{thermal}$ or $MW_{electric}$ with anticipated thermal efficiency)
    b. Reactor capacity factor (fraction of time at full-power equivalent)
    c. Number of units or modules, if modular
    d. Reactor/module physical size and land area occupied by the facility
    e. Anticipated plant lifetime (including license renewals)

2. What is the type of fissile material to be used?
    a. Uranium
    b. Thorium/U^{233}
        i. How will the initial cores be set up?
    c. Plutonium
    d. Mixture (define)

3. What is the initial fuel loading (MTHM or equivalent)?
    Note: The information requested is the amount of fissile material, excluding alloys, cladding, structural materials, or other non-nuclear mass

4. What is the annual average fuel requirement (metric tons)?
    a. Alternatively, what average fuel burnup is anticipated?
    Note: Availability of plant power level and capacity factor (MW-days/year) and burnup (MW-days/ton) allows estimation of enriched fuel requirements (tons enriched fuel/year)
    b. How frequent are deliveries, and what size?

5. Does the primary fuel require isotopic enrichment?
    a. If so, what average enrichment is planned?
    Note: Availability of enrichment level and annual fuel requirement (MT/yr) for uranium, allows calculation of Separative Work Units (SWU) required. SWU may be

determined using available SWU Calculators such as those available at [*https://www.uxc.com/p/tools/FuelCalculator.aspx*](https://www.uxc.com/p/tools/FuelCalculator.aspx) *. This information will yield requirements for uranium mining/milling/conversion. Assuming a 0.1% ore body and a 90% recovery efficiency, the ore requirements can be calculated. Conversion requirements can be estimated using the relationship 2.61285 lbs of* U_30_8 *to 1 kg of* UF_6*. The calculations will also provide uranium tails estimates for storage/disposal*.

6. What is the source of the fuel?
   a. Surface mine
   b. Subsurface mine
   c. In-Situ Leach mine
   d. Other (e.g., existing sources, foreign sources)
      Note: The amount of fuel required per year, plant lifetime, and source can be used to estimate the land use. Current U.S. active uranium mining sites are listed at [*https://www.eia.gov/state/maps.php?v=electricity*](https://www.eia.gov/state/maps.php?v=electricity) *All of these are now ISL; so the default for open-market purchases would be ISL*.
   e. Downblending of highly enriched uranium (e.g. U.S. Department of Energy (DOE) supported process)
      Information on the DOE program for use of high-assay low-enriched uranium (DOE 2019) can be found at [*https://www.energy.gov/sites/prod/files/2019/01/f58/EA-2087-HALEU-2019-01.pdf*](https://www.energy.gov/sites/prod/files/2019/01/f58/EA-2087-HALEU-2019-01.pdf)

7. What type of fuel material enrichment process is anticipated?
   a. Commercially available (assumed to be centrifuge-based)
   b. Gaseous diffusion
   c. Laser Isotope Separation (LIS/AVLIS)
   d. Electromagnetic (e.g., calutron)
      Note: The SWU needs and enrichment process provide estimates of the energy requirements for enrichment. For estimation purposes, the following energy use rates are provided:
         Centrifuge – 50 kW-hour/SWU (kg)
         Gaseous Diffusion – 2500 kW-hour/SWU (kg)
         LIS/AVLIS - 150 kW-hour/SWU (kg)
         Calutron – 25,000 kW-hour/SWU (kg)
      https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx and https://www.nrc.gov/docs/ML1204/ML12045A049.pdf

8. What is the anticipated geographical location (or electrical generation type) of the enrichment facility?

   Note: This question is intended to provide information on the balance of electrical generation types used for enrichment. Emissions from combustion depend on the composition of the fuel, the type and size of the boiler, firing conditions, load, type of control technologies, and the level of equipment maintenance. The major pollutants of concern are particulate matter (PM), sulfur oxides (SOx), and nitrogen oxides (NOx). Some unburned combustibles, including carbon monoxide (CO) and numerous organic compounds, are generally emitted even under proper boiler operating conditions. EPA ([*https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid*](https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid)*)* *lists emission rates for numerous regions within the U.S. This can be coupled with the energy usage for SWU answered above. The type of enrichment/location may also be used to estimate waste heat released to surface water.*

9. In what chemical form must the fuel fissile material be for enrichment?
    a. UF_6
        i. What process is used to convert the fuel material to UF_6?
            1. Dry Conversion
               Note: This should have essentially no liquid effluents. There is a Draft Environmental Assessment (NRC 2018b) available for the only U.S. facility in (standby) operation.
            2. Wet Conversion
               Note: There are no U.S. operating wet conversion plants; emissions estimates can fall back on WASH-1248 or NUREG-1437
    b. Other – describe

10. What enrichment tails assay is anticipated?
    Note: this is needed to estimate the SWU. If not known, in the U.S. it is typically about 0.25%

11. What is the reactor heat transfer material (coolant)? How much is required initially/annually?
    a. Gas (e.g., helium)
    b. Liquid metal (e.g., sodium, lead, lead-bismuth, etc.)
    c. Molten salt (e.g., chloride, fluoride, etc.)
    d. Water
    e. Are other rare or depleted material stocks needed in the cycle?
       Note: The answer can be used to direct subsequent inquiries into sources of specialized materials, from which additional impacts may be derived.
        i. If the material is commercially available, what fraction of annual production is anticipated? (Alternatively: How much will be required per year?)
           Note: The information requested here will be used to estimate whether there is a significant increase in impact caused by the activities.

12. Does the reactor heat transfer material require isotopic enrichment (e.g., ^{37}Cl, ^{7}Li)
    a. If yes, what type of enrichment process is planned to obtain the material(s)
       Note: For molten salt reactors with chloride salts, isotopically pure ^{37}Cl is required for advantageous nuclear characteristics; isotopic enrichment of the ^{37}Cl isotope would need to be done as ^{35}Cl activates to ^{36}Cl (a 709 keV ß-emitter, with a $t_{1/2} = 3.01\times10^{5}$ y that is soluble in water). A concern with Li-based salts for MSR applications is that ^{6}Li will activate to form tritium (^{3}H). Although ^{3}H can be produced through other activation pathways, enrichment of ^{7}Li over ^{6}Li is necessary for tritium management in an MSR. The natural abundance ratio of ^{6}Li to ^{7}Li is about 7.59:92.41 (atomic %), but for an MSR, a ratio 0.001:99.999 (atomic %) is desirable.

       The lithium hydroxide-mercury amalgam column exchange-based (Colex) separation process was used in the U.S. in the 1950–60s on a large scale to separate ^{6}Li from ^{7}Li for the thermonuclear weapons program. The MSR *program made use of the ^{7}Li resulting from the process that was not useful for weapons. This ^{7}Li was further separated again using the Colex process. As industrial-scale mercury usage presents large environmental contamination and health risks, alternative lithium isotope separation processes based on electromigration are being evaluated to support MSR and fusion technologies. Other methods involve selective capture of lithium isotopes with a crown ether, either presented as an immobile phase on a resin, or carried in an immiscible organic phase that is contacted by the aqueous lithium hydroxide phase (McFarlane et al. 2019).*

Isotopically separated chlorine is not available in large quantities commercially, as no large-scale use for specific chlorine isotopes has been established. However, several technologies that would be scalable to large size have been demonstrated in laboratory settings. Gas-phase isotopic separation for chlorine was first demonstrated at the laboratory scale in 1939 by thermal diffusion of HCl with several attempts into the 1950s to increase the quantity produced by this method. Liquid-phase thermal diffusion is also a well understood process for chlorine isotope separation. In this process, the isotope separation was undertaken using CCl_4 as a stable chlorine-bearing compound. The process was carried out in a metal vessel under a pressure of 5 bar to ensure that the CCl_4 remained liquid. Chloroform and other impurities must be considered in the separation process. Room-temperature anion exchange chromatography has also been demonstrated for chlorine isotope separation. Elution of chlorine from the column is done by passing $AgNO_3$ through the bed. Recently, significant chlorine isotope separation has been shown during NaCl crystallization under magnetic fields of 20–80 mT. All of the proposed techniques employ readily available materials at temperatures less than 100°C, so they could be performed with commonly available tools and materials (McFarlane et al. 2019).

  b. What tails assay of the non-fissile-material is anticipated?
  c. Provide an estimate of the energy requirements for the non-fissile-material enrichment.

13. What form will the fuel take in the reactor? Provide fuel material types and mass for a typical fuel unit including a description of fuel, structural, and cladding materials.
    a. UO_2 fuel
    Note: The environmental effects should parallel current practice. Framatome/Areva (NRC 2009b) annual environmental reports may provide insights; WASH-1248 (NRC 1974) still mostly applies.
    b. TRISO fuel
    Note: primarily hydrogen, argon, carbon gaseous emissions, plus combustion (acetylene, propylene, methyltrichlorosilane) for heat and graphite.
    c. UC/UCO fuel
    d. Metallic fuel

14. What fuel cycle is anticipated?
    a. Open (fuel storage and ultimate disposal)
    b. Closed (partial or full recycling of fissile materials)
        i. Will the process involve on-line processing?
            1. If online processing, provide an estimate of radiological and non-radiological emissions

Note: On-line processing should probably be assumed to result in releases of quantities of noble gases as they are produced.

2. If online processing, will there also be recovery of enriched heat transfer materials (e.g., ^{36}Cl, ^{7}Li)?
   Note: Briefly covered in Riley et al. (2018)

15. What is the estimated annual average low-level radioactive waste (LLW) production expected from reactor operations?
    a. Provide an estimate of the expected volumes and curies of LLW
    Note: an IAEA publication (IAEA 2019), Waste from Innovative Types of Reactors and Fuel Cycles, provides background.

16. How much LLW is expected from reactor decontamination and decommissioning?
    a. What D&D process is anticipated?
    Note: If SAFSTOR, temporary land use may be estimated as the planned site area
    b. Provide an estimate of the expected volumes and curies of LLW produced due to reactor decontamination and decommissioning
    Note: To some extent can probably scale to existing LWRs by size. Also, for MSRs Riley et al. (2019) lists, in addition to normal concrete:
    Volatiles/off gases
    Unseparated salt
    Separated salt
    Carbon-based wastes
    Metal-based wastes

17. HLW is addressed in 10 CFR 51.23 and associated Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel, NUREG–2157 (NRC 2014).
    Note: *The revised rule adopts the generic impact determinations made in NUREG–2157 and codifies the NRC's generic determinations regarding the environmental impacts of continued storage of spent nuclear fuel beyond a reactor's operating life (i.e., those impacts that could occur as a result of the storage of spent nuclear fuel at at-reactor or away-from-reactor sites after a reactor's licensed life for operation and until a permanent repository becomes available)." However, NUREG-2157 did not address non-LWRs; NRC is preparing guidance on continued storage of non-LWR fuels. If the degradation rates for storage systems associated with continued storage of non-LWRs fuel are not significantly different than those considered for LWR storage systems, the environmental impacts (e.g., releases of nuclides, etc.) for continued storage of LWRs are applicable assuming appropriate consideration is given to any significant differences in waste volumes and activities.*

4.0 Examples

The following examples illustrate the application of the methodology for estimating the incremental discharges, land use, resource consumption, etc., for the various steps in the fuel cycle. The information would have to be integrated with the discharges, land use, and resource consumption from the reactor to estimate the overall environmental impact. For any specific application, the applicant would have to consider the specific material being used for fuel and the disposition for the irradiated fuel.

4.1 Example 1: Helium Cooled PBMR

The applicant has responded with the following answers to the questions of Section 3 describing a helium cooled pebble bed modular reactor:

1. 50 $MW_{electric}$ single-unit advanced reactor with 40-year planned lifetime, 95% capacity factor, 35% thermal efficiency
2. 5% enriched uranium fuel
3. Initial loading 10 tons heavy metal
4. 40,000 MW days/ton average burnup
5. Yes, to 5% U-235
6. U.S. commercial uranium market fuel source
7. U.S. commercial enrichment process
8. Contracted with Urenco for enrichment
9. Uranium will be in hexafluoride state for enrichment; dry process
10. Enrichment tails will be 0.25%
11. Reactor heat transfer medium will be helium
12. No special requirements for coolant
13. Fuel will be TRISO pebbles
14. Open fuel cycle
15. Operational LLW may be provided
16. Reactor will undergo 50 years of SAFSTOR followed by demolition
17. Spent nuclear fuel will be stored in a manner similar to that analyzed in NUREG-2157.

Impact estimation

The following information may be directly extracted from the responses.

The plant description yields the annual energy generation:

$50\ MW_e * 365\ day/year * 0.95 / 0.35 = \sim 50{,}000\ MW_{thermal}$ days/year

The anticipated fuel burnup provides the annual fuel requirement:

50,000 MW days/year / 40,000 MW days/ton = 1.2 tons/year 5% enriched fuel

The first core will use 10 tons, subsequent annual reloads/discharges of 1.2 tons

The uranium will be mined using ISL (the U.S. default). The uranium will be enriched in a centrifuge plant in Eunice, New Mexico (the Urenco facility). This uses UF_6 as feedstock.

One ton of 5% enriched uranium with 0.25% tails requires 10.3 tons of natural uranium (15.24 t of natural UF_6) which results in 9.3 tons of tails (13.76 t depleted UF_6). This requires 7923 SWU. The product is 1.48 tons of enriched UF_6. Knowing the initial and annual quantities of uranium required for fuel, impacts may be estimated for mining, milling, conversion, and enrichment.

MINING/MILLING IMPACTS: The total fuel loading of the reactor (10 tons initial + 1.2 tons/year for 40 years) is 58 tons of enriched uranium, which requires ~598 tons of unenriched natural uranium (or about 710 MT of fresh U_3O_8) over the plant lifetime. This is approximately the annual production rate of one of the ISL uranium solution mines in Wyoming or South Dakota. As described in the Final EA for the Ludeman Project, (NRC 2018) (which can produce 130,000 lb/year of yellowcake): the proposed ISR Project area covers approximately 7,632 hectares (ha) [18,861 acres (ac)]. The total potential land disturbance would be approximately 372 ha [920 ac] because of the construction of the satellite building, wellfields, ancillary buildings, booster stations, header houses, access roads, trunk lines, evaporation ponds, and permeate ponds. Land within the proposed project area would be converted temporarily from its primary use as rangeland to use as an ISR facility, with facilities constructed and wellfields brought into production over time (i.e., a phased approach). At the end of ISR operations, final site reclamation would occur during decommissioning, and all lands would be returned to their current land use. ISR operations at this ISR Satellite Project are expected to last for a 12-year period. Because the full requirements of the applicant's reactor are about 1/12th of the production of this one site, the impacts may be scaled as about 8.5% of the impacts estimated for this site.

Estimating Separative Work Requirements:

SWU may be determined using available SWU Calculators such as those available at https://www.uxc.com/p/tools/FuelCalculator.aspx .

ISL Mining Information:

A Generic Environmental Impact Statement on in-situ mining is available https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1910/

There are also a number of Environmental Assessments for operational In Situ Leach mining operations. An example is The Final Environmental Assessment for the Ludeman Satellite In Situ Recovery Project, Converse County, Wyoming Docket No. 40-8502 August 2018, available as ML18183A225. These may be used as a basis from which to scale impacts.

Materials that would result from processing ion exchange resins from the ISR Project (including yellowcake, processing chemicals, hazardous material, and byproduct material) would also be shipped to and from the ISR Project. Ion exchange resin shipments would be the most frequent radioactive materials shipments during operations at approximately two (round trip) shipments per day (NRC 2018). For the reactor at 1/12th of the impact, this is about 1 round-trip per week.

Concentrated brines would be disposed using lined evaporation ponds, and treated groundwater restoration permeate would be separately stored in lined permeate ponds (NRC 2018). During ISR operations, a maximum production rate would be approximately 34,000 Lpm [9,000 gpm]. The production bleed would average up to 1 percent of the lixiviant flow from the wellfields. Production bleed is the net withdrawal. From evaporation ponds it is released to the atmosphere. For the reactor at 1/12th of the impact, this is about 7.5 gpm.

During normal operations, Rn-222 (radon) would be the only significant radioactive airborne effluent at the ISR Project. The primary sources of Rn-222 would be wellfield and ion-exchange column venting and resin transfer operations. Total emissions are not given in NRC (2018), but MOI radon doses are shown to be less than 1.5 mrem/year, so the emissions are small. Non-radiological emissions are provided as annual emission rates (NRC 2018,Table B-3). The emissions attributable to the reactor in question would be about 1/12th of these.

Pollutant	Annual Emissions, Short tons	Attributable Emissions, Short tons
CO_2	1,453	121
CO	3.7	0.3
Hazardous Air Pollutants	0.3	0.025
Nitrogen Oxides	5.1	0.42
Particulate Matter PM2.5	3.4	0.28
Particulate Matter PM10	24.5	2
Sulfur Dioxide	1.0	0.085
Volatile Organic Compounds	4.8	0.38

CONVERSION IMPACTS:

The proposed reactor will require conversion of 598 tons of yellowcake to UF_6 by the dry process at an average of 15 tons/year.

Once fed into the conversion process, yellowcake is uniformly sized and reacted with hydrogen at a high temperature to form uranium dioxide. Next, the uranium dioxide is reacted with anhydrous hydrofluoric acid in fluidized bed reactors during Hydrofluorination to yield uranium tetrafluoride (UF_4). UF_4 is reacted with gaseous fluorine to produce crude gaseous uranium hexafluoride (UF_6) in the Fluorination stage, and then enters the final Distillation stage. Here, light fraction gases and impurities are removed to produce a purified liquid UF_6. This liquid UF_6 is drained into cylinders where the UF_6 crystallizes. The bulk of the impurities entering with the crude uranium feed are rejected from the hydrofluor process as solids. Long term observation of an area within a 7-mile radius of a hydrofluor plant has not revealed any adverse effects attributable to fluoride releases from the plant (WASH-1248).

Information for UF_6 Conversion:

The primary source of conversion of U_3O_8 to UF_6 is ConverDyn in Metropolis, Illinois, which uses the dry process. This is the only functional conversion plant in the US, and it is currently shut down. There is a Draft EA (NRC 2018, ML 18283B378) available for this facility, which may be used as a basis from which to scale impacts. An earlier EA (NRC 2006, ML061780260) is available.

The facility sits on a 1000 acre site; about 30 acres are used. Annual capacity of the site is 15,000 metric tons (16,535 tons) of uranium hexafluoride. Because the proposed reactor uses only an average of 15 tons/year, the impacts of the reactor are about 0.1% of the total from the site.

Annual atmospheric radiological and non-radiological emissions are provided in the EA NRC 2018, pp. 2.7 - 2.8). Using a 0.1% contribution, the annual emissions for the reactor are developed.

Air Emissions (metric tons)	**Facility Emissions**	**Attributable to reactor**
Natural uranium (Ci)	0.255	0.00026
Carbon monoxide	14.65	0.015
Carbon dioxide	18,489.8	1.85
Hydrogen fluoride	4.19	0.004
Lead	6.21×10^{-5}	6.2×10^{-8}
Methane	0.34	3.4×10^{-3}
Nitrous oxide	0.04	4×10^{-5}
Nitrogen oxides	17.44	0.017
Particulates	7.93	0.008
PM_{10}	7.93	0.008
PM2.5	7.93	0.008
Sulfur dioxide	130.01	0.13
Volatile organic material	1.15	0.001

The dry process uses cooling water, which is returned to natural receiving bodies. Metropolis discharges 2.87 million gallons/day (EA pg. 2-9). Using 2.87 MGal/day and 0.1%, we obtain 1.05 million gallons/year – slightly less than the older WASH-1248 estimate.

Parameter	**Plant Average**	**Attributable to reactor**
Flow Rate, MGD	2.87	0.0029
Uranium, mg/L	0.34	0.34
pH	7.11	7.11
Temperature, C	19.73	19.73
Total Fluorides, mg/L	4.98	4.98
TSS, mg/L	1.65	1.65
Biological oxygen demand, mg/L	7.79	7.79

Energy use: the EA states that 18,500 tons/year of CO_2 are emitted. Natural gas use can be backed out of this value. ConverDyn produces up to 15,000 tons/year UF_6, so 1.23 tons CO_2 are emitted per ton UF_6. The conversion is 0.0551 (metric tons CO_2/thousand scf) **(**https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references**).** Therefore, 223,200 scf of natural gas are consumed per ton of UF_6, for a total of 3.35Mscf per year. (WASH-1248 uses 20 Mscf for 1 annual requirement, or 1.666 Mscf for 15 tons/yr.)

Transportation impacts may also be scaled from the EA (NRC 2018 Table 3-4). The EA states that about 660 annual shipments of UF_6 are made by truck for the 15,000 ton/year capacity. Therefore, the reactor would require only about 1 shipment (0.66) per year.

ENRICHMENT IMPACTS:

The 58 tons of 5% enriched uranium over 40 years will require a total of 58 * 7923 = 460,000 SWU, or about 11,500 SWU/year. At about 50 kW-hour/SWU, this is an annual average requirement of 575,000 kW-hours.

The applicant will use commercially available enrichment. The Urenco USA enrichment (USSA) facility in New Mexico has a capacity of 10 million SWU/year. The proposed reactor requires about 0.12% of the plant capacity; this may be used as a scaling factor for estimating the fuel cycle impacts for enrichment for this reactor.

The UUSA facility is located within a 220-hectare (ha) (543-acre [ac]) parcel of land, of which approximately 160 ha (394 ac) have been disturbed (NRC 2015). The portion of this attributable to the proposed reactor is thus 0.26 ha (0.65 acres).

No surface water sources are used by the present UUSA facility (NRC, 2005a). The present UUSA facility obtains its water supply from the Eunice Municipal Water Supply System, which withdraws water from highly productive ground-water sources in the High Plains Aquifer near the City of Hobbs, about 32 km (20 mi) north of the UUSA site (NRC 2015). The facility's consumption rate is 62,577 L/d (16,531 gpd). The amount attributable to the reactor is thus about 16 gallons/day.

The UUSA annual emissions of uranium and hydrofluoric acid are reported to be less than about 12 grams/year and 1200 grams/year, respectively (NRC 2015). The amount attributable to the proposed reactor are then 0.012 g/yr uranium and 1.2 g/year HF.

Electrical energy use for separative work was estimated above to be about 575 MW-hours/year. The enrichment facility is in southeastern New Mexico. The emissions from the electrical generation system in this region needed to power the enrichment for the proposed reactor may be estimated as

Pollutant	Regional Factor lb/MW-hr	Attributable Release, lb
CO_2	1248	718,000
CH_4	0.095	55
N_2O	0.015	9
NO_x	0.09	52
SO_2	1.7	978

Uranium Enrichment Information:

EIA report “2018 Uranium Marketing Annual Report” (EIA, 2013) notes that SWU produced in the United States provided approximately 33 percent of U.S. demand in 2018, while SWU produced outside the U.S. provided the remaining 66 percent. Currently, the UUSA enrichment facility provides the only domestic source of enriched uranium. There is a 2015 EA for the Urenco plant (NRC 2015, ML15072A016) from which direct plant emissions may be scaled.

An earlier EIS is also available (NRC 2005a)

Estimating Atmospheric Emissions from Electricity Consumption:

The US EPA provides estimates of emissions from electricity production for different regions in the United States at https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid for CO_2, methane, nitrous and other nitrogen oxides, and sulfur dioxide in units of lb/MWhr. These may be selected for the region of interest and then scaled to the proposed reactor requirements.

The EA (NRC 2015) describes the annual shipments of unenriched uranium feedstock, enriched uranium, and low-level radioactive waste from the entire facility. The number of shipments attributable to the proposed reactor may be scaled from these as:

Feedstock:	1.5 Shipments/year (1 Type 48Y container per truck)
Enriched product	0.28 shipments/year (4 Type 30B cylinders per truck) or 1 cylinder/year
Uranium Byproduct Container (UBC)	1.7 Shipments/year (1 Type 48Y container per truck)
Low-Level Waste	0.12 Shipments/year

HEAT TRANSFER MATERIAL IMPACTS: The heat transfer fluid is defined to be helium.

Helium production in the U.S. totaled 73 million cubic meters in 2014. All commercial helium is recovered from natural gas. In 2012, helium was recovered at 16 extraction plants, from gas wells in Colorado, Kansas, Oklahoma, Texas, and Wyoming. One extraction plant in Utah was idle in 2012. Helium is marketed in two specifications: crude helium, which typically contains 75 percent to 80 percent helium, and Grade A helium, which is 99.995 percent pure. Grade A helium sold for about US$200 per MCF, or $7.21 per cubic meter in 2014.

Although there is a growing shortage of helium, plant use of helium will be a small fraction of world supply. Helium does not require additional separation or enrichment.

Helium Information:

USGS data on helium production and uses can be found at https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-heliu.pdf or https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/historical-statistics/helium-use.pdf

FUEL MANUFACTURE IMPACTS:

Fuel is defined to be TRISO.

NRC (2004) generically describes fuel, manufacture, and testing. High temperature reactors (HTR) operate at 750 to 950°C and are normally helium-cooled. Fuel for these is in the form of TRISO (tristructural-isotropic) particles less than a millimeter in diameter. Each has a kernel (ca. 0.5 mm) of uranium oxycarbide (or uranium dioxide), with the uranium enriched up to 20% U-235, though normally less. This is surrounded by layers of carbon and silicon carbide, giving a containment for fission products which is stable to very high temperatures. Recent trials at two U.S. laboratories confirmed that most fission products remain securely in TRISO particles up to about 1800°C – the performance being much better than previously known. There are two ways in which these particles can be arranged in an HTR: in blocks – hexagonal 'prisms' of graphite, or in billiard ball-sized pebbles of graphite encased in silicon carbide, each with about 15,000 fuel particles and 9 g uranium. Either way, the moderator is graphite.

There are no commercial TRISO fuel manufacturing facilities in the U.S. The main existing HTR fuel fabrication plant is at Baotou in China, the Northern Branch of China Nuclear Fuel Element Co Ltd. Since 2015, this plant makes 300,000 fuel pebbles per year for the HTR-PM under construction at Shidaowan. In Japan, NFI at Tokai has 400 kgU/yr HTR fuel capacity. Previous production has been on a small scale in Germany. In the USA, BWX Technologies is making TRISO fuel on an engineering scale, funded by the DOE which is aiming to take it to commercial scale. In September 2017 X-energy signed an agreement with Centrus Energy to develop TRISO fabrication technology for uranium carbide fuel. The TRISO-X methods are described by (Pappano 2018, ML18254A086) - the process uses a substantial amount of argon and acetylene, propylene, methyltrichlorosilane, and hydrogen. The equipment in the TRISO-X Pilot Facility at ORNL will be transferred/replicated in the TRISO-X Fuel Fabrication Facility. No further upscaling of the equipment capabilities is necessary. The production line will be replicated in the commercial to achieve reactor production demand (ML 18283B378). (https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx) (https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx). The steps in fuel manufacture are shown here: (https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/033/33033032.pdf?r=1&r=1)

Fuel manufacturing facilities are not large; the Framatome site in Richland, WA, with an 1,800 ton/year fuel capacity, is located within an approximately 53 acre fenced, secured area; within a 320 acre site. The plant includes a Dry Conversion Facility; the Uranium Dioxide Building, and a Specialty Fuels (SF) Building. It is assumed that a TRISO facility would be of the same order of magnitude. The hypothetical TRISO-X plant (Pappano 2018) appears to be of this general size. An Environmental Report for the Framatome (previously Areva) plant is available as is an Environmental Assessment (NCR 2009b).

Because the proposed reactor requires 15 tons/year of fuel fabrication, the land use impacts attributable to the reactor would be on the order of 1% of this size, or about 0.5 acres.

Any fuel manufacturing plant must include a step to convert the input UF_6 to the form (usually UO_2 but possibly carbide) used in the fuel. The Richland Framatome plant reports annual emissions of less than 10 uCi of alpha, 3.30 metric tons of NOx, and 20 kg of fluoride. Scaled to the proposed reactor, these would be about 0.1 uCi of alpha and 0.2 kg of fluoride per year.

Manufacture of TRISO fuel will differ significantly from that for UO_2 pellets encased in fuel rods. The process involves preparation of fuel kernels as droplets of uranyl nitrate and additives; TRISO particle coating at high temperatures in a fluidized bed in atmospheres of hydrogen, argon, acetylene, propylene, and methyltricholorosilane; Matrix production with graphite and phenolic resins; Overcoating with additional graphite; and Pebble pressing and heat treating. These steps all have the potential for releases of carbon dioxide and other process gases. The quantities are undefined at this time. An estimation of the emissions is given in EDF-3747, Early Site Permit ER Sections and Supporting Documentation (INEEL 2003) as:

> “The fuel fabrication facility for the New Production Reactor was for a modular high temperature gas reactor (MHTGR) design and was sized for just one plant, so any comparisons with the much larger reference LWR fuel fabrication plant are problematic. The dimensions for the fuel fabrication building were 230 ft x 150 ft. The annual production was about 2 MTU. The plant required 960 kW of electrical power and 45 liters per minute of water. Effluents consisted of 60 m^3/yr of miscellaneous noncombustible solids and filters; 50 m^3/yr of combustible solids; 50 m^3/yr of process off-gas and HVAG filters; 2.0 m^3/yr of tools and failed equipment; and process off-gases of 900,000 m^3/yr. The process off-gases consisted of 74% N_2, 12% 0_2, 7.2% Ar, 6.4% CO_2, 0.2% CO, and 0.02% CH_3CCl_3. The activity associated with this off-gas: 0.01 pCi alpha/rn^3, and 0.01 pCi beta/rn^3.
>
> The information gathered from one of the current reactor vendors was for a plant producing 6.3 MTU, about 19% more than the annual reload of 5.31 MTU for its reactor. Again, this plant was sized for just one reactor. This plant would require 10 MW of electrical power with an annual electrical usage of 35,000 MW-hr. The gaseous emissions consist of 80 MT of nitrogen, 52 MT of argon, 22.4 MT of CO, 22 MT of hydrogen and 3.7 MT of CO_2. The solid

> waste totals about 84 m^3 of LLW, 3 m^3 of intermediate level waste, and the remainder sanitary/industrial wastes. The liquid processing system would generate an additional 3.8 m^3 of LLW, would discharge about 3700 m^3 of low activity aqueous effluent, and would discharge about 45,000 m^3 of industrial cooling water.
>
> Because of the differences in scale and the state of design of the facilities, it is not possible or appropriate to make a direct comparison of the impacts. Obviously, there are economies of scale and design improvements that will occur for a plant comparable in size to the reference plant. Regardless, the projected impacts of a TRISO fuel plant based on the two conceptual designs are not inconsistent with the reference plant and would be operated within existing air, water, and solid waste regulations. Further; like the impacts associated with the sintered U02 pellet Plant, the impacts from a TRISO fuel plant would still be a minor contributor to the overall fuel cycle impacts. By characterizing the impacts as "not inconsistent," we mean that while certain parameters such as electrical usage for fuel fabrication might be higher for the gas-cooled plants on an annual fuel loading basis, the environmental impacts from the TRISO plants as conceptualized would still be bounded by the overall LWR fuel cycle impacts."

Extrapolating from this information, the emissions from a plant producing TRISO for the subject reactor would release <0.1 µCi of alpha and beta radionuclides, require about 30 MW of electrical power, 70 MT of CO_2, 10 MT of CO, 150,000 m^3 of cooling water, and generate about 300 m^3 of LLW.

FUEL CYCLE:

Because TRISO is so structurally sound, reprocessing is currently unlikely. An open fuel cycle is anticipated. Used TRISO fuel is assumed to be stored onsite until ultimate disposal. Note: The Ft. St. Vrain fuel is still onsite in Colorado. A typical ISFSI is considered (NRC 2014).

Ault et al. (2017) provide a generic estimate of LLW generation of conventional PWR sources of about 288 m^3/year per $GW_{electric}$. This implies about 14 m^3/year for the proposed reactor.

DECOMMISSIONING IMPACTS:

The only helium-cooled graphite reactor to be decommissioned in the U.S. is Fort St. Vrain. During the Ft. St. Vrain dismantlement, decontamination and system-removal process, 511 shipments containing 71,412 curies of low-level waste and weighing approximately 15 million pounds were made without incident to the low-level radioactive waste burial site. This effort was required to meet the NRC's release criteria of 5 microrem (.05 microsievert) per hour exposure rate above background 1 meter from previously activated surfaces and components, and less than 5000 disintegrations per minute per 100 cm2 (0.75 becquerel per cm2) for previously contaminated surfaces and components.
(Fisher 1997).

Because the facilities will not scale directly upon power output, the proposed reactor should produce fewer than 500 shipments of LLW.

Table 1. Fuel Cycle Data Summary for Example 1.

Mining/Milling	
Land Use (acres)	
Temporarily Committed	1,570
Disturbed	77
Permanently Committed	0
Overburden moved	0
Water Use (gallons)	
Discharged to air	3,950,000
Discharged to Surface Water	0
Discharged to Ground	0
Emissions to air (tons)	
CO_2	121
Hazardous pollutants	0.025
Particulates	2
Shipments	1
Conversion	
Land Use (acres)	
Temporarily Committed	1
Disturbed	0.03
Permanently Committed	0
Water Use (gallons/yr)	
Consumption	1,000,000
Discharged to Surface Water	1,000,000
Emissions to air (tons or Ci)	
Uranium	0.00026
HF	0.004
Particulate	0.008
Air Emissions (tons)	
CO_2	1.85
CH_4	0.0034
N_2O	0.00004
NO_x	0.017
SO_2	0.13
Shipments	1
Enrichment	
Land Use (acres)	
Temporarily Committed	0.65
Disturbed	0.47
Permanently Committed	0
Water Use (gallons/yr)	
Consumption	580,000
Discharged to Ground	580,000
Emissions to air	
Uranium/Thorium	0.012 grams/yr
HF	1.2 grams/yr
Energy Use (MW-years)	66

Associated Electricity Generation Air Emissions (lb)	
CO_2	718,000
CH_4	55
N_2O	9
NO_x	52
SO_2	978
Waste	
Tails (tons)	9.3
Shipments	4/yr

Fuel Manufacturing

Land Use (acres)	
Temporarily Committed	0.5
Disturbed	0.5
Permanently Committed	0
Water Use (gallons)	
Consumption	40,000,000
Discharged to Surface Water	40,000,000
Emissions to air (tons or Ci)	
CO_2	70
CO	10
Uranium (alpha)	<0.1
Waste	300 m^3

Spent Fuel Storage

Land Use (acres)	
Temporarily Committed	1
Disturbed	1
Permanently Committed	0
Offsite Shipments	0

Decommissioning

Land Use (acres)	
Temporarily Committed	0
Permanently Committed	0
Shipments	<500

4.2 Example 2: Molten Salt Reactor

The applicant has responded with the following answers to the questionnaire describing a molten salt reactor:

1. 50 $MW_{electric}$ single-unit advanced reactor with 40-year planned lifetime, 95% capacity factor, 35% thermal efficiency
2. 5% enriched uranium fuel
3. Initial loading 1 MT heavy metal
4. 40,000 MW days/ton average burnup
5. Yes, to <20% U-235
6. U.S. commercial uranium market fuel source
7. U.S. commercial enrichment process
8. Contracted with Urenco for enrichment
9. Uranium will be in hexafluoride state for enrichment; dry process
10. Tails will be 0.25%
11. Reactor heat transfer medium will be lithium fluoride salts, about 10 tons on primary circuit. This is about 2.5 tons Li-7.
12. Coolant needs to be enriched to 99.95% ^{7}Li
13. Fuel will be dissolved in the coolant
14. Open fuel cycle
15. Operational LLW may be provided
16. Reactor will undergo 50 years of SAFSTOR followed by demolition
17. Fuel will be separated to the extent feasible, fission products will be stored in dry casks on-site as a solid.

Impact Estimation

MINING, MILLING, CONVERSION, AND ENRICHMENT: With the exception of the additional enrichment SWU needed, the process is the same as Example 1.

HEAT TRANSFER MATERIAL IMPACTS:

Lithium-7:

LiF is exceptionally stable chemically, and the LiF-BeF_2 mix (‘FLiBe’) is eutectic (at 459°C it has a lower melting point than either ingredient – LiF is about 500°C). FLiBe is a potential MSR primary coolant, and when uncontaminated has a low corrosion effect. The three nuclides (Li-7, Be, F) are among the few to have low enough thermal neutron capture cross-sections not to interfere with fission reactions.

Current world production of Li-7 is on the order of one metric ton per year. Primary sources are the Russian Novorsibirsk Chemical Concentrates Plant in Siberia (about 80% of total world demand where lithium-7 hydroxide monohydrate is produced by electrolysis of lithium chloride using a mercury cathode.), and by SINAP in China using a centrifugal extraction method and counter-current extraction. Previous Li-6 enrichment programs in the U.S. used the Colex (column extraction) process, in which lithium hydroxide in aqueous solution is used in counter-current extraction in a mercury amalgam. The Colex process resulted in serious environmental contamination through releases of liquid mercury in excess of 2000 tons via wastes, spills and evaporation. Production of lithium-7 ceased in the USA in 1963, partly because of environmental and OHS concerns with the mercury used in its enrichment (https://www.world-nuclear.org/information-library/current-and-future-generation/lithium.aspx).

A single charge of a small reactor of the size envisioned here would require a substantial investment in the preparation of the Li-7 for the salt fuel, as an initial expense and a small continuing replenishment stream. There are no available suppliers of the quantity required (about 2.5 tons initially, multiple kg per year thereafter.).

At a conservative average 20 ppm in the Earth's crust, lithium is the 25th most abundant element. Lithium carbonate prices were stable at about $4700 per MT, but are now reported as about $9,000 per MT. According to some projections, demand for lithium carbonate (19% Li) is expected to rise from 165,000 MT in 2015 to more than 500,000 MT by 2025. According to estimates by the United States Geological Survey (USGS), which have been modified by Geoscience Australia for Australia's resources, known world lithium resources in 2012 totaled about 13.5 million MT. Chile holds approximately 7.5 million MT, or about 56% of the total world resources, followed by China with 3.5 million MT (about 26%), Australia with 1.5 million MT (11.4%), and Argentina with 0.85 million MT (6.3%). Bolivia has also reported considerable resources. World production in 2016 was about 35,000 MT. Australia was the leading producer with 14,300 MT, closely followed by Chile (12,000 MT), then Argentina (5700 MT) and China (2000 MT). Chile and Argentina recover the lithium from brine pools, Australia from hardrock mines. Mining of lithium for a reactor would not substantially increase the world demand.

Enrichment options must be detailed by the applicant. As a minimum, impacts for construction of a facility, operating parameters, and energy consumption should be detailed.

Chlorine-37:

Chloride salts have some attractive features compared with fluorides, in particular the actinide trichlorides form lower melting point solutions and have higher solubility for actinides so can contain significant amounts of transuranic elements. While NaCl has good nuclear, chemical and physical properties, its high melting point means it needs to be blended with $MgCl_2$ or $CaCl_2$, the former being preferred in eutectic, and allowing the addition of actinide trichlorides. The major isotope of chlorine, Cl-35 gives rise to Cl-36 as an activation product – a long-lived energetic beta source, so Cl-37 is much preferable in a reactor.

Sodium chloride is ubiquitous and inexpensive; a small reactor would not require substantial amounts except for the enrichment of chlorine.

Chlorine-37 enrichment is not currently performed anywhere in the world in bulk. A single charge of a small reactor of the size envisioned here would require a substantial investment in the preparation of the Cl-37 for the salt fuel, as an initial expense and a small continuing replenishment stream. There are no available suppliers of the quantity required.

Enrichment options must be detailed by the applicant. As a minimum, impacts for construction of a facility, operating parameters, and energy consumption should be detailed.

Unenriched coolants:

Alternative coolants with less desirable neutronic qualities, but not requiring expensive and/or unattainable stable-isotope enrichment include ZrF_4-NaF coolant salt stabilized with ZrF_2, sodium rubidium fluoride, and sodium-beryllium fluoride (BeF_2-NaF). (https://www.world-nuclear.org/Information-Library/Current-and-future-generation/Molten-Salt-Reactors.aspx).

OPERATING EMISSIONS:

Molten salt reactors will release noble gasses from fission products derived in the fuel on a continuous basis, even if on-line reprocessing of the fuel is not performed. A system for capture and holdup for decay should be described. As an upper bound, the generation rate from fission will be a linear function of the power of the reactor. Riley et al. (2019) describe options.

MSRE also noted substantial diffusion of tritium through the metal containment piping (>30%).

Ault et al. (2016) estimate about 288 m^3/year of LLW per $GW_{electric}$ for molten salt reactors.

FUEL CYCLE:

Reprocessing is currently unlikely. An open fuel cycle is anticipated. Used salt fuel is assumed to be stored onsite in solid form until ultimate disposal. It is likely that the salt would be converted to U_3O_8 for long-term storage (as at Oak Ridge MSRE, https://web.ornl.gov/info/ridgelines/nov12/msre.htm). However, this processing would require construction of a major, unique, remote-operated system in a well-shielded facility. Ault et al. (2016) estimate about 0.18 m^3/year of LLW per metric ton of heavy metal circulating in a molten salt reactor if on-line reprocessing is performed.

Radiolysis of cold fluorine salt results in substantial evolution of fluorine gas and also UF_6. How will this be dealt with? (Haubenreich 1970, National Research Council 1997).

Under current rules, any processing of fuel salts may prevent their classification as spent nuclear fuel. Potential salt waste forms are discussed by Riley et al. (2019).

DECOMMISSIONING IMPACTS:

Early decommissioning estimates for the Molten Salt Reactor Experiment (MSRE) were in the range of 1000 cubic yards of LLW (Peretz FJ. 1984).

Table 2. Fuel Cycle Data Summary for Example 2.

Mining/Milling	
Land Use (acres)	
Temporarily Committed	1,570
Disturbed	77
Permanently Committed	0
Overburden moved	0
Water Use (gallons)	
Discharged to air	3,950,000
Discharged to Surface Water	0
Discharged to Ground	0
Emissions to air (tons)	
CO_2	121
Hazardous pollutants	0.025
Particulates	2
Shipments	1

Conversion

Land Use (acres)	
Temporarily Committed	1
Disturbed	0.03
Permanently Committed	0
Water Use (gallons/yr)	
Consumption	1,000,000
Discharged to Surface Water	1,000,000
Emissions to air (tons or Ci)	
Uranium	0.00026
HF	0.004
Particulate	0.008
Air Emissions (tons)	
CO_2	1.85
CH_4	0.0034
N_2O	0.00004
NO_x	0.017
SO_2	0.13
Shipments	1

Enrichment

Land Use (acres)	
Temporarily Committed	0.65
Disturbed	0.47
Permanently Committed	0
Water Use (gallons/yr)	
Consumption	580,000
Discharged to Ground	580,000
Emissions to air	
Uranium/Thorium	0.012 grams/yr
HF	1.2 grams/yr
Energy Use (MW-years)	66
Associated Electricity Generation Air Emissions (kg)	
CO_2	718,000
CH_4	55
N_2O	9
NO_x	52
SO_2	978
Waste	
Tails (tons)	9.3
Shipments	4/yr

Heat Transfer Materials

Mining Land Use (acres)	(requires environmental assessment of new processes)
Processing Land Use (acres)	(requires environmental assessment of new processes)
Water Use (gallons)	(requires environmental assessment of new processes)
Emissions to air (kg)	(requires environmental assessment of new processes)
Energy Use (MW-years)	(requires environmental assessment of new processes)
Associated Electricity Generation Air Emissions (kg)	(requires environmental assessment of new processes)
Thermal Effluents (BTU)	(requires environmental assessment of new processes)

Fuel Manufacturing

Land Use (acres)	(requires environmental assessment of new processes)
Water Use (gallons)	(requires environmental assessment of new processes)
Emissions to air (kg)	(requires environmental assessment of new processes)
Energy Use (MW-years)	(requires environmental assessment of new processes)
Associated Electricity Generation Air Emissions (kg)	(requires environmental assessment of new processes)

Reactor Operations

Air/Water Emission Rates (Ci/year)	(requires environmental assessment of new processes)

Spent Fuel Storage

Land Use (acres)	(requires environmental assessment of new processes)
Water Use (gallons)	(requires environmental assessment of new processes)
Emissions to Air (Ci/year)	(requires environmental assessment of new processes)
Offsite Shipments	(requires environmental assessment of new processes)

Decommissioning

Land Use (acres)	(requires environmental assessment of new processes)
Shipments	(requires environmental assessment of new processes)

4.3 Example 3: Thorium-Fueled reactor (various types possible)

The responses to the questionnaire describe a thorium fueled, heavy water reactor.

MINING/MILLING:

Thorium is widely distributed with an average concentration of 10 ppm in earth’s crust in many phosphates, silicates, carbonates and oxide minerals and is 3 to 4 times more abundant in nature than uranium and has not been exploited commercially so far. In general, thorium occurs in association with uranium and rare earth elements (REE) in diverse rock types: as veins of thorite, thorianite, uranothorite and as monazite in granites, syenites, pegmatites and other acidic intrusions. Monazite is also present in quartz–pebble conglomerates sand stones and in fluviatile and beach placers. Monazite, a mixed thorium rare earth uranium phosphate, is the most popular source of thorium and is available in many countries in beach or river sands along with heavy minerals–ilmenite, rutile, monazite, zircon, sillimenite and garnet. The present production of thorium is almost entirely as a by–product of rare earth extraction from monazite sand.

Information on Thorium Mining and Milling

The IAEA publication *Thorium fuel cycle — Potential benefits and challenges* IAEA-TECDOC-1450 (https://www-pub.iaea.org/mtcd/publications/pdf/te_1450_web.pdf) provides details on the process of monazite mining and conversion of monazite to thorium oxide.

As discussed in Ault et al. (2017), thorium recovery is ancillary to rare earth metal recovery (i.e., titanium).

The total known U.S. reserves of thorium in the Reasonably Assured Reserves (RAR) and Estimated Additional Reserves (EAR) categories are 137,000 and 295,000 metric tons of thorium, respectively.

The mining and extraction of thorium from monazite is relatively easy and significantly different from that of uranium from its ores. The overburden during mining is much smaller than in the case of uranium and the total radioactive waste production in mining operation is about 2 orders of magnitude lower than that of uranium. The impact of radon also much smaller than in the uranium case due to the short lifetime of thoron as compared to that of radon and needs therefore much simpler tailings management than in the case of uranium to prevent long term public doses. As far as occupational doses are concerned, there is no need to control ventilation with respect to Rn–220 inhalation because monazite extraction is done in open pits. Thorium may also be recovered as a byproduct of titanium mining (Ault et al. 2016).

Typically, 3 to 9 percent of the content of monazite is thorium, with some ores exceeding 20 percent. For this example, it is assumed that 5% thorium monazite is placer mined. To obtain 10 tons of thorium from monazite, 200 tons of monazite sand would need to be collected. This is a volume of about 40 m^3. For a 40-year life, about 1,600 m^3 of monazite would be mined – a cube about 11 m on a side.

Thorium concentrate and nuclear grade ThO_2 are produced from monazite by involving the following process steps:

- Extraction and pre-concentration of beach sands.
- Conversion of ore (beach sand concentrates) to monazite.
- Conversion of monazite into thorium concentrate, uranium concentrate, and rare earths.
- Storage of thorium concentrate in suitable form or conversion of thorium concentrate to nuclear grade ThO_2 powder.

The monazite is finely ground and dissolved in 50–70% sodium hydroxide at ~1400 C and subjected to a series of chemical operations, including solvent extraction and ion exchange processes to obtain pure thorium nitrate, which is precipitated in the form of thorium oxalate and subjected to controlled calcinations to obtain ThO_2 powder.

Ault et al. (2017) estimate a mine/mill tailings volume attributable to thorium in titanium extraction of 0.24 m^3 per metric ton of thorium recovered.

Because an initial driver fuel is required in a thorium-cycle reactor, an additional uranium mining/milling impact similar to that for Example 1 but proportionally smaller will also occur.

CONVERSION/ENRICHMENT:

Enrichment of thorium is not needed, however because an initial driver fuel is required in a thorium-cycle reactor, additional uranium conversion and enrichment impacts similar to that for Example 1 but proportionally smaller will also occur.

FUEL FABRICATION:

For a once-through (no reprocessing) cycle, fuels containing naturally occurring fissile ^{235}U in combination with fertile ^{238}U or ^{232}Th, emitting only alpha particles of relatively low specific activity, can be manufactured with direct contact with the fuel material. However, process operations that involve generation and handling of fine powders of ^{235}U, ^{238}U or ^{232}Th bearing fuels are carried out in ventilated enclosures for minimizing radioactive aerosol. Therefore, fuel fabrication impacts will be similar to those currently encountered for uranium oxide fuels. Ault et al.(2016) estimates about 2.4 m^3 of LLW per metric ton of thorium oxide fuel manufactured.

A closed fuel cycle (with reprocessing) is much different, and an entirely new facility with the capability of remote handling of all steps in the fabrication process would be required to handle the high-gamma dose rates anticipated from the ^{232}U accompanying the fissile ^{233}U. As a minimum, impacts for construction of a facility, operating parameters, and energy consumption should be detailed by the applicant.

HEAT TRANSFER MATERIAL IMPACTS:

There are several options for which thorium fuels may be employed. In addition to modifications on standard light-water reactors, thorium fuels may also be used in high-temperature gas-cooled reactors (helium), molten salt reactors, and heavy water reactors (e.g., CANDU). Gas or salt reactors would have impacts as in Examples 1 or 2.

If heavy water is proposed, Argentina is the main producer of heavy water, using an ammonia/hydrogen exchange based plant. It is also a major exporter to Canada, Germany, the US, and other countries. The Industrial Heavy Water Plant (PIAP), located at Arroyito (Province of Neuquén) has production capacity amounting to 200 tons per year and is split into two production lines of 100 tons each. The process selected and applied by the PIAP for obtaining heavy water is based on a method known as "Monothermal Ammonia-Hydrogen Isotopic exchange". The electromechanic equipment plus the structures include 250 heat exchangers, 240 pressure vessels, 90 gas compressors, 13 reactors, 30 distillation columns Additionally, the PIAP contains two ammonia-synthesis reactors, each one of them with a production capacity of 2150 tons per day. These synthesis units are the largest in the world and are currently used in a closed circuit for obtaining virgin heavy water. Energy usage must be substantial. The Argentine facility is oversized and in danger of shutting down for lack of customers. The Bruce plants in Canada were permanently shut down in 1997; the Savannah River plants in the U.S. are shut down.

FUEL CYCLE:

In ^{232}Th– ^{233}U fuel cycles, a much lesser quantity of plutonium and long-lived minor actinides (e.g., Np, Am and Cm) are formed as compared to the ^{238}U–^{239}Pu fuel cycle, thereby minimizing toxicity and decay heat problems. Also, the stability of ThO_2 may help retard the migration of actinides in the repository.

An open fuel cycle is anticipated. Used fuel is assumed to be stored onsite until ultimate disposal.

DECOMMISSIONING IMPACTS:

Assuming a generic pressurized heavy-water reactor like a CANDU, some information is available (Unsworth 1979a; 1979b).

In respect to disposal requirements, the estimated volumes of the various types of material resulting from each decommissioning method are low. For dismantling, which involves the highest volume, the specific requirements are:

- The highly active material will be encased in concrete or lead liners and will occupy approximately 250 m^3.
- The remaining active material will occupy a volume roughly estimated at 7000 m^3.

The components of systems that are not contaminated will, wherever possible, be sold as scrap but the remaining material to be disposed of will occupy a volume of approximately 25 000 m^3.

Table 3. Fuel Cycle Data Summary for Example 3.

Mining	
Land Use – Thorium only (acres)	
Temporarily Committed	1
Disturbed	1
Permanently Committed	0.01
Overburden moved	0
Heat Transfer Materials	
Processing Land Use (acres)	
Water Use (gallons)	
Emissions to air (kg)	
Energy Use (MW-years)	
Associated Electricity Generation Air Emissions (kg)	
Thermal Effluents (BTU)	
Fuel Manufacturing (Once through cycle)	
Land Use (acres)	
Temporarily Committed	0.5
Disturbed	0.5
Permanently Committed	0
Water Use (gallons)	
Consumption	40,000,000
Discharged to Surface Water	40,000,000
Waste	960 m^3
Spent Fuel Storage	
Land Use (acres)	
Temporarily Committed	1
Disturbed	1
Permanently Committed	0
Offsite Shipments	0
Decommissioning	
Land Use (acres)	
Temporarily Committed	0
Permanently Committed	0
Shipments	<250

4.4 Example 4: High-Assay Low-Enriched Uranium (HALEU) Metallic Fuel Fast Reactor

The applicant has responded with the following answers to the questions of Section 3 describing a metallic HALEU fueled reactor:

1. 5 $MW_{electric}$ single-unit advanced reactor with 40-year planned lifetime, 95% capacity factor, 35% thermal efficiency
2. 10% enriched uranium fuel
3. Initial loading 1 ton heavy metal
4. 40,000 MW days/ton average burnup
5. N/A
6. U.S. DOE fuel source
7. N/A
8. N/A
9. N/A
10. N/A
11. Reactor heat transfer medium will be supercritical CO_2
12. No special requirements for coolant
13. Fuel will be metallic uranium-zirconium alloy
14. Open fuel cycle; single core loading per reactor lifetime
15. Operational LLW may be provided
16. Reactor will be small enough for one-piece removal
17. Spent nuclear fuel will be stored in a manner similar to that analyzed in NUREG-2157.

Supplies of high-assay LEU are being made available to commercial developers, at least initially, from the supplies of the DOE. The initial source of uranium is recycled material from the EBR-II experimental reactor. This material will be melted and cast into reactor components at Idaho National Laboratory. The first castings have been made in late 2019 (https://morningconsult.com/2019/10/17/oklo-fabricates-fuel-prototypes-at-idaho-national-laboratory/). Congress is considering a bill that directs the Office of Nuclear Energy in the DOE to develop and deploy high-assay low-enriched uranium for domestic commercial use (https://www.congress.gov/bill/116th-congress/house-bill/1760).

A reactor designed to use such fuel would enter the fuel cycle at the fuel fabrication step, bypassing the mining, milling, conversion, and enrichment processes in the generic fuel cycle.

Sources of Information Concerning HALEU

The DOE has prepared an Environmental Assessment describing the impacts of fuel preparation using recycled EBR-II fuel. Up to 10 tons of HALEU may be processed, at rates of 2.5 to 5 tons/year at INL.

Environmental Assessment for Use of DOE-Owned High-Assay Low-Enriched Uranium Stored at Idaho National Laboratory, DOE/EA-2087 (2019).

Impact Estimation

FUEL FABRICATION:

The DOE EA on casting of available HALEU (DOE 2019) describes releases to the atmosphere from melting and casting the available materials. It is based on processing of 2.5 tons/year of uranium, so the impacts for the reactor proposed may be scaled from the emissions by a factor of 0.4. Because the source material is recycled, it contains a small amount of residual fission and activation products.

The process is described (DOE 2019) as “Casting and alloying can be a one- or two-step process. In a single-step process, the HALEU feedstock and other alloying components, such as zirconium, are loaded into a crucible. The crucibles are usually coated with a non-reactive ceramic (typically yttrium oxide). The loaded crucible is placed into a furnace and heated, usually to about 1500°C and held for about 1-2 hours to melt and mix the constituents into a homogeneous alloy. The exact casting temperature used depends on alloy composition and specific process needs. The molten alloy is then poured or injected into a mold of specific shape. In a two-step process, the material is melted and poured into an interim shape, usually sized for convenient handling. The first casting step results in chemical homogeneity and allows inspection for the proper chemical composition. During the second casting step, the product is melted again and cast into the desired final fuel form.”

No emissions to surface or groundwater are anticipated.

Operations of the casting facility for 1 ton of fuel will generate less than 8 m^3 of low-level waste per year.

Shipping of feedstock will occur only on DOE-controlled roads within the INL site.

Atmospheric releases from casting of recycled HALEU uranium scaled from DOE (2019) are:

Radionuclide	Emission (Ci/year)	Radionuclide	Emission (Ci/year)
Mn-54	2.36E-02	Np-237	1.21E-05
Co-60	3.14E-05	Pu-239	5.20E-03
Sr-90	2.16E+00	Pu-240	5.08E-04
Tc-99	2.56E-09	Am-241	2.10E-01
Sb-125	1.07E-01	U-234	9.92E-03
Cs-134	3.22E-02	U-235	4.16E-04
Cs-135	3.07E-03	U-236	3.35E-04
Cs-137	6.96E-01	U-238	2.67E-04
Ce-144	2.14E-04	U-232	1.11E-04
Eu-154	5.96E-02	U-233	3.07E-06
Eu-155	1.07E-01	U-237	1.80E-05

HEAT TRANSFER MATERIAL IMPACTS:

The proposed reactor will use CO_2 as a coolant. This is a readily available atmospheric gas, and no additional processing will be necessary.

FUEL CYCLE:

Reprocessing is currently unlikely. An open fuel cycle is anticipated. Fuel may be removed with the reactor as an integral unit.

DECOMMISSIONING IMPACTS:

The proposed reactor is very small and may be removed as an integral piece. Storage of fuel and reactor together will generate minimal impacts.

Table 4. Fuel Cycle Data Summary for Example 4.

Fuel Manufacturing	
Land Use (acres)	Process uses existing DOE facilities
Emissions to air (kg)	See table above
Energy Use (MW-years)	The EA does not provide energy use, but it is assumed to be small.
Spent Fuel Storage	
Land Use (acres)	Minimal, except at final defueling
Offsite Shipments as few as 1	
Decommissioning	
Land Use (acres)	
Temporarily Committed	0
Permanently Committed	0
Shipments	1

4.5 Example 5: Liquid Metal Cooled Fast Reactor

The applicant has responded with the following answers to the questions of Section 3 describing a fast reactor cooled by liquid sodium:

1. 50 $MW_{electric}$ single-unit advanced reactor with 40-year planned lifetime, 95% capacity factor, 35% thermal efficiency
2. PU/U Mixed Oxide fuel (25% PU, 75% natural U)
3. Initial loading 10 MT heavy metal
4. 50,000 MW days/ton average burnup
5. Pu from available DOE sources
6. U.S. DOE fuel source
7. N/A
8. N/A
9. N/A
10. N/A
11. Reactor heat transfer medium will be liquid sodium
12. No special requirements for coolant
13. Fuel will be mixed oxide in ceramic cladding
14. Closed fuel cycle when reprocessing is available; fuel stored in dry casks prior
15. Operational LLW may be provided
16. The D&D quantities will be similar to those estimated for the FFTF reactor
17. Fuel will be removed and stored in dry casks

Information on Liquid Metal Reactor Impacts:

The US DOE operated the Fast Flux Test Facility from 1978 through 1993. An Environmental Statement (WASH-1510, AEC 1972) was prepared detailing the impacts of FFTF construction and operation.

Information on Mixed Oxide Fuel Fabrication Impacts:

The NRC prepared an EIS on construction and Operation of a Mixed Oxide Fuel Fabrication Facility, NUREG-1767 (NRC 2005b). The report NUREG/CR-0129 (PNNL 1979) discusses decommissioning of a MOX facility.

In this example, as in Example 4, the fuel material is pre-existing and made available from U.S. stores by the DOE. The analysis enters the fuel cycle at the fuel manufacturing stage.

The proposed fuel burnup indicates that the proposed reactor would require about 0.4 MT/yr of new fuel (0.1 MT of plutonium) after the first loading.

Impact Estimation

FUEL FABRICATION:

A MOX facility would convert plutonium dioxide and uranium dioxide to MOX fuel. Operations at the facility would begin with the receipt of the plutonium dioxide and uranium dioxide feed materials. The plutonium dioxide would be blended with the uranium dioxide. The blended material would then be formed into pellets, sintered, and ground to size, and then the pellets would be incorporated into fuel rods, the fuel rods placed in fuel assemblies, and the assemblies loaded into transport casks for shipment to the nuclear power plant.

The facility described in NRC (2005b) would handle an average of 3.5 MT of Pu per year. The proposed reactor requires about 0.1 MT/year of replacement plutonium, so the scaling factor is about 0.03.

The proposed site would be about 17 acres of buildings, facilities, and paving; the area attributable to the proposed reactor would be about 0.5 acre.

The facility is projected (NRC 2005b) to require about 2.4 million gallons of water use per year from groundwater; the reactor fraction is about 72,000 gallons/year. No surface water use is projected. The effluents estimated (Table 4.11 of the EIS) may be scaled to the annual needs of the proposed reactor.

Waste Type	MOX Plant	Amount attributable to reactor
TRU (m^3/yr)	234	7
Liquid LLW (L/yr)	1,800,000	54,000
Solid LLW (m^3/yr)	176	5
Hazardous (m^3/yr)	11	0.3
Nonhazardous Liquid (L/yr)	33,300,000	1,000,000
Nonhazardous solid (M^3/yr)	1.340	40

HEAT TRANSFER MATERIAL IMPACTS:

The proposed reactor will use sodium metal as a coolant. This is a readily available material, and no additional processing will be necessary.

Other potential liquid metal coolants include sodium/potassium eutectic (NaK), lead, and lead/bismuth eutectic. Both lead and bismuth block gamma radiation while simultaneously being virtually transparent to neutrons. In contrast, sodium will form the potent gamma emitter sodium-24 (half-life 15 hours) following intense neutron radiation, requiring a large radiation shield for the primary cooling loop. However, lead and lead/bismuth coolant are more corrosive to steel than sodium. In addition, bismuth activates to alpha-emitting polonium-210.

FUEL CYCLE:

Reprocessing is currently unlikely. An open fuel cycle is anticipated. Use of an on-site ISFSI is assumed; impacts would be similar to other types of fuel storage

DECOMMISSIONING IMPACTS:

The DOE's Fast Flux Test facility (FFTF) has been closed. Decommissioning of the reactor including evaluations of proposed actions and alternatives for the final decommissioning end state for FFTF and its support buildings/facilities/structures located within the FFTF Property Protected Area, management of waste generated by the decommissioning process, and disposition of the inventory of radioactively contaminated bulk sodium is discussed in the DOE Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (DOE/EIS–0391, December 2012, https://www.hanford.gov/page.cfm/FinalTCWMEIS). FFTF was a 400 $MW_{thermal}$ test reactor approximately 3 times the size of the proposed reactor.

In DOE (2012), It was assumed that Hanford‘s bulk sodium inventory would be converted to a caustic solution for use in processing tank waste or for Hanford tank corrosion control (thus its inclusion in the tank waste EIS). However, there is uncertainty regarding whether an alternative disposition pathway for this material would be necessary. There is also uncertainty regarding the potential shipment of the remote-handled containers to INL for processing, as no NRC-licensed transportation cask currently exists with the capacity to handle these components for shipment.

Table 5. Fuel Cycle Data Summary for Example 5.

Fuel Manufacturing	
Land Use (acres)	0.5
Water Use (gallons)	72,000
Spent Fuel Storage	
Land Use (acres)	
Temporarily Committed	1
Disturbed	1
Permanently Committed	0
Offsite Shipments	0
Decommissioning	
Land Use (acres)	
Temporarily Committed	0
Permanently Committed	0
Shipments	<500

5.0 Summary

Each applicant for a permit to construct or operate a reactor must submit with its application a separate Environmental Report which contains the information specified in 10 CFR 51 sections 45, 51, and 52. This report outlines an approach for non-light-water reactors for evaluating the contribution of the environmental effects of uranium mining and milling, mining of non-fissile materials required for unique designs, the production of uranium hexafluoride, uranium and other fuel material isotopic enrichment, fuel fabrication, and management of low-level wastes and high-level wastes related to uranium fuel cycle activities. The reprocessing of irradiated fuel is not addressed because reprocessing is currently not performed in the U.S. Effects of transportation of radioactive materials are addressed in a companion report.

The method requires basic information about the proposed reactor under consideration. A generic method based upon scaling to existing environmental documentation, where available, and approximations in other cases, is used. Suggested starting documents are provided.

6.0 References

National Environmental Policy Act of 1969, as amended (NEPA). 42 USC 4321, et seq.

10 CFR Part 50. Code of Federal Regulations, Title 10, Energy, Part 50, "Domestic Licensing of Production and Utilization Facilities."

Ault T, Van Gosen B, Krahn S, Croff A, 2016. Natural thorium resources and recovery: options and impacts. Nucl. Technol. 194 (2), 136-151.

Ault T, Krahn S, Croff A. 2017. Comparing the environmental impacts of uranium- and thorium-based fuel cycles with different recycle options. Progress in Nuclear Energy 100, 114-134.

Fisher M. 1997. Fort St. Vrain Decommissioning Project, Public Service Company of Colorado. (http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/059/29059907.pdf)

Haubenreich PN. 1970. Flouride Production and Recombination in Frozen MSR Salts after Reactor Operation. ORNL-TM-3144. Oak Ridge National Laboratory, Oak Ridge, TN. (http://moltensalt.org/references/static/downloads/pdf/ORNL-TM-3144.pdf)

IAEA. 2005. Thorium fuel cycle — Potential benefits and challenges, IAEA-TECDOC-1450 (https://www-pub.iaea.org/mtcd/publications/pdf/te_1450_web.pdf)

IAEA. 2019. Waste from Innovative Types of Reactors and Fuel Cycles, IAEA Nuclear Energy Series No. NW-T-1.7, Vienna, AU https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1822_web.pdf

Idaho National Engineering and Environmental Laboratory (INEEL). 2003. Early Site Permit Environmental Report Sections and Supporting Documentation, Engineering Design File Number 3747. Idaho Falls, ID. [ML040580285]

McFarlane J, Taylor P, Holcomb D, Poore WP. Review of Hazards Associated with Molten Salt Reactor Fuel Processing Operations, ORNL/TM-2019/1195, Oak Ridge National Laboratory, Oak Ridge, TN. [ML 19205A386]

National Research Council. 1997. Evaluation of the U.S. Department of Energy's Alternatives for the Removal and Disposition of Molten Salt Reactor Experiment Fluoride Salts. National Academy Press, Washington, D.C. (https://www.nap.edu/read/5538/chapter/1)

Pappano 2018, TRISO-X Fuel Fabrication Facility Overview ML18254A086

Peretz FJ. 1984. Preliminary Decommissioning Study Reports, Volume 5: Molten Salt Reactor Experiment. X-OE-231, Vol. 5. Oak Ridge National Laboratory, Oak Ridge, TN. (https://www.osti.gov/servlets/purl/5765164).

Riley BJ, McFarlane J, DelCul GD, Vienna JD, Contescu CI, Hay LM, Savino AV, Adkins HE. 2018. Identification of Potential Waste Processing and Waste Form Options for Molten Salt Reactors, PNNL-27723, Pacific Northwest National Laboratory, Richland, WA.

Riley BJ, McFarlane J, DelCul GD, Vienna JD, Contescu CI, Forsberg CW. 2019. Molten salt reactor waste and effluent management strategies: A review. Nuclear Engineering and Design 345: 94-109. Doi: 10.1016/j.nucengdes.2019.02.002

Unsworth GN. 1979a, Decommissioning of the CANDU-PHW reactor, AECL—6756, Atomic Energy of Canada Limited, Pinawa, Manitoba (Canada) https://inis.iaea.org/search/search.aspx?orig_q=RN:41011567

Unsworth GN. 1979b, Decommissioning of the CANDU Nuclear Power Stations, AECL—6332, Atomic Energy of Canada Limited, Pinawa, Manitoba (Canada) https://www.ipen.br/biblioteca/rel/R42114.pdf

US DOE. 2012. Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington. DOE/EIS–0391US Department of Energy, Richland WA. https://www.hanford.gov/page.cfm/FinalTCWMEIS

US DOE. 2019. Environmental Assessment for Use of DOE-Owned High-Assay Low-Enriched Uranium Stored at Idaho National Laboratory. DOE/EA-2087. US Department of Energy, Idaho Operations Office, Idaho Falls, ID. https://www.energy.gov/sites/prod/files/2019/01/f58/EA-2087-HALEU-2019-01.pdf

US AEC. 1974. Environmental Survey of the Uranium Fuel Cycle. WASH-1248. US Atomic Energy Commission, Washington, D.C.

US AEC. 1972. Environmental Statement, Fast Flux Test Facility, Richland, Washington. WASH-1510. US Atomic Energy Commission, Washington, D.C.

US NRC. 2019. Information 1Digest 2019-2020, NUREG-1350, Volume 31. US Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/

US NRC. 2009. Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities, NUREG-1910, US Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1910/v1/

US NCR. 2009b. Environmental Assessment for the Renewal of U.S. Nuclear Regulatory Commission License No. SNM–1227 for AREVA NP, Inc. Richland Fuel Fabrication Facility. US Nuclear Regulatory Commission, Docket No. 70-1257 [ML090700258]

US NRC 2004. TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents, NUREG-6844 Volume 1, US Nuclear Regulatory Commission. [ML042300668] https://www.nrc.gov/docs/ML0423/ML042300668.pdf

US NRC. 2005a. Environmental Impact Statement for the Proposed National Enrichment Facility in Lea County, New Mexico, NUREG-1790; https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1790/v1/

US NRC. 2005b. Environmental Impact Statement on the Construction and Operation of a Proposed Mixed Oxide Fuel Fabrication Facility at the Savannah River Site, South Carolina. NUREG-1767, Vol. 1.

US NRC. 2014. Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel, NUREG–2157, US Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2157/

US NRC. 2015. Environmental Assessment for the Proposed Louisiana Energy Services, URENCO USA Uranium Enrichment Facility Capacity Expansion in Lea County, New Mexico, Docket No. 70-3103 [ML 15072A016] https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML15072A016

US NRC. 2018. Final Environmental Assessment for the Ludeman Satellite In Situ Recovery Project, Converse County, Wyoming Docket No. 40-8502 [ML18183A225.]

US NRC. 2018b. Draft Environmental Assessment for the Proposed Renewal of Source Material License SUB–526 Metropolis Works Uranium Conversion Facility (Massac County, Illinois), US Nuclear Regulatory Commission, [ML18283B378] https://www.nrc.gov/docs/ML1828/ML18283B378.pdf

Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov