Security of the Fuel Cycle

Jeremy Pencer

World Institute for Nuclear Security, Security of Small Modular Reactors
Ottawa, Canada, 20-21 November 2019

Abstract

Introduction of SMR fuel cycles into the Canadian energy landscape will present new considerations for non-proliferation and physical protection because of their differences from the conventional natural uranium-based CANDU fuel cycle. Considerations span the entire cycle from front to back and include

- manufacturing processes for different fuel types,
- transportation to diverse and potentially remote locations,
- in reactor use, and
- on site storage and subsequent transportation of used fuel.

Approaches for non-proliferation and physical protection for conventional reactors will be reviewed along with a high level discussion on how these approaches might be adapted for non-conventional systems.

Introduction

- Introduction of SMRs to Canada will also introduce fuel cycles that differ from conventional CANDU fuel cycles
- New fuel cycles, in turn, introduce potential new considerations for non-proliferation and physical protection
- How do differences impact each stage of the fuel cycle?
- How do these differences impact requirements to satisfy nuclear security regulations?
- How can current approaches for non-proliferation and physical protection be adapted in order to accommodate different fuel cycles?

Fuel Cycles Overview

A High Level Introduction

Conventional once through

- CANDU – Natural Uranium; used fuel goes to DGR
- LWR – Enriched Uranium; used fuel goes to DGR

Partly closed and closed fuel cycles

- Used CANDU or LWR fuel is reprocessed and fissile / fertile material is used to make new fuel
- Recycled fuel likely contains reactor grade (RG) plutonium
- Thorium may be used as a substitute for or supplement to U-238 in order to reduce the production of transuranics during irradiation

Fuel Cycles Overview

Scenario Studies

- Predict uranium consumption based on projected energy demand and deployment scenarios
- Recycling / synergies among reactors intended to
  - Preserve mined uranium reserves
  - Reduce decay heat and radiotoxicity of used fuel material
  - Reduce inventory of Pu and other fissile isotopes in used fuel
- Considerations given to proliferation resistance of fuel
  - Material attractiveness (potential proliferative end use)
  - Self protection (dose from fuel)
  - Ease of separation of fissile component (made more difficult with isotopic denaturation)

SMR Vendor Designs

CNSC Pre-Licensing Vendor Design Review

- 8 designs under review with various design and operating characteristics
- Power: ranges from 3 to 300 MW
- Fuel: molten salt, TRISO, metallic, oxide
- Fissile component: U-235, Pu-239 (RG Pu), TRU
- Fissile enrichment: ranges from 5% to 20%
- Cycle Length: ranges from 2 years to 20 years
- Total fuel in core: ranges from 4000 kg to 15,000 kg

https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm
http://ontarioenergyreport.ca/pdfs/MOE%20-%20Feasibility%20Study_SMRs%20-%20June%202016.pdf

SMR Vendor Fuel Types

A short summary; information from Vendor websites

- Terrestrial Energy: < 5% enriched U
- Ultrasafe MMR: 9-12% enriched U
- LeadCold SEALER: 19.9% enriched U
- ARC Nuclear ARC-100: Initial fuel load < 20% enriched uranium; option for use of recycled Pu
- Moltex Energy Stable Salt Reactor: Uranium fuelled, with options for thorium-based fuel and fuel recycling
- Holtex SMR-160: Low enriched uranium
- NuScale Intregral PWR: < 5% enriched U
- U-Battery High temperature gas reactor: enriched U

Categorization of Nuclear Materials

Definitions of Category I, II, and III Nuclear Material

Item	Nuclear Substance	Form	Quantity (Category I)	Quantity (Category II)	Quantity (Category III)
1	Plutonium	Unirradiated	2 kg or more	2 kg > m > 500 g	500 g > m > 15 g
2	U-235	Unirradiated; ≥ 20% U^{235}	5 kg or more	5 kg > m > 1 kg	1 kg > m > 15 g
3	U-235	Unirradiated; 20% >U^{235}≥ 10%	N/A	10 kg or more	10 kg > m > 1 kg
4	U-235	Unirradiated; 10 % > U^{235} > 0.711%	N/A	N/A	m ≥ 10 kg
5	U-233	Unirradiated	2 kg or more	2 kg > m > 500 g	500 g > m > 15 g
6	Dep U, NU, Th, LEU (<10%)	Irradiated	N/A	m > 500 g Pu	500 g Pu ≥ m > 15 g Pu
-	NU, Dep U, Th	Unirradiated	N/A	N/A	N/A

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Categorization of Nuclear Materials

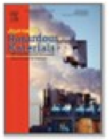
Other factors for potential consideration

- Should self-protection (dose) from "fresh" fuel be a consideration?
- Should the physical state, in particular its potential impact on ease of reprocessing, be a consideration?

Categorization of Nuclear Materials

Other factors for potential consideration

Journal of Hazardous Materials
Volumes 241–242, 30 November 2012, Pages 456-462



Uranium extraction from TRISO-coated fuel particles using supercritical CO_2 containing tri-n-butyl phosphate

Liyang Zhu [a, b], Wuhua Duan [a], Jingming Xu [a], Yongjun Zhu [a]

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Abstract

High-temperature gas-cooled reactors (HTGRs) are advanced nuclear systems that will receive heavy use in the future. It is important to develop spent nuclear fuel reprocessing technologies for HTGR. A new method for recovering uranium from tristructural-isotropic (TRISO-) coated fuel particles with supercritical CO_2 containing tri-n-butyl phosphate (TBP) as a complexing agent was investigated. TRISO-coated fuel particles from HTGR

"The cumulative extraction efficiency was above 98% after 20 min of online extraction at 50 °C and 25 MPa, whereas the SiC shells were not extracted by TBP. The results suggest an attractive strategy for reprocessing spent nuclear fuel from HTGR to minimize the generation of secondary radioactive waste."

Security Requirements for Fuels

Storage and Use of Category I, II, and III Nuclear Material

- Category I nuclear material must be processed, used and stored in an “inner area”
- Category II nuclear material must be processed, used and stored in a “protected area”
- Category III nuclear material must be processed, used and stored in a “protected area” or “an area under direct surveillance by the licensee” or an area to which access is controlled and that is designed and constructed to prevent unauthorized access to material using hand held tools
- “…any quantities of natural uranium, depleted uranium, and thorium should be protected at least in accordance with prudent security practice”

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Security Requirements for Fuels

Transportation of Category I, II, and III Nuclear Material

Requirements include

- Name, quantity, radiation level, isotopic composition, and physical / chemical characteristics of the material,
- A threat assessment,
- Description of conveyance,
- Proposed security measures,
- Communication arrangements during transport,
- Arrangements with off site response force during transportation,
- The planned route,
- An alternate planned route in case of emergency.

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Categorization of Nuclear Fuels

Fresh Fuels (assuming quantities required to fuel 1 SMR core)

- CANDU Natural Uranium: Less than Category III
- LWR fuel: m ≤ 5% enriched U: Category III
- Enriched uranium: m ≤ 10% enriched U: Category III
- Enriched uranium: 10% ≤ m ≤ 20% enriched U: Category II
- Enriched uranium: m ≥ 20% enriched U: Category I
- Recycled fuel containing Pu: Category I
- Recycled fuel containing U-233: Category I

Irradiated Fuels

- Depleted U, NU, Th, LEU (<10%): Category II*
- LEU (>10%), other: Category I, but may be reduced one category level while the radiation level from the fuel exceeds 1 Gy/h at 1 m unshielded.

*assuming > 10 CANDU bundles for NU or equiv

Safeguards

General Overview

- The intent is to apply measures to deter authorized actor(s) or a State from diverting and misusing nuclear material for military purposes.

Measures include:

- Nuclear Material Accountancy (NMA),
- Containment and Surveillance (C&S),
- Design Information Verification (DIV),
- Reports, and
- Inspections.

The design of nuclear facilities is a key enabler for safeguards measures, i.e. “safeguards by design”.

Safeguards and Fuel Cycles

General Overview

- Designed safeguards depend primarily on plant and infrastructure design
- Safeguards do not depend on the choice of nuclear materials used in the fuel cycle, except for potential variability in material attractiveness
- Key challenges discussed elsewhere include:
  - Remoteness of facilities, which may make inspections difficult
  - Reliability of remote monitoring for materials accountability
  - For molten salt reactors, materials accountability is further complicated by potential difficulties in tracking nuclear materials as they circulate through the core

CANDU Characteristics

CANDU 6

- Power: 600 MWe
- Fuel: Natural uranium, UO_2
- Weight % U-235: 0.711%
- Burnup: 7.5 MWd / kg heavy element
- Cycle Length: N/A (online refuelling; fuel residence time ranges from 160 to 360 FPD)
- Weight of uranium per bundle: 19.2 kg
- Fuel bundles in core: 4560
- Total uranium in core: 87,552 kg

https://canteach.candu.org/Content%20Library/CANDU6_TechnicalSummary-s.pdf
http://www.nuceng.ca/candu/pdf/21%20-%20In-core%20FM.pdf

The CANDU Nuclear Fuel Cycle

Each step in the CANDU fuel cycle takes place partly or entirely in Canada. Transportation may be required in between each step.

The stages of the fuel cycle where non-proliferation and security become important are:

- Post refinement,
- Conversion,
- Fuel fabrication,
- Nuclear power generation,
- Waste management, and
- Long term storage

Adapted from
https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/uranium-nuclear/canada_nuclear_fuel_cycle_access_e.pdf

Post Refinement, natural uranium

Security Aspects

- Milled uranium (yellow cake, U_3O_8) has been refined to UO_3
- The uranium is "natural uranium" (a mixture of 0.711% U-235 and U-238 by weight)
- The security requirements for protection of natural uranium are that "…any quantities of natural uranium, depleted uranium, and thorium should be protected at least in accordance with prudent security practice"
- The requirements related to transportation do not include the additional measures associated with Category I, II, or III nuclear materials

SOR/2000-209,
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Current to July 1, 2019

Conversion and Fuel Fabrication

Security Aspects

- UO_3 is converted to UO_2 (or UF_6 exported for enrichment)
- UO_2 is shipped to manufacturing plants and assembled in pellet form into fuel bundles for CANDU reactors
- Since there's been no change to the isotopic composition, the security requirements remain as previous: "...any quantities of natural uranium, depleted uranium, and thorium should be protected at least in accordance with prudent security practice" and do not require the additional steps or precautions needed for Category I, II, or III nuclear materials

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Nuclear Power Generation

Security Aspects

- UO_2 fuel bundles are used in-reactor
- Storage is also provided for both unused and used UO_2 fuel bundles
- Nuclear power plants are considered “high-security sites”
- Facilities where Category I or II nuclear materials are stored, processed or used are also considered “high-security sites”
- Because of its isotopic composition, used (irradiated) CANDU fuel is a Category II material

Waste Management and Long Term Storage

Security Aspects

- Immediately after removal from the reactor, irradiated CANDU fuel is stored for several years in deep cooling pools adjacent for the reactor, in order for short lived fission products to decay
- Used CANDU fuel is then transferred to concrete containers where it is air-cooled by natural circulation and where it can be stored for as long as 100 years
- After dry storage, it is intended that irradiated CANDU fuel eventually be sent for long term storage in a deep geological repository

http://www.nuceng.ca/candu/pdf/19%20-%20Fuel%20Storage%20and%20Disposal.pdf

Scenario 1: m < 10 % enriched UO_2 OT cycle

Illustrative Example

- Post refinement – same as CANDU
- Conversion – same as CANDU, except with UF_6 end product
- Enrichment – requires Category III security measures
- Fuel fabrication – requires Category III security measures
- Nuclear power generation –requirements similar to CANDU
- On site and Long term storage – requirements similar to CANDU

If enrichment and/or fuel fabrication occur outside of Canada, then additional measures are required for transportation and movement across borders.

Scenario 2:10% < m <20% enriched UO_2 OT

Illustrative Example

- Post refinement – same as CANDU
- Conversion – same as CANDU, except with UF_6 end product
- Enrichment – requires Category II security measures
- Fuel fabrication – requires Category II security measures
- Nuclear power generation – requirements similar to CANDU
- On site and Long term storage – requirements similar to CANDU

If enrichment and/or fuel fabrication occur outside of Canada, then additional measures are required for transportation and movement across borders.

Scenario 3: Recycled fuel

Illustrative Example

- Transportation and store of used fuel – requirements depend on irradiated fuel type
- Reprocessing – requires Category I security measures*
- Fuel fabrication – requires Category I security measures
- Nuclear power generation – requirements similar to CANDU
- On site and Long term storage – requires Category I security measures (possible exceptions?)

If enrichment and/or fuel fabrication occur outside of Canada, then additional measures are required for transportation and movement across borders.

*assumes reprocessed fuel contains Pu or U233 with enrichment and quantity suitable for SMR

Related Capabilities at CNL

Support for various stages of the fuel cycle

Through our research and decommissioning activities, staff at CNL perform:

- Scenario studies to understand implications of different fuel cycles for non-proliferation, sustainability, and waste streams
- Fuel depletion and dose calculations to support diverse activities including decommissioning, and transportation of used fuel and irradiated research fuels
- Analysis of fresh and used fuel isotopic compositions and physical state to assess factors such as “material attractiveness” and ease or difficulty of extraction and separation of fissile material

Summary / Conclusions

- The choice of fuel for various SMR types will have a significant impact on security requirements for manufacturing, transportation and storage
- Security requirements for manufacturing, transportation and storage of enhanced enrichment or recycled fuels are greater than conventional HWR or LWR enriched uranium fuels
- Fuel cycles that include recycling of Pu or U-233 will require the same level of security for manufacturing, and storage as that for an NPP
- Unless Canada builds enrichment and reprocessing capabilities, it is likely that some categories of SMR fuels will need to be transported into Canada from elsewhere
- There are also fuel cycle security implications for used fuel that should be considered

Thank you.

Questions?

Jeremy.Pencer@cnl.ca