FINAL PROJECT REPORT (2014-2017)

Development of Fuel Cycle Data Packages for Thorium Fuel Cycle Options

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Performed Under:

Department of Energy, Nuclear Energy University Programs

Award DE-NE0000735

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June 2017

Contents

1. Executive Summary

This report presents cumulative information for the accomplishments spanning the entirety (from February 2014 to June 2017) of the "Development of Fuel Cycle Data Packages for Thorium Fuel Cycle Options" project, led by Vanderbilt University with the collaboration of Oak Ridge National Laboratory.

Report Organization

The report is broken into six chapters, including this executive summary chapter. Following an introduction, this report discusses each of the project's three major components (Fuel Cycle Data Package (FCDP) Development, Thorium Fuel Cycle Literature Analysis and Database Development, and the Thorium Fuel Cycle Technical Track and Proceedings). A final chapter is devoted to summarization. Various outcomes, publications, etc. originating from this project can be found in the Appendices at the end of the document.

Milestones

During this reporting period, the following formal project milestones (denoted with *) and other project deliverables were completed:

- *October 2014: Completed Year 1 Annual Report
- *November 2014: Executed Thorium Fuel Cycle Technical Track within the ANS Winter Meeting 2014 in Anaheim, CA, USA
- *January 2015: Held Year 2 Kickoff Meeting to update TPOCs on project progress and to identify FCDP objectives for Year 2
- *January 2015: Completed Year 1 Fuel Cycle Data Package
- *September 2015: Completed Thorium Fuel Cycle Technical Literature Report
- September 2015: Presentation of major Year 1 FCDP results at Global 2015 International Fuel Cycle Conference
- *December 2015: Recorded final acceptance of all constituent papers of the special thorium fuel cycle edition of the journal Nuclear Technology
- *January 2016: Held Year 3 Kickoff Meeting to update TPOCs on project progress and to identify FCDP objectives for Year 3
- *February 2016: Completed First of Two Year 2 Fuel Cycle Data Packages
- *February 2016: Completed Second of Two Year 2 Fuel Cycle Data Packages
- *May 2016: Completed Year 2 Annual Report
- May 2016: Final publication of Special Thorium Fuel Cycle edition of Nuclear Technology
- June 2016: Presentation of major Year 2 FCDP results at ANS Annual Meeting 2016
- June 2016: Presentation of interim thorium literature findings at ANS Annual Meeting 2016
- *January 2017: Completed First of Three Year 3 Fuel Cycle Data Packages
- *January 2017: Completed Second of Three Year 3 Fuel Cycle Data Packages
- *February 2017: Completed Third of Three Year 3 Fuel Cycle Data Packages
- April 2017: Presented selected Year 3 FCDP results at International High Level Radioactive Waste Management Conference 2017

- April 2017: Drafted manuscript of journal article highlighting most important FCDP findings from the entire project
- May 2017: Drafted manuscript of journal article highlighting most important thorium literature findings from the entire project
- *September 2017: Completed this final project report

Key Accomplishments and Insights

FCDPs: The team successfully completed all six of its planned fuel cycle data packages. The first FCDP was part a benchmarking exercise to make the team familiar with the FCDP development process, while the other five FCDPs represented more interesting cases with deeper levels of analysis. Some of the results were more intriguing than others; the fuel cycle options that consistently showed the most promise within the boundary of thermal-spectrum, multi-stage, thorium-based systems tended to be those that utilized heavy water reactors in some capacity. Different systems were configured to achieve operational missions such as reduced reliance on uranium resources, plutonium inventory management, and minor actinide inventory management. A manuscript for the journal *Nuclear Technology*, which highlights the most important findings of the FCDP development process, has been prepared and submitted.

Literature: The thorium literature review resulted in the completion of the Thorium Fuel Cycle Literature Report, which catalogued the insights of 1400+ thorium fuel cycle literature items in a narrative format. Some of the most important trends have been distilled in a journal manuscript, which also identifies “keystone publications” that represent the most significant findings of various subject matter categories. Various information associated with thorium fuel cycle publications has been catalogued as part of a searchable thorium literature database with accompanying publication files. A manuscript for the journal *Annals of Nuclear Energy*, which analyzes the contents of the database, reviews the most important trends for thorium literature, and identifies “keystone” publications by topic using a multi-step methodology, has been prepared and submitted.

Thorium Track and Proceedings: The first year of the project saw the successful organization execution of the Thorium Fuel Cycle Technical Track at the ANS Winter Meeting 2014, which entailed four paper sessions and one panel session. The subsequent documentation of key findings in a 12-paper (not counting a short introductory paper) special edition of the journal *Nuclear Technology* was also successful, and the special edition was publicly released in May 2016.

2. Introduction

At a glance, thorium (Th) fuel cycles (FCs) may offer particular advantages relative to those currently in commercial use. In particular, Th/U-233 FCs produce far less plutonium and minor actinides (MAs) than FCs based on U-235 or Pu-239, and Pu fuel may be combined with thorium to achieve net plutonium elimination. In spite of these potential capabilities, quantitatively assessing and comparing the benefits of the Th FC is difficult since experience, while extensive, is not consolidated. The inclusion of thorium fuel cycles in DOE-NE's ongoing development of Fuel Cycle Data Packages (FCDPs) represented a unique opportunity to comprehensively examine FC options beyond those which have traditionally been considered.

In collaboration with Oak Ridge National Laboratory (ORNL), Vanderbilt University (VU) has developed FCDPs for six thorium fuel cycle options. As pursuant to the stipulations of this project's initial workscope (FC-5.1), the fuel cycles were multi-stage and entirely in the thermal spectrum. The inclusion of thorium provides inherent Pu/MA-reducing capabilities. VU and ORNL have gathered an extensive collection of thorium fuel cycle literature and performed subsequent organization and analysis. In combination with inclusions from ORNL's extensive literature archives, VU assembled a Thorium Fuel Cycle Database of thorium literature, which facilitated not only the development of FCDPs in conjunction with this project but also any future evaluations of the thorium fuel cycle.

The pool of technical expertise applied to the project was expanded by VU and ORNL's joint organization of a Thorium Fuel Cycle Technical Track, which brought the international thorium technology status up to date, identified potential alternative candidate FCs for FCDP development, and identified key data gaps which must be resolved to support eventual implementation of commercial thorium fuel cycles. With this arsenal of information, VU developed FCDP content through the use of reactor physics and fuel cycle calculations using software packages such as SCALE and ORIGEN. The quality of this project's deliverables were assured by extensive peer review and documentation.

Project Objectives:

- Developed six fuel cycle data packages (FCDPs) for multi-stage, thermal fuel cycles which incorporate thorium, as pursuant to NEUP FY 2013 Workscope FC-5.1, over the duration of three years
- Initiated and continually developed a Thorium Fuel Cycle Database which centralizes access to thorium fuel cycle literature
- Organized and documented an International Technical Symposium on the Thorium Fuel Cycle

Each of the three major project objectives was completed, along with incremental accomplishments related to each of those topics. The subsequent chapters of this project report each discuss one of the major objectives and their associated achievements.

3. Fuel Cycle Data Package Analysis

As part of DOE-NE Fuel Cycle Option Evaluation and Screening Effort, numerous fuel cycle options were quantitatively evaluated; the results of these analyses were catalogued in a standardized template called a Fuel Cycle Data Package (FCDP). Each of the reference options considered by the Fuel Cycle Option campaign, in addition to a handful of others, has a corresponding FCDP. While the FCDPs developed prior to VU's involvement were intended to be varied and comprehensive, there were nonetheless a few areas of fuel cycle option space that were deemed to be underrepresented; universities were targeted to fill these gaps. As discussed in the Introduction, the VU-ORNL team looked at the region of fuel cycle option space that includes thorium, multiple reactor-fuel stages, and the thermal neutron energy spectrum. The scope of the project called for the completion on FCDP in Year 1, two FCDPs in Year 2, and three FCDPs in Year 3.

During the first-year, the team selected a fuel cycle option (described further in Section 3.1) that had been discussed qualitatively by thorium fuel cycle experts for decades but had not yet been analyzed at the FC level. Since this option used a relatively simple fuel recycle strategy and well-understood reactor technologies, the first year was dedicated in part to bringing the team up to speed with the FCDP development process and subsequent analysis of the resulting data. The fuel cycle option did not prove to be especially promising (high reliance on natural uranium resources and enrichment in spite of the use of fuel recycle), but the results were useful for addressing some pre-conceived notions regarding the use of thorium in limited-recycle systems (See Appendix A8), and the experience provided a framework for the subsequent analysis of other options.

Subsequent identification of fuel cycle options for analysis involved a two-step process. First, Vanderbilt and ORNL used brainstorming exercises to identify plausible fuel cycle options for analysis. Some of these options were identified prior to the project's start date, while others were identified later during the project. A subset of these was selected to discuss with the project's technical points of contact on annual basis. These annual meetings helped to select and refine the specific options that would be evaluated for the coming year of the project.

The following sections briefly describe the high-level characteristics of the fuel cycle options that were targeted for FCDP development. More detailed results are available in the "A" set of appendices.

3.1. FCDP 1 (PWR-Th/U-MOX to HTGR—RTh/RU-Carbide)

The first stage is a pressurized water reactor (PWR) with two distinct fuel types, a seed fuel and a blanket fuel. The driver fuel contains low-enriched uranium and is intended to provide high-flux regions of the core to breed U-233 in the blanket fuel, which is mostly thorium with some low-enriched uranium homogenously mixed in. After irradiation, the driver fuel is directed to interim storage and then disposal, while the blanket fuel is reprocessed for its thorium and uranium content. Much of the thorium is recycled back to the first stage, while the remainder of the thorium and all of the uranium in the blanket fuel are sent to stage 2 (minor actinides, plutonium, and fission products in the blanket fuel are sent for storage/disposal). Stage 2 uses the recycled thorium and uranium in a "deep-burn" high-temperature gas reactor (HTGR). Quantitative results and diagrams for this fuel cycle option can be found in Appendix A2.

3.2. FCDP 2 (PWR-LEU-Oxide to HWR—Th/RU/Pu-MOX)

The first stage is a pressurized water reactor (PWR) which uses low-enriched uranium (LEU) [1, 2]. After irradiation, the PWR fuel is reprocessed for its uranium (RU) and plutonium content, while the minor actinides (MAs) and fission products (FP) are sent to disposal. Stage 2 is a pressure-tube heavy water reactor (PT-HWR, or simply "HWR") which uses a heterogeneous fuel bundle composed of $(RU,Pu)O_2$ driver fuel (30 pins) and ThO_2 blanket fuel (7 pins) mixed driver-blanket fuel in 37-element CANDU-type fuel bundles [3]. While the HWR fuel bundle is heterogeneous, the HWR core is homogeneous, in that it uses one fuel bundle type. The reprocessed uranium and plutonium from Stage 1 are sent to Stage 2 for fabrication into the HWR driver fuel. The HWR blanket fuel consists of pure thorium oxide. Spent HWR fuel is not reprocessed. Quantitative results and diagrams for this fuel cycle option can be found in Appendix A3.

3.3. FCDP 3 (HWR(LEU) to MSR(Th/U3/TRU))

The first stage is a heavy water reactor (HWR) which uses low-enriched uranium oxide fuel. After irradiation, the HWR fuel is reprocessed for its uranium, plutonium, and minor actinide content (including protactinium), while the fission products are sent to disposal. Stage 2 is a molten salt reactor (MSR) which uses mixed heavy metal fluorides dissolved in a molten carrier fluoride-lithium-beryllium salt. Stage 2 has an online-reprocessing capability which recovers thorium, uranium, plutonium, and minor actinides for recycle within Stage 2. Fission products are sent to disposal. The reprocessed uranium, plutonium, and minor actinides from Stage 1 are combined with natural thorium to constitute the replacement feed material for Stage 2. Quantitative results and diagrams for this fuel cycle option can be found in Appendix A4.

3.4. FCDP 4 (HWR-Th/U3-MOX to HTGR—Th/U3-C)

The first stage is a pressure-tube heavy water reactor (PT-HWR, or simply "HWR") which uses recycled thorium and uranium-233 as well as natural thorium [1, 2] to fabricate thorium-uranium mixed-oxide (MOX) fuel. After irradiation, the used HWR fuel is reprocessed for its thorium (RTh) and uranium (U3) content, where the U3 includes all uranium isotopes in addition to U-233. All of the RTh and some of the U3 are sent to Stage 1, while any excess U3 beyond the Stage 1 input requirements is dedicated to Stage 2. Plutonium (Pu) and the minor actinides (MAs, which includes protactinium) are disposed, in addition to the disposal of fission products. Stage 2 is a high-temperature gas-cooled reactor (HTGR) which uses prismatic oxycarbide fuel containing RTh and U3, in combination with some natural thorium [3]. After irradiation, the used HTGR fuel is reprocessed for its RTh and U3 content, with these streams being re-directed to the fabrication of new Stage 2 fuel. As with Stage 1, Pu, MAs, and FPs are sent to disposal. Quantitative results and diagrams for this fuel cycle option can be found in Appendix A5.

3.5. FCDP 5 (PWR-LEU-Oxide to HWR—Th/TRU-MOX)

The first stage is a pressurized water reactor (PWR) which uses low-enriched uranium (LEU) [1, 2] from both natural and recycled sources. After irradiation, the PWR fuel is reprocessed for its uranium (RU) and transuranic (TRU) content, where the TRU includes plutonium as well as the minor actinides. The RU is re-directed to the enrichment phase for Stage 1, where it is combined with natural uranium prior to enrichment. The TRU is sent to Stage 2 for subsequent fuel fabrication.

Stage 2 is a pressure-tube heavy water reactor (PT-HWR, or simply "HWR") which uses a heterogeneous fuel bundle composed of two fuel types: a $(Th/U3/TRU)O_2$ "Type A" fuel (13 pins, designated as fuel type 2.1 in the system data sheet) and a $(Th/U3/TRU)O_2$ "Type B" fuel (24 pins, designated as fuel type 2.2 in the system data sheet) in 37-element CANDU-type fuel bundles [3]. The difference between the "Type A" and "Type B" fuel types is that the "Type A" fuel incorporates the recycled TRU from Stage 1 as well as intra-recycled Th, U-233, and TRU from recycled Type A fuel (plus a balance of natural thorium), while the Type B fuel only incorporates intra-recycle Th, U-233, and TRU from recycled Type B fuel plus the natural thorium balance. Thus, Type A fuel is considerably more concentrated in TRU than Type B fuel. While the HWR fuel bundle is heterogeneous, the HWR core is homogeneous, in that it uses one fuel bundle type. Both HWR fuel types are sent to reprocessing, with all actinides (i.e., thorium, protactinium, uranium, and TRU) being recycled for re-use in Stage 2. The fuel types are not mixed (i.e., recycled Type A fuel is only used to make additional Type A fuel and Type B fuel is only used to make additional Type B fuel).

Quantitative results and diagrams for this fuel cycle option can be found in Appendix A6.

3.6. FCDP 6 (PWR-HEU-Oxide to HWR—Th/TRU-MOX)

The first stage is a pressurized water reactor (PWR) which uses highly-enriched uranium (HEU) [1, 2] from both natural and recycled sources. After irradiation, the PWR fuel is reprocessed for its uranium (RU) and transuranic (TRU) content, where the TRU includes plutonium as well as the minor actinides. The RU is re-directed to the enrichment phase for Stage 1, where it is combined with natural uranium prior to enrichment. The TRU is sent to Stage 2 for subsequent fuel fabrication.

Stage 2 is a pressure-tube heavy water reactor (PT-HWR, or simply “HWR”) which uses a heterogeneous fuel bundle composed of two fuel types: a $(Th/U3/TRU)O_2$ “Type A” fuel (13 pins) and a $(Th/U3/TRU)O_2$ “Type B” fuel (24 pins) in 37-element CANDU-type fuel bundles [3]. The difference between the “Type A” and “Type B” fuel types is that the “Type A” fuel incorporates the recycled TRU from Stage 1 as well as intra-recycled Th, U-233, and TRU from recycled Type A fuel (plus a balance of natural thorium), while the Type B fuel only incorporates intra-recycle Th, U-233, and TRU from recycled Type B fuel (plus a balance of natural thorium. Thus, Type A fuel is considerably more concentrated in TRU than Type B fuel. While the HWR fuel bundle is heterogeneous, the HWR core is homogeneous, in that it uses one fuel bundle type. Both HWR fuel types are sent to reprocessing, with all actinides (i.e., thorium, protactinium, uranium, and TRU) being recycled for re-use in Stage 2. The fuel types are not mixed (e.g., recycled Type A fuel is only used to make additional Type A fuel).

Quantitative results and diagrams for this fuel cycle option can be found in Appendix A7.

4. Thorium Fuel Cycle Literature Analysis and Database Development

The thorium fuel cycle often faces the perception of having limited experience, thereby imposing a barrier to its implementation. While thorium fuel cycles do not have the extensive commercial-scale experience associated with the uranium fuel cycle (especially the use of uranium oxide in a once-through configuration in light- or heavy-water reactors), the abundance of major research campaigns — and the literature which has documented these campaigns — illustrate that significant knowledge concerning the use of thorium is available. Part of the reason for thorium's perceived underdevelopment is that the information is scattered among many sources and has not previously been consolidated and evaluated on a comprehensive scale.

Vanderbilt University and Oak Ridge National Laboratory (ORNL) recognized this challenge and included a thorium fuel cycle literature review task as this NEUP project. The first phase of the literature review task entailed identifying and reviewing the majority of available thorium fuel cycle literature. The second phase of the literature review task incorporated the identified literature items into an information database, which ideally can initially be used by an internal group of fuel cycle researchers and eventually be adapted to a widely accessible platform for many users.

4.1. Description of Literature Categories

To focus the discussions on thorium fuel cycle literature and to enable prospective reviewers to identify specialized areas which may be of interest to them, the identified thorium fuel cycle literature items have been divided into eleven topical categories. Many of these categories are further divided into sub-categories where logically sensible. In subsequent portions of this report, a chapter is afforded to each of these technical categories, along with a reference listing for literature items within each category. This section will briefly describe the nature of each of the categories and what types of subject matter is included within the given chapter.

Literature items in the **"Resources and Recovery"** category focus on what is conventionally known as the "front end" of the thorium fuel cycle, prior to fuel fabrication. The first sub-category is "Thorium Resources", which discusses identified natural thorium resources which have, or continue to be, potentially appealing for recovery. The other sub-category, "Thorium Recovery Processing", concerns physical and chemical processing steps to isolate nuclear-grade thorium products from sources of natural thorium. This includes mineral/ore separations, mineral extraction procedures, and advanced chemical techniques for product purification.

The **"Fuels"** category addresses a variety of topics pertaining to nuclear thorium-based fuels. The first sub-category, "Fuel Fabrication", includes developments in fuel fabrication processes, for a variety of fuel types (e.g., oxide, graphitic, metallic) and fabrication methods (e.g., pelletization, sol-gel). This includes the refabrication of recycled fuels, although this topic overlaps with the **"Reprocessing and Waste Management"** category. The next sub-category, "Unirradiated Fuel Properties", examines studies of the physical properties of different thorium-based fuels before irradiation. Representative studies include hardness tests, thermal conductivity measurements, observations of crystal structure, and tensile strength tests. The third sub-category, "Irradiated Fuel Properties", discusses thorium fuel irradiation campaigns (e.g., of a few thorium fuel pins amidst an otherwise uranium-thorium fuel core) and post-irradiation examinations of those fuels. Post-irradiation examination tests include fission gas release and standard measurements of radiation damage. The **"Fuels"** category concludes with a sub-category of "Fuel Economics", which examines the impact of fuel or fuel fabrication process selection from an economic perspective.

While physics and nuclear data are pertinent to all of the reactor chapters that follow, a number of papers and reports focus specifically on nuclear data for important radionuclides in the thorium fuel cycle from a technology-independent perspective. Such documents constitute the **"Physics and Nuclear Data"** category. Example topics include improving neutron cross section libraries for thorium-232 and uranium-233, experiments to measure particular cross sections under certain conditions, and resonance integrals. The chapter is not further divided into sub-categories.

The **"Thorium Utilization in Light Water Reactors"** category addresses experience with thorium fuels in this widely-used reactor design. Many of the reports are systems studies, although operational planning and experience is available for prototype reactors such as the Shippingport Light Water Breeder Reactor (LWBR). Most of the category is logically broken into "Pressurized Water Reactors" (PWRs) and "Boiling Water Reactors" (BWRs) sub-categories; a shorter sub-category on "Supercritical Water-Cooled Reactors" (SCWRs) is also included.

The bulk of the "**Thorium Utilization in Heavy Water Reactors"** category is dedicated to the "Pressurized Heavy Water Reactors" sub-category, covering designs such as those used in Canada and elsewhere. There have also been a variety of other designs which have featured heavy water in other contexts for thorium-based systems. These are covered in the "Solution Reactors and Heavy-Water-Moderated Reactors" sub-category, which also includes studies with the heavy-water-moderated, organic-cooled reactor design.

The **"Thorium Utilization in Liquid-Metal-Cooled Reactors"** category focuses on the use of thorium-based fuel in designs which use liquid metals, such as sodium or lead-bismuth, as a coolant. These designs are almost always associated with the fast neutron energy spectrum (with few citations of epithermal-spectrum designs). While historically not as closely associated with thorium-based fuels as other reactor types, this category has seen increased attention in recent years. The category is not further divided into sub-categories.

The **"Thorium Utilization in Molten-Salt-Cooled Reactors"** category discusses the use of thorium-based fuel systems in molten salt-cooled reactors. The first sub-category, "Liquid-Fueled Fluoride-Salt-Cooled Reactors", discusses the most extensively analyzed class of designs that uses a liquid-fueled system in the thermal spectrum in which the fissile and fertile materials are dissolved in the molten salt. The next sub-category, "Non-Traditional Liquid-Fueled Salt-Cooled Reactors", covers liquid-fueled molten-salt systems which either use chloride salts or employ the fast neutron energy spectrum (or both). The third sub-category, "Solid-Fueled Salt-Cooled Reactors", discusses reactor systems which use molten salt coolants to remove heat from solid fuels containing thorium and/or uranium-233.

The **"Thorium Utilization in Gas-Cooled Reactors"** category covers systems which employ a pressurized gas such as helium or carbon dioxide as a coolant. The first sub-category, "Block-Type-Fueled Gas Reactors", covers the majority of the literature and involves a conventional arrangement of fuel elements mostly composed of graphite (frequently of the "prismatic" variety) in a fixed core position. The next sub-category, "Pebble Bed Gas Reactors", considers designs which use a bed of spherical fuel elements, frequently in conjunction with a pneumatic approach to determine whether to recirculate a pebble to the core or remove it from circulation in the reactor. The third sub-category, “Gas-Cooled Fast Reactors”, deals with non-moderated gas-cooled systems intended to operate in the fast neutron energy spectrum.

The **“Thorium Utilization in Externally-Driven Systems”** category addresses reactor systems which achieve near-criticality by supplying neutrons through additional means other than purely nuclear fission. The chapter is divided into two sub-categories which cover the two main types of externally-driven systems, “Fusion-Fission Hybrids” and “Accelerator-Driven Systems”. Fusion-fission hybrid reactors use nuclear fusion of hydrogen isotopes (deuterium and tritium) to provide an external source of fast neutrons to drive and sustain a nuclear fission reaction and/or breed fissile material for use elsewhere; accelerator-driven systems use accelerator-based methods for neutron production (typically by spallation of heavy metal targets through high-energy proton bombardment) to achieve the same purpose.

The **“Reprocessing and Waste Management”** category includes literature on what is sometimes referred to as the “back-end” of the fuel cycle, encompassing topics of fuel reprocessing and waste management. Reprocessing topics comprise the bulk of the chapter and are contained within three separate sub-categories, “Aqueous Reprocessing Methods for Oxide and Metallic Fuels”, “Reprocessing of Graphitic Fuels”, and “Nonaqueous Reprocessing Methods”. The balance of the chapter is the “Waste Characteristics and Management” sub-category, which addresses topics such as long-term risks from disposal and decay heat.

The **“Safeguards”** category addresses nuclear material safeguards and related subjects, as pertinent to thorium fuel cycles, including non-proliferation and secure management of uranium-233 inventories. The chapter is not further divided into sub-categories.

The **“Overviews, System Studies, and Impacts”** category covers various miscellaneous topics that are not addressed in other chapters. Within this generalized category, usually the sub-categories are not closely associated with one-another and might be better viewed as a series of individual “mini-chapters”. These sub-categories include:

- “Programmatic Overviews”, summary reports for a nation or large organization which address many aspects of thorium fuel cycle efforts at a summary level
- “Comparisons or Synergies of Multiple Reactor Concepts” , papers which examine multiple reactor families, either comparatively or as part of a multi-stage fuel cycle or transition scenario
- “Fuel Cycle Economics”, including cost estimates and the financial implications of thorium use compared to alternatives
- “Environment, Health, and Safety”, including radiological impacts, chemical hazards, and other topics
- “Conference, Symposia, and Meeting Summaries” , large events which were partly or specifically devoted to thorium fuel cycles, which often include many diverse topics
- “General Science” , papers which involve isotopes from the thorium fuel and may not be particularly focused on nuclear power, but have relevant implications
- “Information Repositories” , collections and/or analyses of thorium fuel cycle literature

4.2. High-Level Trends in Thorium Literature

Figure Intro-1 and Table Intro-1, below, indicate the extent to which each thorium fuel cycle category has been studied. In general, continued fundamental research in the 1950s gave way to the first “golden age” for thorium fuel cycle research and development in the 1960s and 1970s, a period which featured several large-scale efforts spanning thorium fuel fabrication, thorium reactor deployment, and thorium/uranium-233 fuel reprocessing. The waning of interest in the

1980s and 1990s is evident from the sharp publication drop-off within many categories, with only a few major campaigns continuing and nationwide programmatic efforts being restricted to India and the German gas-cooled reactor program. It is readily apparent, though, that interest has been renewed since 2000 based on the notable increase in publications during this time across many topics. Indeed, the 2010s are currently on pace to surpass the 1970s as the decade with the most total thorium fuel cycle publications. Of course, much of the work in recent years has consisted of options studies rather than large-scale campaigns, and the rise in publications may in part be due to increased accessibility of resources in the internet era.

There are a few differences in trends between the various topical categories. Some categories, such as externally driven systems, are relatively modern concepts and have generally seen a continually increasing presence over time. Other categories, such as molten salt reactors, gas reactors, and fuels, are associated with a distinct "spike" during a period of extensive work as part of one or more major programmatic campaigns, and while interest has continued since that peak it has not yet returned to that same level of interest. Still other categories, such as Heavy Water Reactors and Physics, have remained fairly consistent and have followed the overall trend of thorium fuel cycle interest on the whole.

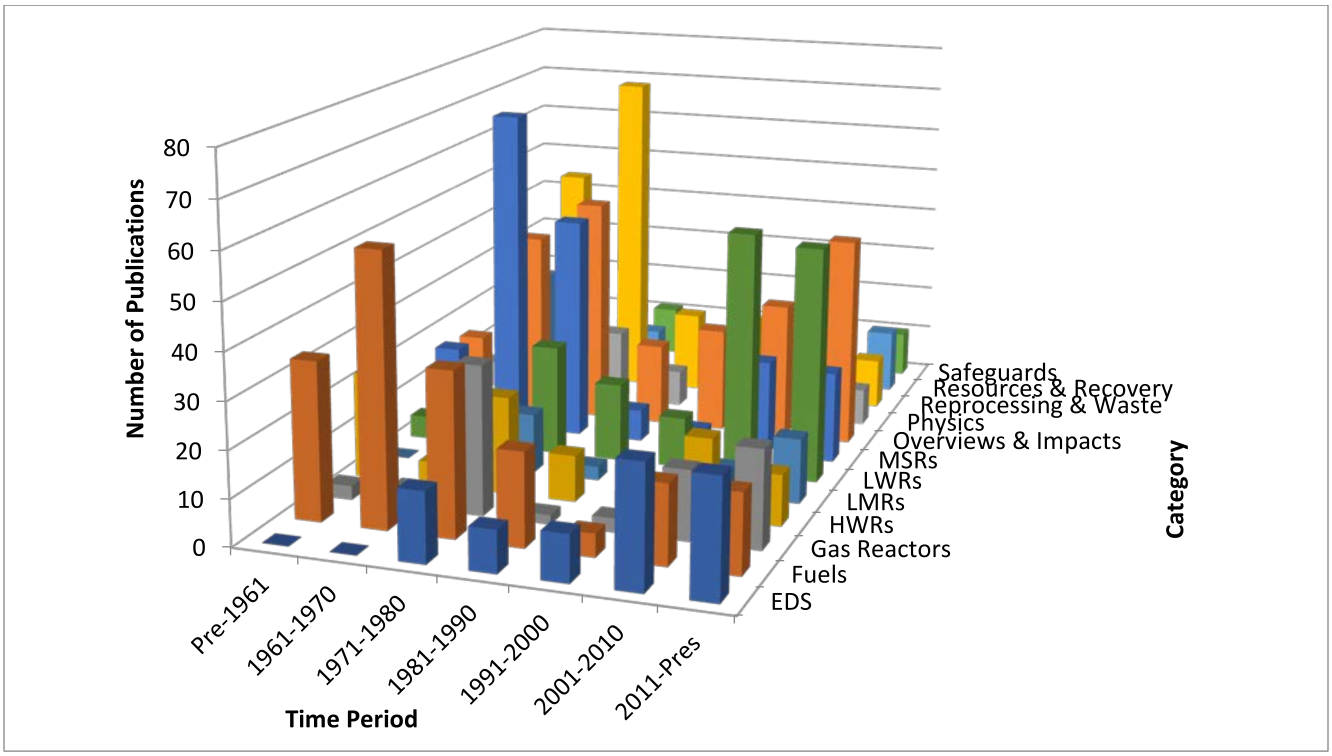

Figure 4-1, Trends in Thorium Fuel Cycle Literature by Category

TABLE 4-1, Trends in Thorium Fuel Cycle by Category (Tabular Form)

	Pre-1961	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-Present	Total by Category

EDS	0	0	15	9	10	26	25	85
Fuels	34	58	35	20	5	17	17	186
Gas Reactors	3	4	32	2	3	15	21	80
HWRs	23	5	21	10	3	17	11	90
LMRs	0	1	13	3	0	6	14	37
LWRs	5	6	24	17	11	53	51	167
MSRs	17	72	49	7	4	21	20	190
Overviews	16	41	50	18	23	30	46	224
Physics	6	8	16	8	6	5	8	57
Repro. & Waste	26	50	73	18	18	14	11	210
Resources & Recovery	21	3	9	10	4	21	14	82
Safeguards	0	0	11	1	4	13	10	39
Total By Decade	151	248	348	123	91	238	248	**1447**

EDS = externally-driven system, HWR = heavy water reactors, LMRs = liquid-metal-cooled reactors, LWRs = light water reactors, MSRs = molten salt reactors

Additional quantitative trends and extended discussions can be reviewed in a full-length manuscript that has been prepared on this subject, and is included in Appendix B1. A shorter treatment that highlights major trends in subject matter and experience can be found in Appendix B2.

5. Thorium Fuel Cycle Technical Track and Proceedings

This section primarily concerns the planning and execution of the Thorium Fuel Cycle Technical Track, which was held at the American Nuclear Society's (ANS) Winter Meeting 2014 in Anaheim, California, USA from November 9-13, 2014. The resulting publication of a special thorium fuel cycle edition of Nuclear Technology will also be discussed. In its conception, the Thorium Track was intended to synergize with the FCDP and literature database efforts by bringing together thorium experts to gain a modern, comprehensive perspective on the status of thorium fuel cycle endeavors.

Three specific objectives were outlined to the participants:

- Produce a summary of the latest information on the performance, progress and requirements of the thorium fuel cycle.
- Identify alternative thorium fuel cycles that are candidates for future FCDPs to be prepared by this project, as well as data sources for those candidate fuel cycles
- Identify key gaps in knowledge/data to assist DOE in prioritizing future R&D on thorium fuels and the associated fuel cycle.

5.1. Planning

An early decision to make was the selection of the venue for the Thorium Track. To facilitate international participation, as well as to effectively manage project resources, it was determined that the best course of action was to designate a technical track within the ANS Winter 2014 Meeting at Anaheim, CA. This conference was appealing for its large and diverse attendance as well as its high regard among many professional communities. The location near a major international airport enabled attendance by a significant number of international attendees. Furthermore, participating in an ANS conference allowed a clear publication route for the proceedings of the Thorium Track, which will be discussed in further detail later in this section.

5.1.1. Working Group

For the Thorium Track to have the greatest impact, thorium fuel cycle experts from a diverse set of backgrounds and played an essential role in the Thorium Track's overall success. Key contributors to this effort collectively constituted an international "Working Group" and played various roles, such as subject matter expertise, paper invitations, paper synthesis and organization, and chairing or co-chairing technical sessions. Initial members of this Working Group were contacted in December 2013, and additional members were added to the Working Group between that time and June 2014, when abstracts were due for the conference.

VU-ORNL coordinated the Working Group's effort by issuing detailed updates on approximately a monthly basis. Through the course of these updates and follow-up exchanges, and under the leadership direction of VU and ORNL, the Working Group was able to communicate near-term action items and requirements, outline the scope of the technical sessions and paper topics, and identify authors to invite for paper submission. When summary-abstracts were submitted to the online ANS abstract submission system, Working Group members also participated in reviewing these abstracts.

The members of the working group were:

- Steven Krahn, Vanderbilt University (Chair)

- Andrew Worrall, Oak Ridge National Laboratory (ORNL, Co-Chair)
- Raymond Wymer, ORNL-Retired (Honorary Chair)
- Blair Bromley, Canadian Nuclear Laboratories
- Allen Croff, Vanderbilt University
- Charles Forsberg, Massachusetts Institute of Technology
- Jess Gehin, Oak Ridge National Laboratory
- Julian Kelly, Thor Energy
- T.K. Kim, Argonne National Laboratory
- Andrew Sowder, Electric Power Research Institute
- Temitope Taiwo, Argonne National Laboratory
- Michael Todosow, Brookhaven National Laboratory
- Luc Van Den Durpel, AREVA
- P.K. Wattal, Bhabha Atomic Research Centre
- Timothy Ault, Vanderbilt University
- Bethany Burkhardt, Vanderbilt University

5.1.2. Publication Planning

In December 2013, under advisement of what would later evolve into the Working Group, VU and ORNL identified the ANS publication *Nuclear Technology* as the best option for documentation of the proceedings of the Thorium Track. This option was appealing since *Nuclear Technology* has broad readership in the nuclear fuel cycle arena and, more specifically, because copyright transfer would not present an issue since both the conference and the journal are operated by ANS.

After some initial communication between VU-ORNL and the editors of *Nuclear Technology*, it was determined that the best publication route would be a "special edition" of the journal comprised of about 15-25 full-length papers. These papers would primarily consist of expansions of the summary-abstracts submitted for the conference (synthesizing two or more summaries where sensible), in addition to a smaller number of additional papers for the purposes of completeness (e.g., a summary of the panel session). Gradually, this strategy evolved from a tentative plan to a highly organized effort. As authors were identified and invited to submit abstracts for the conference, they were also told to keep in mind the possibility of expanding their topics into full papers after the conference.

5.1.3. Structure and Organization

In October and November 2013, VU and ORNL engaged with appropriate section leaders at ANS to formally introduce a Thorium Fuel Cycle Technical Track into the structure of the ANS Winter Meeting 2014. It was determined that the Thorium Track would primarily be sponsored by the ANS Fuel Cycle & Waste Management Division (FCWMD); in addition, one paper session (Thorium Reactors) would eventually become co-sponsored by the Reactor Physics division. VU and ORNL communicated frequently with the FCWMD in the months leading up to the conference. Around the time of abstract submission, the Working Group used information provided by FCWMD to stimulate papers where gaps appeared to exist in the early stages of the submission process. This collaboration was helpful in ensuring a comprehensive range of papers by the time the submission period was closed.

The organization, description, and title of the individual technical sessions evolved over time, but the final session titles were:

- Thorium Fuel Cycle—Overview (Paper)

- Thorium Resources, Recovery, Fuels and Fuel Cycles (Paper)
- Thorium Reactors (Paper)
- Thorium Fuel Reprocessing and Waste Management (Paper)
- Promising Thorium Fuel Cycles, Technology Gaps, and Identification of Data Needs to Support Them (Panel)

5.2. Executing Technical Sessions

Each of the following sub-sections goes into additional detail about the constituent sections of the Thorium Track.

5.2.1. Thorium Fuel Cycle – Overview

This paper session was chaired by Andrew Worrall of Oak Ridge National Laboratory and co-chaired by Kevin Hesketh of the UK National Nuclear Laboratory (NNL). The session was intended to present top-level overviews of comprehensive national and/or organizational efforts. To this end, the topics included:

- The role and performance of thorium fuel cycles in DOE's Fuel Cycle Option Evaluation and Screening effort
- A look at the review of thorium fuel cycles being undertaken by the Nuclear Energy Agency in Europe
- A review of thorium significance's in nuclear R&D in the UK
- An overview of the active thorium fuel cycle campaign in China
- Thor Energy's Thorium Fuel Development Program in Norway

In addition to these programmatic overview papers, two other papers served as introductory papers for the sessions to follow: one introducing the Thorium Track itself, and another addressing the general characteristics associated with thorium use in nuclear reactors.

5.2.2. Thorium Resources, Recovery, Fuels, and Fuel Cycles

This paper session was chaired by Allen Croff of Vanderbilt University and co-chaired by Hongjie Xu of the Chinese Academy of Sciences. This session was dedicated to processes that are collectively referred to as the "front end" of the fuel cycle: mining, milling, refining, and fuel fabrication. This definition was expanded somewhat to also include papers pertaining to general fuel cycle issues, such as safety, regulation, and actinide inventory management.

The papers in this session covered diverse topics that spanned the similarly broad definition. Two papers presented complementary views on thorium resource recovery, looking at both rare earth element deposits and extant titanium mines as potential "by-product" recovery scenarios. Chinese advances in thorium purification technology, using advanced solvent extraction reagents and materials, constituted another paper. The thorium fuels research at Thor Energy was also presented, highlighting key programmatic steps which include using cerium as a material surrogate, incorporation of plutonium into fuel matrices, and various irradiation tests. Other papers addressed thorium from a safety and regulatory perspective (highlighting recent collaborative NUREG work between the DOE and the NRC[1]) as well as thorium's potential to eliminate transuranic elements in a light water reactor.

5.2.3. Thorium Reactors

[1] Ade, B. et al. "Safety and Regulatory Issues of the Thorium Fuel Cycle", Report NUREG/CR-7176, February 2014

This paper session was chaired by Blair Bromley of Canadian Nuclear Laboratories and co-chaired by TK Kim of Argonne National Laboratory. The papers covered almost every major reactor category, including: light water reactors, heavy water reactors, gas-cooled reactors, liquid-metal-cooled reactors, and molten-salt reactors[2]. The objectives of the systems presented were similarly variable, ranging from plutonium elimination to improved resource utilization to reactor applications in space. Collectively, these papers clarified that thorium need not be limited to a particular class of reactors and that interest in thorium-fuelled reactors remains particularly diverse.

5.2.4. Thorium Fuel Reprocessing and Waste Management

This paper session was chaired by Andrew Sowder of the Electric Power Research Institute and co-chaired by Steve Krahn of Vanderbilt University. To round out the direction established by the previous sessions, this section focused on the "back-end" processes of the fuel cycle, namely fuel reprocessing and waste management. The experiences and technical characteristics of the reprocessing of thorium fuels were addressed in separate, independent papers for oxide and graphitic fuels, noting distinct challenges for both technologies. An additional paper looked at the experiences and lessons from Oak Ridge's thorium fuel cycle facilities, with an emphasis on the Thorium Fuel Cycle Pilot Plant. Two papers focused specifically on the issue of waste characteristics of the thorium fuel cycle, with one comparing waste generation rates and the other comparing radiotoxicity. In addition to traditional "back-end" topics, this session also accommodated nuclear security topics: two papers were presented on materials attractiveness and safeguards considerations.

5.2.5. Promising Thorium Fuel Cycles, Technology Gaps, and Identification of Data Needs

The panel session was chaired by Steve Krahn of Vanderbilt University. The four panelists were:

- Øystein Asphjell, Thor Energy
- Chen Kun, Shanghai Institute of Applied Physics
- Luc Van Den Durpel, AREVA
- Andrew Worrall, Oak Ridge National Laboratory

In the preceding paper sessions, members of the audience had been issued index cards to write down questions regarding the thorium fuel cycle which would later be asked during the panel session. These index cards were also distributed at the start of the panel session to stimulate additional questions. At the onset of the panel session, the session chairs of each of the paper sessions were invited to present a one-slide summary of the content and subsequent discussions of their sessions. Following this, Mark Floyd of Canadian Nuclear Laboratories was invited to present on the Thoria Roadmap R&D project, which is exploring the potential of heavy water reactors using thorium oxide fuels to meet future energy needs in Canada. Following this, each panel member was allowed to make a short (5-10 minute) presentation on a thorium fuel cycle topic of their choice and were encouraged to identify areas which appear promising or challenging.

Following the introductory portions of the panel, a short break was held to collect additional questions from the audience and collate them with the questions that had already been collected. Accounting for some redundancy between questions, about 15 distinct questions of varying detail were posed to the panelists. Questions were matched to panel members who would be in a position to best provide an answer, but for many questions several panelists provided input on the topic. In some instances, members of the audience also contributed to the conversation. Major

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[2] A number of papers on the use of thorium in externally-driven systems such as fusion-fission hybrids were presented in an embedded topical which was executed concurrently with the Thorium Track

discussion topics included the driving factors for thorium fuel cycle development, barriers to thorium's advancement and implementation, disposal challenges, shielding complications arising from U-232, materials safeguards concerns, economic challenges, and the effective communication of accurate fuel cycle characteristics.

5.3. Special Thorium Fuel Cycle Edition of Nuclear Technology

Following the Thorium Track, VU and ORNL coordinated the authors of the leading Thorium Track presentations to expand their work in a special edition of the American Nuclear Society journal, *Nuclear Technology*. In a few instances, authors of different presentations at the Thorium Track consolidated their findings to form new combined papers. VU and ORNL continuously interfaced with both the authors and the editors of the journal to ensure a smooth manuscript development and review process, including a preliminary review of paper abstracts and the identification of subject matter experts for manuscript review. Furthermore, VU and ORNL participated in or led the authorship of seven papers, not counting an additional short introduction to the special edition. In late 2015, the constituent papers of the special edition were finalized in publication-ready form, and in May 2016 Nuclear Technology published the special thorium fuel cycle edition as the 2nd issue of their 194th volume.

Below are the 13 papers (one short introductory paper and twelve full technical papers) that comprise the special edition:

- Krahn, S. and Worrall, A. "The Reemergence of the Thorium Fuel Cycle: A Special Issue of Nuclear Technology", pp. iii-iv (Introductory Paper, VU-led, ORNL co-authored)
- Taiwo, T., Kim, T., and Wigeland, R. "Thorium Fuel Cycle Option Screening in the United States", pp. 127-135
- Ault, T., Van Gosen, B., Krahn, S., and Croff, A. "Natural Thorium Resources and Recovery: Options and Impacts", pp. 136-151 (VU-led)
- Gehin, J. and Powers, J. "Liquid Fuel Molten Salt Reactors for Thorium Utilization", pp. 152-161 (ORNL-led)
- Ade, B., Worrall, A., Powers, J., and Bowman, S. "Analysis of Key Safety Metrics of Thorium Utilization in LWRs", pp. 162-177 (ORNL-led)
- Golesorkhi, S., Bromley, B., and Kaye, M. "Simulations of a Pressure-Tube Heavy Water Reactor Operating on Near-Breeding Thorium Fuel Cycles", pp. 178-191
- Bromley, B. "Multiregion Annular Heterogeneous Core Concepts for Plutonium-Thorium Fuels in Pressure-Tube Heavy Water Reactors", pp. 192-203
- Andrews, N., Shirvan, K., Pilat, E., and Kazimi, M. "Steady State and Accident Transient Analysis Burning Weapons-Grade Plutonium in Thorium and Uranium with Silicon Carbide Cladding", pp. 204-216
- You, W. and Hong, S. "A Core Physics Study of Advanced Sodium-Cooled TRU Burners with Thorium- and Uranium-Based Metallic Fuels", pp. 217-232
- Brown, N., Powers, J., Todosow, M., Fratoni, M., Ludewig, H., Sunny, E., Raitses, G., and Aronson, A. "Thorium Fuel Cycles with Externally Driven Systems", pp. 233-251 (ORNL Co-authored)
- Croff, A., Collins, E., Del Cul, G., Wymer, R., Krichinsky, A., Spencer, B., and Patton, B. "ORNL Experience and Perspectives Related to Processing of Thorium and 233U for Nuclear Fuel", pp. 252-270 (VU-led, ORNL co-authored)
- Croff, A. and Krahn, S. "Comparative Assessment of Thorium Fuel Cycle Radiotoxicity", pp. 271-280 (VU-led)
- Worrall, L., Worrall, A., Flanagan, G., Croft, S., Krichinsky, A., Pickett, C., McElroy, R., Cleveland, S., Kovacic, D., Whitaker, J., and White-Horton, J. "Safeguards Considerations for Thorium Fuel Cycles", pp. 281-293 (ORNL-led)

The introductory paper to the special edition is included as Appendix C2.

6. Conclusions

This project has used three major components (FCDP development, literature review and database development, and technical track/publication) to advance the state of knowledge on the thorium fuel cycle.

With regards to the study of fuel cycle options, six FCDPs have been prepared and will be available to the public as part of the Fuel Cycle Option Catalog (and are also included in the "A" Appendices of this report). The fuel cycle options span a variety of reactor technologies, fuel cycle missions, and recycle strategies, inherently demonstrating the flexibility of thorium as a nuclear energy option. Some options were more successful than others at achieving their intended mission and at being attractive on the whole. Generally, the more attractive options featured the use of heavy water reactors. The rationale for this conclusion and the corresponding results are discussed comprehensively in Appendix A1. Collectively, the results have shown that for certain operational missions, multi-stage, thermal-spectrum thorium fuel cycles have the potential to offer capabilities that may warrant in conjunction with or as an alternative to uranium-plutonium-based counterparts.

The literature review coalesced the experience of eight decades into several consolidated deliverables, namely a thorium literature report, a thorium literature database, a journal manuscript that describes the key takeaways of the much larger literature report and database. The thorium fuel cycle publications span many nations, projects, time periods, objectives, technologies, and motivations. The number of publications related to thorium over time clearly reflects the change in overall interest, reaching a distinct peak during thorium's "golden age" of the 1960s and 1970s, followed by a sharp decline in the 1980s and 1990s as other objectives took precedent, followed more recently by a 21st century revival of interest, especially from academic institutions. For certain topics within the thorium fuel cycle, there are more specific conclusions. The journal manuscript (See Appendix B1) is a useful guide for reviewing these more detailed conclusions and is intended to be an ideal starting point for future thorium researchers in general.

The Thorium Track that was organized as part of the 2014 American Nuclear Society Winter Meeting in Anaheim, CA brought together many of the world's current leading thorium experts; in contrast to other thorium-oriented conferences in recent years, the Thorium Track sought to discuss thorium objectively without the intended purpose of advocacy. The proceedings of that conference were useful in capturing the state of the art on thorium; furthermore, the key findings of the Thorium Track were captured in a special edition of the American Nuclear Society journal *Nuclear Technology* (Vol. 194, Issue 2, May 2016). About half of the constituent papers were related to the proposed use of thorium fuels in a variety of reactor and nuclear fission systems (LWRs, HWRs, MSRs, SFRs, externally-driven systems), while the remaining papers covered other fuel cycle topics such as resources, reprocessing, waste management, safeguards, and overall fuel cycle analysis.

Certain aspects of this project would benefit from future attention. This project considered a specific range of fuel cycle option space (multi-stage, thermal spectrum); however, many other thorium-based fuel cycle options fall outside of these constraints and may also prove to be of interest. Furthermore, of the fuel cycles that have been studied by this project and are judged to be of further interest, more detailed analyses of reactor safety and/or thermal hydraulics would complement the relatively simplified analyses that were conducted to identify basic fuel cycle properties during this project. The body of thorium fuel cycle literature is constantly evolving, with the rate of new publications as high as it has ever been. The database most comprehensively accounts for literature up to 2015 (with a handful of 2016 publications), and new research projects may shift the way that thorium fuel cycles are understood. Future projects may wish to pursue the long-term maintenance and updating of the literature collection and correspondingly the database as well. Future installments of the Thorium Track will ensure that a level-headed, comprehensive dialogue on thorium will continue to complement and document future thorium research efforts.

FCDP Appendices ("A")

A1 – Draft Manuscript on FCDP Highlights ("Applications for Thorium in Multi-Stage Fuel Cycles with Heavy Water Reactors")

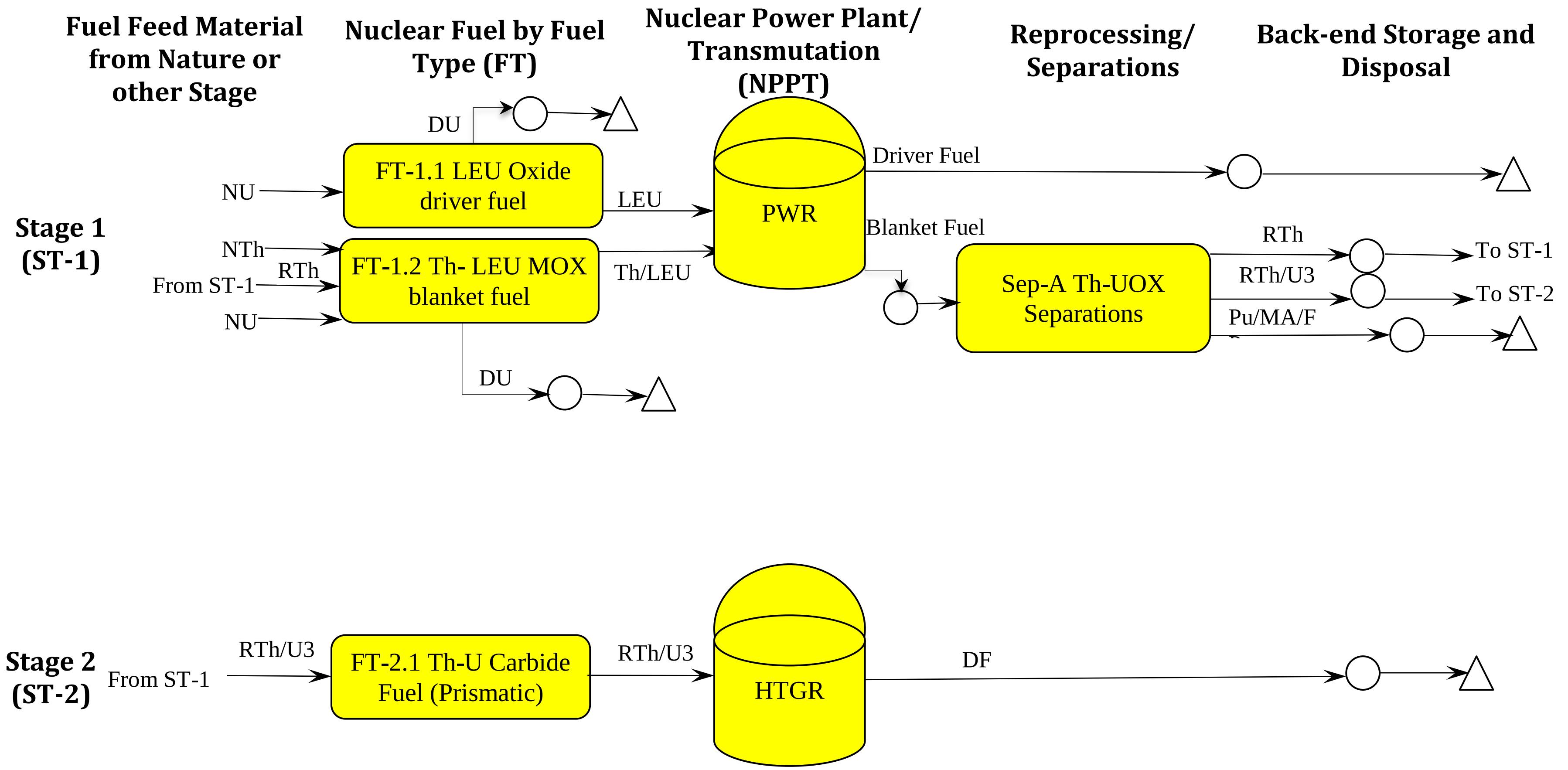
This manuscript has been submitted to *Nuclear Technology* for review at the time of this writing. Readers are invited to check the American Nuclear Society's website for Nuclear Technology or to contact Steven Krahn at (steve.krahn@vanderbilt.edu) for more information.

A2 – FCDP 1 System Datasheet and Supporting Information

Summary Description

Fuel Cycle Option No.	TBD	**Roadmap Strategy**	Modified Open	**Recycle Strategy**	Limited Recycle
Fuel Cycle Option Title	PWR-Th/U-MOX to HTGR—RTh/RU-Carbide				
Revision number	**Revision remarks**				
Rev. 0.0 Rev. 0.1 Rev. 0.2	Initial Revision Revised due to changes of references and FCDP template version (rev. 0.1) Template Revision				
High-level Objective(s)	1) Produce electricity 2) Provide or enhance ability to use natural resources 3) Can utilize existing thermal reactor infrastructure 4) Provide input as needed (new proposed HLO)				
No. of Stages 2	**Stage Description**				
Stage 1 UOX fuel (driver) Th-U MOX fuel (blanket) PWR	LEU oxide driver fuel and Th-LEU MOX blanket fuel is irradiated in PWR. The driver fuel burnup is 115 GWd/MTIHM, and the blanket fuel burnup is 75 GWd/MTIHM. Discharged blanket is stored and then reprocessed. The driver fuel is replaced at twice the frequency of the blanket fuel. Recycled uranium (RU) recovered from the blanket is sent to Stage 2. 80% of recycled thorium recovered from the blanket is sent to Stage 1, and the remaining 20% is sent to Stage 2. The driver fuel, and the fission products (FPs) and actinides other than thorium and uranium in the blanket fuel, are stored and then sent to a disposal site.				
Stage 2 Th-U Carbide fuel HTGR	RTh and RU from Stage 1 are used to make mixed (thorium/uranium) TRISO fuel particles which are used in prismatic graphite fuel. The RTh/RU oxycarbide fuel is irradiated to a burnup of 100 GWd/Mt IHM in HTGRs. Discharged fuel is stored and then sent to a disposal site.				
Prepared by	Timothy Ault (VU)	**Date**	12-11-14		
Internally Reviewed by	Andrew Worrall (ORNL)	**Approval Date**	TBD		

Externally Reviewed by	TK Kim (ANL)	**Approval Date**	TBD
Accepted by	FCDP coordinator	**Acceptance Date**	TBD



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium DF = Discharged Fuel PWR = Pressurized Water Reactor △ = Nuclear Waste Disposal

DU = Depleted Uranium FP = Fission Products HTGR = High-Temperature Gas Reactor ○ = Nuclear Material Storage

LEU = Low-enriched Uranium RTh = Recovered Thorium UOX = Uranium Oxide → = Nuclear Material Transport

High Level Parameter Data

Technology category	Parameter	Stage Number 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	PWR	HTGR		
	Core Configuration	PWR with UOX Driver, Th-U MOX blanket	HTGR with Th-U Oxycarbide Prismatic Fuel		
	Core Thermal Power, MWth	3000	3000		
	Net Thermal Efficiency, %	33	33		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	49	100		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	86.6	13.4		
	Reference(s)	1, 2, 3	4		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL may be provided at a later date

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	1.2	2.1		
Nuclear Fuel	Fuel Technology Identifier		PWR-UOX	PWR–MOX	HTGR-Carbide		
	Purpose		Driver	Blanket	Driver		
	Chemical Form		Oxide	Oxide	Oxycarbide		
	Physical Form		Pin Bundle – Annular	Pin Bundle – Ductless	Prismatic Block		
	Average Discharge Burnup, GWd/t		115	75	100		
	Fuel Composition	Initial Nuclear Material(s)	LEU	LEU/Th	RTh/RU		
		(U-235+ U-233)/Total U, %	19.9	12.2	10.3		
		Th/Total HM, %	0	85.9	55.0		
		TRU/Total HM, %	0	0	0		
	Non-fissionable Target materials		n.a.	n.a.	n.a.		
	Non-fissionable Target Charge Rate, kg/GWe-yr		n.a.	n.a.	n.a.		
	Non-fissionable Target Transmutation Fraction, %		n.a.	n.a.	n.a.		
	Fabrication Losses, %		0.1	0.1	0.1		
	Separation Process(es) Used as Source		n.a.	A	A		
	Enrichment Tailing, %		0.25	0.25	n.a.		
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	1.0	1.0		
	Fuel Residence Time in Reactor, EFPY		4	8	2.738		
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	5.0 for All	5.0 for All		
	Technology Readiness Level (TRL)*		TBD	TBD	TBD		
	Brief Justification of TRL:		TBD	TBD	TBD		
	Reference(s)		1, 2, 3	1, 2, 3	4		

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	Parameter	Reprocessing/Separation Processes				
		A				
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD				
	Separation	RTh, RTh/U3, Pu/MA/FP				
	Fuel Type Used as Source	1.2				
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99.9% for Th, U. All others (0.1% Th/U and 100% FP, Pu, MA) are treated as waste				
	Technology Readiness Level (TRL)**	TBD				
	Brief Justification of TRL:	TBD				
	Reference(s)	1				

Note: 1) Additional information included in the Material Flow Diagram.
2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data - Elements

Stage		1			2						Sum b)
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sec**	
Electricity, GWe-yr		86.6			13.4						100
Feed or product of nuclear materials (metric ton) a)											
Natural resource	NU	-19132.2									-19132.2
	Th	-105.4									-105.4
Products from fuel or NPPT technology	DU	+18.664.1									+18,664.1
	Th	+466.0	-466.0		+90.3	-90.3					+0.0
	U3				+73.9	-73.9					+0.0
	LEU	+467.6	-467.6								+0.0
	DF		+933.7	-542.5		+164.2					+555.4
Products from Rep/Sep technology	U3			+73.9	-73.9						+0.0
	RTh	-361.5		+451.9	-90.4						+0.0
	TRU (in. Pu)			+2.2							+1.6
	FP			+13.9							+9.4
Loss		+0.9	+0.0	+0.5	+0.2	+0.0					+1.6
References		1, 2, 3			4						

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Mass Flow Data – Fuel Type

Stage		1			2						Sum [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sec**	
Electricity, GWe-yr		86.6			13.4						100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU	-19132.2									-19132.2
	Th	-105.4									-105.4
Products from fuel or NPPT technology	DU	+18,664.1									+18,664.1
	LEU-Seed	+391.2	-391.2								+0.0
	LEU-Blanket	+76.4	-76.4								+0.0
	Th-Blanket	+466.0	-466.0								+0.0
	U3				+73.9	-73.9					+0.0
	RTh				+90.3	-90.3					+0.0
	DF		+933.7	-542.5		+164.2					+555.4
Products from Rep/Sep technology	U3			+73.9	-73.9						+0.0
	RTh	-361.5		+451.9	-90.4						+0.0
	TRU (in. Pu)			+2.2							+1.6
	FP			+13.9							+9.4
Loss		+0.9	+0.0	+0.5	+0.2	+0.0					+1.6
References		1, 2, 3			4						

c) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

d) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

References

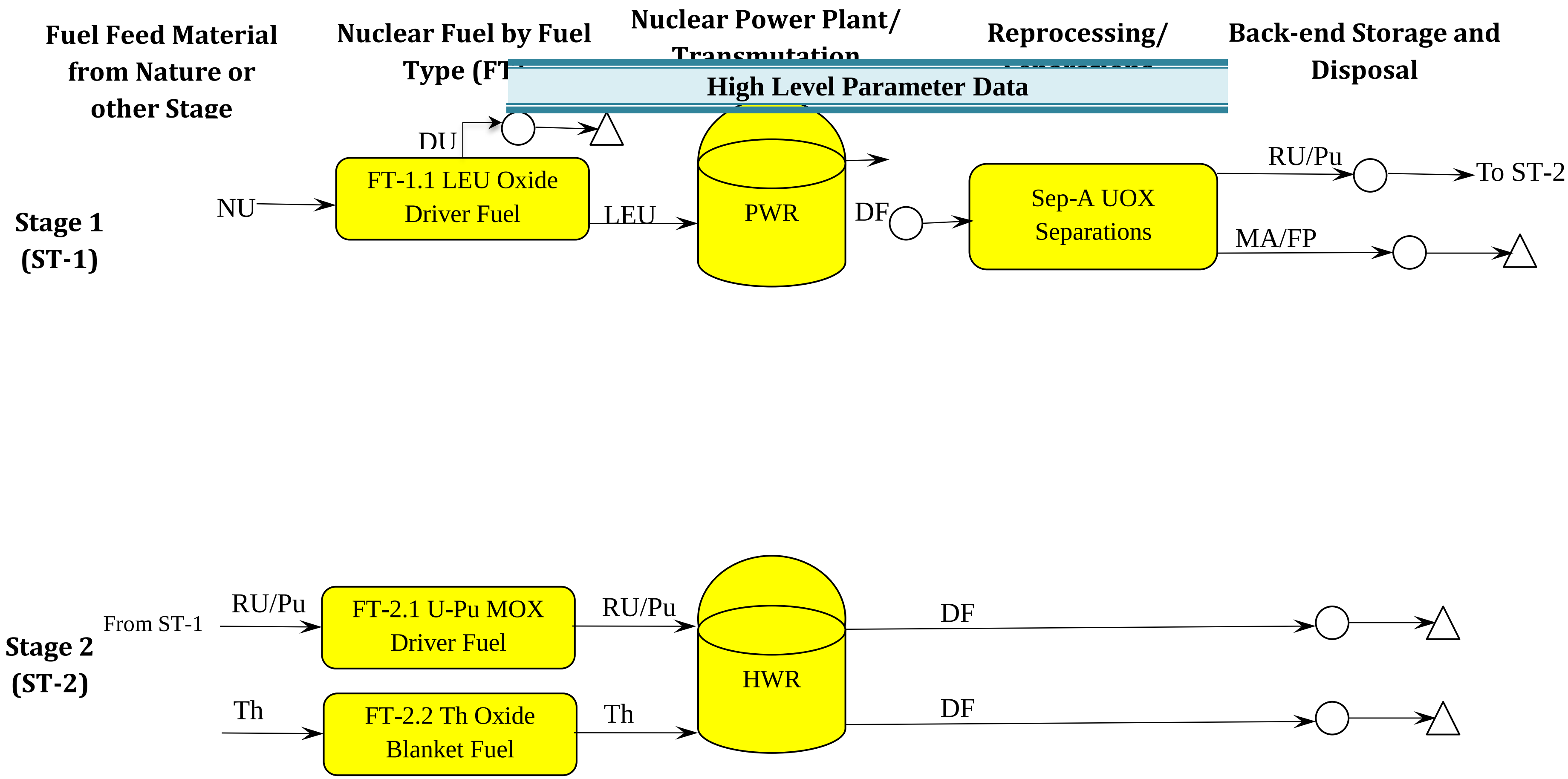
Reference	Distribution Restrictions
1. A. Galperin, M. Todosow, A. Morozov, N. Ponomarev-Stepnoi, M. Kazimi, A. Radkowsky, S. Grae. "A Thorium-Based Seed-Blanket Fuel Assembly Concept to Enhance PWR Proliferation Resistance", Proceedings of the International Conference on Future Nuclear Systems – Global '99, August 29 – September 3, Jackson Hole, Wyoming, 1999	None
2. G. Raitses, M. Todosow, A. Galperin, "Non-Proliferative, Thorium-Based, Core and Fuel Cycle for Pressurized Water Reactors", Proceeding of the 17th International Conference on Nuclear Engineering, Upton, NY, 2009, Revision, April 2012	None
3. M. Todosow, M. Kazimi. "Optimization of Heterogeneous Utilization of Thorium in PWRs to Enhance Proliferation Resistance and Reduce Waste", Report BNL-73152-2004, 2004	None
4. J. Bess, N. Fujimoto. "Evaluation of the Start-up Core Physics Tests at Japan's High Temperature Engineering Test Reactor (Fully-Loaded Core), INL/EXT-08-14767, Revision 0, March 2009	None

Note: If possible, reference with distribution limitations should be avoided.

A3 – FCDP 2 System Datasheet and Supplementary Information

Summary Description

Fuel Cycle Option No.	TBD (EG-17)	**Roadmap Strategy**	Modified Open	**Recycle Strategy**	Limited Recycle
Fuel Cycle Option Title	PWR-LEU-Oxide to HWR—Th/RU/Pu-MOX				
Revision number	**Revision remarks**				
Rev. 0.0 Rev. 0.1	Initial Revision Switched Template Version to Rev 0.4 and Addressed Multiple Internal Reviewer Comments from ORNL				
High-level Objective(s)	5) Produce electricity 6) Provide or enhance ability to use natural resources 7) Can utilize existing thermal reactor infrastructure 8) Reprocess uranium and plutonium while avoiding thorium fuel processing				
No. of Stages	2	**Stage Description**			
Stage 1 UOX fuel (driver) PWR	LEU oxide driver fuel is irradiated in a PWR. The driver fuel is enriched to 2.5% and the burnup is 30 GWd/MTIHM. Discharged fuel is stored and then reprocessed. Both recycled uranium (RU) and plutonium (Pu) are recovered and sent to Stage 2. The fission products (FPs) and other actinides are stored and then sent to a disposal site.				
Stage 2 RU-Pu MOX fuel (driver) ThOX fuel (blanket) HWR	RU and Pu from Stage 1 are used to make mixed (uranium/plutonium) oxide (MOX) driver fuel. Natural thorium is used as the blanket fuel. The combined burnup of the two fuels is 22.5 GWd/MTIHM. Discharged fuel is stored and then sent to a disposal site.				
Prepared by	Timothy Ault (VU)	**Date**	10-23-15		
Internally Reviewed by	Eva Sunny/ Andrew Worrall (ORNL)	**Approval Date**	1-29-16		
Externally Reviewed by	TK Kim (ANL)	**Approval Date**	TBD		
Accepted by	FCDP coordinator	**Acceptance Date**	TBD		



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium DF = Discharged Fuel PWR = Pressurized Water Reactor = Nuclear Waste Disposal

DU = Depleted Uranium FP = Fission Products HWR = Heavy Water Reactor = Nuclear Material Storage

LEU = Low-enriched Uranium RTh = Recovered Thorium UOX = Uranium Oxide = Nuclear Material Transport

Technology category	**Parameter**	**Stage Number** 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	PWR	HWR		
	Core Configuration	PWR with UOX Driver Fuel	HWR with RU/Pu Oxide Driver Fuel, ThOx Blanket Fuel		
	Core Thermal Power, MWth	3000	3000		
	Net Thermal Efficiency, %	33	33		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	40	30		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	50.1	49.9		
	Reference(s)	1, 2	3, 4		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	2.1	2.2		
Nuclear Fuel	Fuel Technology Identifier		PWR-UOX	HWR–MOX	HWR-ThOX		
	Purpose		Driver	Driver	Blanket		
	Chemical Form		Oxide	Oxide	Oxide		
	Physical Form		Pin Bundle – Ductless	Pin Bundle – Ductless	Pin Bundle – Ductless		
	Average Discharge Burnup, GWd/t		30	26.3	6.4		
				22.5 (combined)			
	Fuel Composition	Initial Nuclear Material(s)	LEU	RU/Pu	Th		
		(U-235+ U-233)/Total U, %	2.5	0.6	n.a.		
		Th/Total HM, %	0	0	100		
		TRU/Total HM, %	0	1.0	0		
	Non-fissionable Target materials		n.a.	n.a.	n.a.		
	Non-fissionable Target Charge Rate, kg/GWe-yr		n.a.	n.a.	n.a.		
	Non-fissionable Target Transmutation Fraction, %		n.a.	n.a.	n.a.		
	Fabrication Losses, %		0.2	0.2	0.2		
	Separation Process(es) Used as Source		n.a.	A	n.a.		
	Enrichment Tailing, %		0.25	n/a	n.a.		
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	1.0	1.0		
	Fuel Residence Time in Reactor, EFPY		2.05	2.05	2.05		
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	5.0 for All	5.0 for All		
	Technology Readiness Level (TRL)*		TBD	TBD	TBD		
	Brief Justification of TRL:		TBD	TBD	TBD		
	Reference(s)		1, 2	3	3, 4		

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	Parameter	Reprocessing/Separation Processes				
		A				
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD				
	Separation	Ru/Pu, MA/FP				
	Fuel Type Used as Source	1.1				
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99% for U, Pu. All others (1% U/Pu and 100% FP, MA) are treated as waste				
	Technology Readiness Level (TRL)**	TBD				
	Brief Justification of TRL:	TBD				
	Reference(s)	1, 2				

Note: 1) Additional information included in the Material Flow Diagram.
2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data

Stage		1			2						Sum [b]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sec**	
Electricity, GWe-yr		53.1			46.9						100
Feed or product of nuclear materials (metric ton) [a]											
Natural resource	NU	-10,787.0									-10,787.0
	Th				-481.5						-481.5
Products from fuel or NPPT technology	DU	+8,629.6									+8,629.6
	LEU	+2,153.1	-2,153.1		+2,039.9	-2,039.9					+0.0
	Th				+480.5	-480.5					+0.0
	Pu				+19.8	-19.8					+0.0
	DF		+2,153.1	-2,153.1		+2,540.2					+2,540.2
Products from Rep/Sep technology	RU			+2,044.0	-2,044.0						+0.0
	Pu			+19.8	-19.8						+0.0
	MA			+1.7							+1.7
	FP			+66.8							+66.8
Loss		+4.3	+0.0	+20.8	+5.1	+0.0					+30.2
References		1, 2			3, 4						

e) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

f) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

References

Reference	Distribution Restrictions
5. DeHart, M. "SCALE-4 Analysis of Pressurized Water Reactor Critical Configurations: Volume 1- Summary", Oak Ridge National Laboratory Report ORNL/TM-12294/V1, 1995	None
6. Cerne, S., Hermann, O., and Westfall, P. "Reactivity and Isotopic Composition of Spent PWR Fuel as a Function of Initial Enrichment, Burnup, and Cooling Time", Oak Ridge National Laboratory Report ORNL/CSD/TM-244, 1987	None
7. Chen M., Zhang Z., Meng Z., Cottrell, C., and Kuran, S. "CANDU Flexible and Economical Fuel Technology in China", Pacific Basin Nuclear Conference 2014, Vancouver, BC, Canada, August 24-28, 2014	None
8. Ellis, R. "Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program", Transactions of the American Nuclear Society, Vol. 97, 2007	None

Note: If possible, reference with distribution limitations should be avoided.

For the Ellis paper, the FCDP actually relied on unpublished data that supported that publication, rather than information presented in the publication itself. However, this is the closest publicly available document to the actual methodology that was used.

A4 – FCDP 3 System Datasheet and Supplementary Information

Summary Description

<table>
<tr><td>Fuel Cycle Option No.</td><td colspan="2">TBD (EG-18)</td><td>Roadmap Strategy</td><td>Modified Open</td><td>Recycle Strategy</td><td>Limited Recycle</td></tr>
<tr><td>Fuel Cycle Option Title</td><td colspan="6">HWR(LEU) to MSR(Th/U3/TRU) with limited recycle</td></tr>
<tr><td>Revision number</td><td colspan="6">Revision remarks</td></tr>
<tr><td>Rev. 0.0
Rev. 0.1</td><td colspan="6">Initial Revision
Switched Template Version to Rev 0.4 and Addressed Multiple Internal Reviewer Comments from ORNL</td></tr>
<tr><td>High-level Objective(s)</td><td colspan="6">9) Produce electricity
10) Provide or enhance ability to use natural resources
11) Manage waste disposal by partitioning and/or transmuting actinide isotopes</td></tr>
<tr><td>No. of Stages | 2</td><td colspan="6">Stage Description</td></tr>
<tr><td>Stage 1
UOX fuel (driver)
HWR</td><td colspan="6">LEU oxide driver fuel is irradiated in a HWR. The LEU driver fuel is enriched to 3.0% and the burnup in the HWR is 7.5 GWd/MTIHM. Discharged HWR fuel is stored and then reprocessed. Recycled uranium (RU), plutonium (Pu), and minor actinides (MAs, including protactinium) are recovered and sent to Stage 2. The fission products (FPs) are stored and then sent to a disposal site.</td></tr>
<tr><td>Stage 2
RTh/RU/Pu/MA-F MSR</td><td colspan="6">RU, Pu, and MAs from Stage 1 and U3, Pu, MAs, and Th intra-recycled from Stage 2 are combined with natural thorium to make a mixed-actinide molten fluoride fuel salt. Most actinides are recycled within Stage 2, but 10.6% of the salt is discarded annually. Separated FPs are stored and then sent to a disposal site.</td></tr>
<tr><td>Prepared by</td><td colspan="2">Timothy Ault (VU)</td><td colspan="2">Date</td><td colspan="2">11-30-15</td></tr>
<tr><td>Internally Reviewed by</td><td colspan="2">Jeff Powers and Andrew Worrall (ORNL)</td><td colspan="2">Approval Date</td><td colspan="2">1-29-16</td></tr>
<tr><td>Externally Reviewed by</td><td colspan="2">TK Kim (ANL)</td><td colspan="2">Approval Date</td><td colspan="2">TBD</td></tr>
<tr><td>Accepted by</td><td colspan="2">FCDP coordinator</td><td colspan="2">Acceptance Date</td><td colspan="2">TBD</td></tr>
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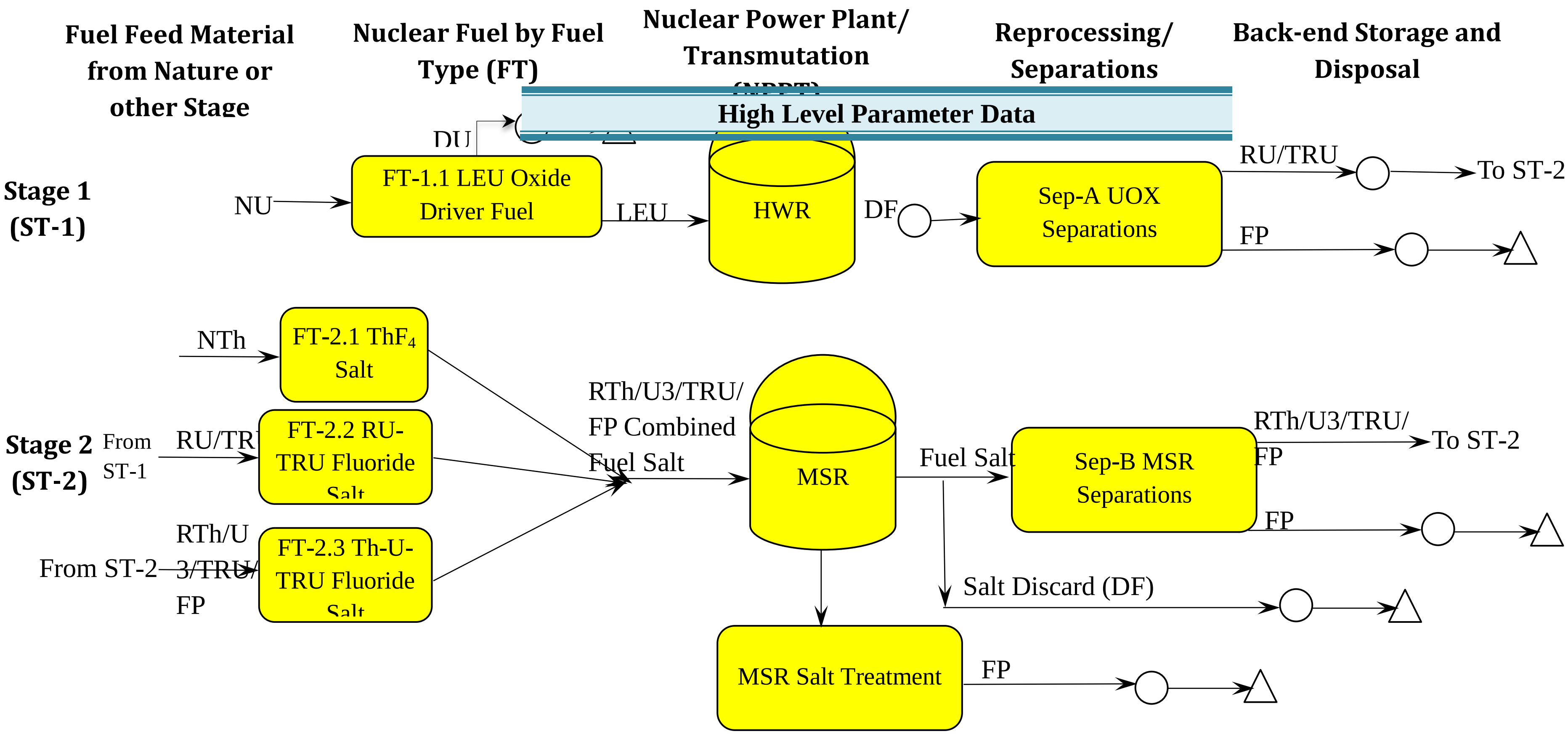
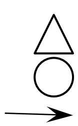


Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
DF = Discharged Fuel
FP = Fission Products
RTh = Recovered Thorium
HWR = Heavy Water Reactor
MSR = Molten Salt Reactor
UOX = Uranium Oxide



= Nuclear Waste Disposal
= Nuclear Material Storage
= Nuclear Material Transport

Technology category	Parameter	Stage Number 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	HWR	MSR		
	Core Configuration	HWR with UOX Driver	MSR with Th-U-Pu-MA Molten Fluoride Fuel		
	Core Thermal Power, MWth	3000	2250		
	Net Thermal Efficiency, %	33	44.4		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	32.5	49.5		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	2.62	97.38		
	Reference(s)	1	2-5		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	2.1	2.2	2.3	
Nuclear Fuel	Fuel Technology Identifier		HWR-UOX	MSR-Fluoride	MSR-Fluoride	MSR-Fluoride	
	Purpose		Driver	Driver	Driver	Driver	
	Chemical Form		Oxide	Fluoride	Fluoride	Fluoride	
	Physical Form		Pin Bundle – Ductless	Fluid – Molten Salt	Fluid – Molten Salt	Fluid – Molten Salt	
	Average Discharge Burnup, GWd/t		7.5	n/a	n/a	n/a	
	Fuel Composition	Initial Nuclear Material(s)	LEU	Th	U-TRU	Th-U-TRU	
		(U-235+ U-233)/Total U, %	3.0	0.0	2.58	4.39	
		Th/Total HM, %	0	100.0	0.0	49.6	
		TRU/Total HM, %	0	0.0	0.15	0.51	
	Non-fissionable Target materials		n/a	n/a	n/a	n/a	
	Non-fissionable Target Charge Rate, kg/GWe-yr		n/a	n/a	n/a	n/a	
	Non-fissionable Target Transmutation Fraction, %		n/a	n/a	n/a	n/a	
	Fabrication Losses, %		0.2	0.2	0.2	<0.01	
	Separation Process(es) Used as Source		n/a	n/a	A	B	
	Enrichment Tailing, %		0.25	n/a	n/a	n/a	
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	0.0	0.0	0.0	
	Fuel Residence Time in Reactor, EFPY		0.63	9.41	9.41	9.41	
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	0.0 for fabrication, 5.0 for Disposal	0.0 for fabrication, 5.0 for Disposal	0.0 for fabrication, 5.0 for Disposal	
	Technology Readiness Level (TRL)*		TBD	TBD	TBD	TBD	
	Brief Justification of TRL:		TBD	TBD	TBD	TBD	
	Reference(s)		1	2-5	2-5	2-5	

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	Parameter	Reprocessing/Separation Processes				
		A	B			
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD	TBD			
	Separation	RU/TRU, FP	Th/U3/TRU/FP, FP			
	Fuel Type Used as Source	1.1	2.1, 2.2, 2.3			
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99% for U, Pu. All others (1% U/Pu and 100% FP, MA) are treated as waste	Recovery of 100% for non-discarded Th, U, TRU. FPs treated and sent to waste with efficiencies according to reference 2			
	Technology Readiness Level (TRL)**	TBD	TBD			
	Brief Justification of TRL:	TBD	TBD			
	Reference(s)	1	2, 3			

Note: 1) Additional information included in the Material Flow Diagram.
2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data

Stage		1			2						Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sec	
Electricity, GWe-yr		1.92			98.08						100
Feed or product of nuclear materials (metric ton) a)											
Natural resource	NU	-1,908.4									-1,908.4
	Th				-307.4						-307.4
Products from fuel or NPPT technology	DU	+1,596.1									+1,596.1
	LEU	+311.7	-311.7								+0.0
	U d)				+300,444.7	-300,444.7					+0.0
	Th				+299,125.0	-299,125.0					+0.0
	Pu				+2,989.6	-2,989.6					+0.0
	MA				+157.6	-157.6					+0.0
	FP				+11,980.4	-11,980.4					+0.0
	DF e)		+311.7	-311.7		+614,697.3	-614,123.2				+574.1
Products from Rep/Sep technology	RU or U3 d)			+306.9	-300,444.7		+300,137.9				+0.0
	Th				-298,817.0		+298,816.5				+0.0
	Pu			+0.5	-2,989.6		+2989.1				+0.0
	MA			+0.0	-157.6		+157.6				+0.0
	FP			+1.1	-11,980.4		+12,019.9				+40.6
Loss		+0.6		+3.1	+1.2		c)				+4.9
References		1			2-5						

g) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
h) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
i) For MSBR proposed separations, U-233 loss was demonstrated to be extremely low. Since MSR "fuel fab" and separations are integrated, losses are only shown under fuel fabrication.
j) U and U3 in these rows are actually the sum of U and Pa; this is approximated in this manner due to the fact that Pa directly decays to U. In addition, U3 is not high quality U-233, but rather simply designates that the uranium is recovered for thorium fuels; the fissile content of the U is noted elsewhere.
k) The "Sum" for DF includes two separate waste streams: directly discarded fuel (526.2 MT) and FP from salt treatment within the NPPT stage (47.9 MT).

References

Reference	Distribution Restrictions
9. Ellis, R. "Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program", Transactions of the American Nuclear Society, Vol. 97, 2007	None
10. Powers, J., Harrison, T., and Gehin, J. "A New Approach for Modeling and Analysis of Molten Salt Reactors Using SCALE", International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2013), Sun Valley, ID, USA, May 5-9, 2013	None
11. Powers, J., Gehin, J., Worrall, A., Harrison, J., and Sunny, E. "An Inventory Analysis of Thermal-Spectrum Thorium-Fueled Molten Salt Reactor Concepts", PHYSOR 2014, Kyoto, Japan, Sep. 28 – Oct. 3, 2014	None
12. Robertson, R. "Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor", Oak Ridge National Laboratory Report ORNL-4541, 1971	None
13. Marsden, B. "Nuclear Graphite of High Temperature Reactors", Section of International Atomic Energy Agency's "Gas Turbine Power Conversion Systems for Modular HTGRs", IAEA Report IAEA-TECDOC-1238, 2001, pp. 177-192	None

Note: If possible, reference with distribution limitations should be avoided.

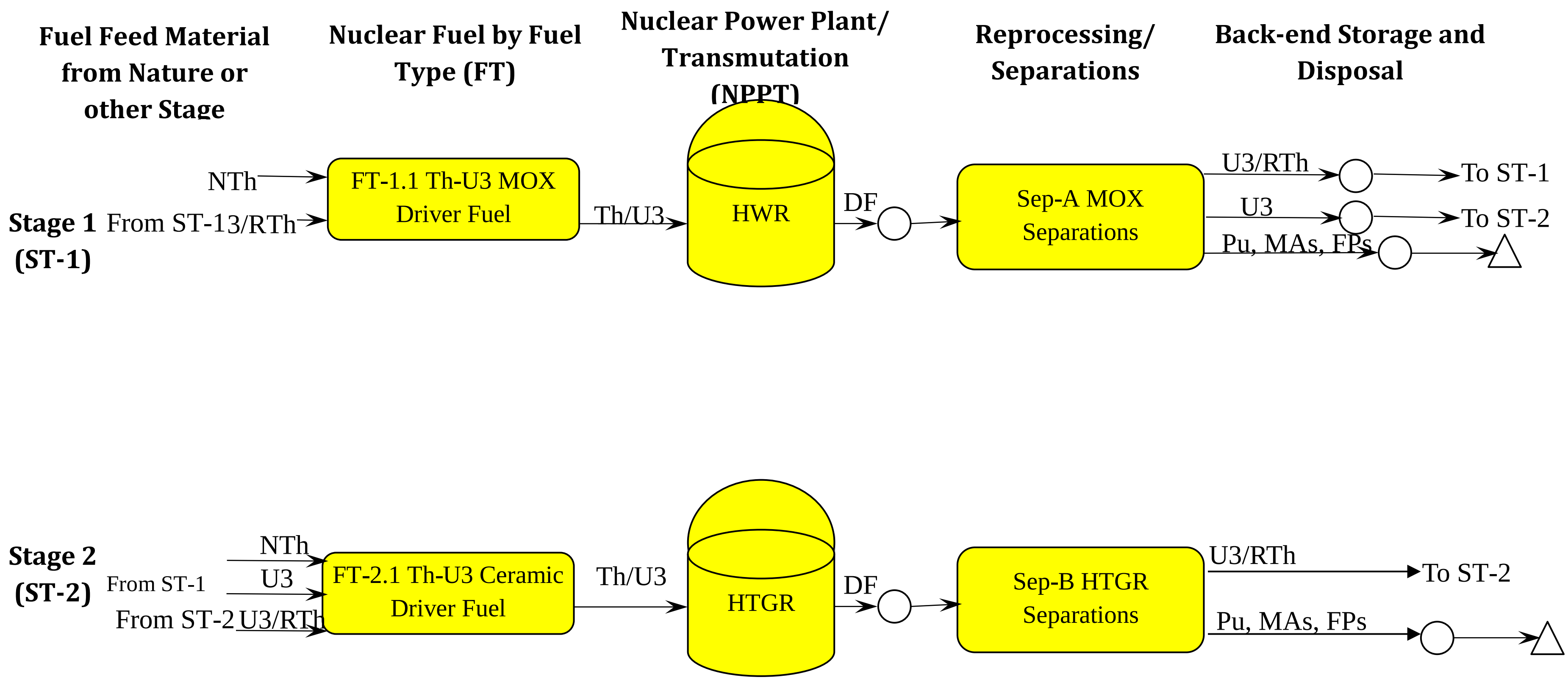
This FCDP relied on unpublished data underlying Ref. 1, rather than information presented in the publication itself. However, Ref. 1 is the closest publicly available document to the actual methodology that was used.

A5 – FCDP 4 System Datasheet and Supplementary Information

Summary Description

Fuel Cycle Option No.	EG-26 (MC-C-T/T-UTh-U3-N)	**Roadmap Strategy**	Full Recycle	**Recycle Strategy**	Continuous Recycle
Fuel Cycle Option Title	HWR-Th/U3-MOX to HTGR—Th/U3-C				
Revision number	**Revision remarks**				
Rev. 0.0 Rev. 0.1 Rev. 0.2	Initial Revision Addressed Internal Reviewer Comments from ORNL Addressed External Reviewer Comments from BNL				
High-level Objective(s)	12) Produce electricity 13) Provide or enhance ability to use natural resources 14) Reduce quantity of plutonium (or strategic SNM) generated per unit energy 15) Improve U-233 breeding in thermal spectrum				
No. of Stages	2	**Stage Description**			
Stage 1 Th-U3 MOX fuel (driver) HWR	Thorium and uranium-233 mixed oxide driver fuel is fabricated from recycled Stage 1 fuel and natural thorium. This fuel is irradiated in an HWR to a burnup of 30 GWd/MTIHM. Discharged fuel is stored and then reprocessed. The required entering amount of U-233 is sent to Stage 1, while surplus U-233 is sent to Stage 2. Recycled thorium is also recovered and sent back to Stage 1. Fission products, plutonium, and minor actinides (including protactinium) are stored and then sent to a disposal site. However, the storage period between discharge and reprocessing is sufficiently long such that nearly all of the Pa-233 has decayed to U-233; most of the protactinium being sent to disposal is Pa-231.				
Stage 2 Th-U3 C fuel (driver) HTGR	U-233 from Stage 1 is combined with recycled Stage 2 thorium and U-233, plus natural thorium, to make a mixed (thorium/uranium-233) prismatic carbide fuel type for a high-temperature gas-cooled reactor. This combined fuel is taken to a burnup of 100 GWd/MTIHM and then discharged and stored. Eventually the stored fuel is reprocessed, and thorium and U-233 are recovered for re-use in Stage 2. Fission products, plutonium, and minor actinides (including protactinium) are stored and then sent to a disposal site.				
Prepared by	Timothy Ault (VU)	**Rev. 0 Date**	12-2-16		
	Timothy Ault (VU)	**Rev. 1 Date**	1-11-17		
Internally Reviewed by	Joshua Peterson (ORNL)	**Approval Date**	1-13-17		
Externally Reviewed by	Gilad Raitses (BNL)	**Approval Date**	TBD		
Accepted by	FCDP coordinator	**Acceptance Date**	TBD		

Material Flow Diagram



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NTh = Natural Thorium
RTh = Recovered Thorium
Pu = Plutonium
DF = Discharged Fuel
HTGR = High-Temperature Gas-Cooled Reactor
Th = Thorium
PWR = Pressurized Water Reactor
FPs = Fission Products
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

High Level Parameter Data

Technology category	Parameter	Stage Number 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	HWR	HTGR		
	Core Configuration	HWR with Th/U3 MOX Driver Fuel	HTGR with Th/U3 Oxycarbide Prismatic Fuel		
	Core Thermal Power, MWth	3000	2000		
	Net Thermal Efficiency, %	33	50		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	30	100		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	84.27	15.73		
	Reference(s)	1, 2	3		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	2.1			
Nuclear Fuel	Fuel Technology Identifier		HWR-MOX	HTGR-Carbide			
	Purpose		Driver	Driver			
	Chemical Form		Oxide	Oxycarbide			
	Physical Form		Pin Bundle – Ductless	Prismatic Block			
	Average Discharge Burnup, GWd/t		30	100			
	Fuel Composition		Th/U3	Th/U3			
	Fuel Composition Non-fissionable Target materials	(U-235+ U-233)/Total U, %	67.25	28.45			
		Th/Total HM, %	98.19	48.45			
		TRU/Total HM, %	0	0			
		n.a.	n.a.	n.a.			
	Non-fissionable Target Charge Rate, kg/GWe-yr		n.a.	n.a.			
	Non-fissionable Target Transmutation Fraction, %		n.a.	n.a.			
	Fabrication Losses, %		0.2	0.2			
	Separation Process(es) Used as Source		A	A, B			
	Enrichment Tailing, %		n/a	n/a			
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	1.0			
	Fuel Residence Time in Reactor, EFPY		2.74	2.74			
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	5.0 for All			
	Technology Readiness Level (TRL)*		TBD	TBD			
	Brief Justification of TRL:		TBD	TBD			
	Reference(s)		1, 2	3			

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	**Parameter**	**Reprocessing/Separation Processes**				
		A	B	C		
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD	TBD			
	Separation	U3, U3/RTh, Pu/MA/FPs	U3/RTh, Pu/MA/FPs			
	Fuel Type Used as Source	1.1	2.1			
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99% for U3, Th. All others (1% U3, Th and 100% Pu, MA, FP) are treated as waste	Recovery of 99% for U3, Th. All others (1% U3, Th and 100% Pu, MA, FP) are treated as waste			
	Technology Readiness Level (TRL)**	TBD	TBD			
	Brief Justification of TRL:	TBD	TBD			
	Reference(s)	4	4			

Note: 1) Additional information included in the Material Flow Diagram.

2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data

Note: Some columns may not add to precisely zero due to the rounding of certain values to the nearest 0.1 metric tons.

Stage		1			2						Sum [b)]
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sec	
Electricity, GWe-yr		84.27			15.73						100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU										+0.0
	Th	-163.4			-3.3						-166.8
Products from fuel or NPPT technology	DU										+0.0
	LEU										+0.0
	Th	+3,391.8	-3,391.8		+61.9	-61.9					+0.0
	U3	+62.6	-62.6		+65.8	-65.8					+0.0
	MA (inc. Pu)										+0.0
	DF		+3,454.5	-3,454.5		+127.7	-127.7				+0.0
Products from Rep/Sep technology	RU										+0.0
	Th	-3,235.2		+3,235.2	-58.6		+58.6				+0.0
	U3	-62.7		+76.1	-65.9		+52.5				+0.0
	MA (inc. Pu)			+0.7			+2.1				+2.8
	FP			+109.0			+13.3				+122.3
Loss		+6.9	+0.0	+33.4	+0.3	+0.0	+1.1				+41.7
References		1, 2			3						

l) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

m) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

References

Reference	Distribution Restrictions
14. Ellis, R. "Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program", Transactions of the American Nuclear Society, Vol. 97, 2007	None
15. Chen M., Zhang Z., Meng Z., Cottrell, C., and Kuran, S. "CANDU Flexible and Economical Fuel Technology in China", Pacific Basin Nuclear Conference 2014, Vancouver, BC, Canada, August 24-28, 2014	None
16. Bess, J. and Fujimoto, N. "Evaluation of the Start-up Core Physics Tests at Japan's High Temperature Engineering Test Reactor (Fully-Loaded Core), INL/EXT-08-14767, Revision 0, March 2009	None
17. Wigeland, R., Taiwo, T., Ludewig, H., Todosow, M., Halsey, W., Gehin, J., Jubin, R., Buelt, J., Stockinger, S., Jenni, K., and Oakley, B. "Nuclear Fuel Cycle Evaluation and Screening – Final Report", Report No. INL/EXT-14-31465, 2014	None
18. Ault, T., Krahn, S., Croff, A., and Worrall, A. "Fuel Cycle Data Package (FCDP) Calculation Notes for "HWR-Th/U3-MOX to HTGR-Th/U3-C", 2017	None

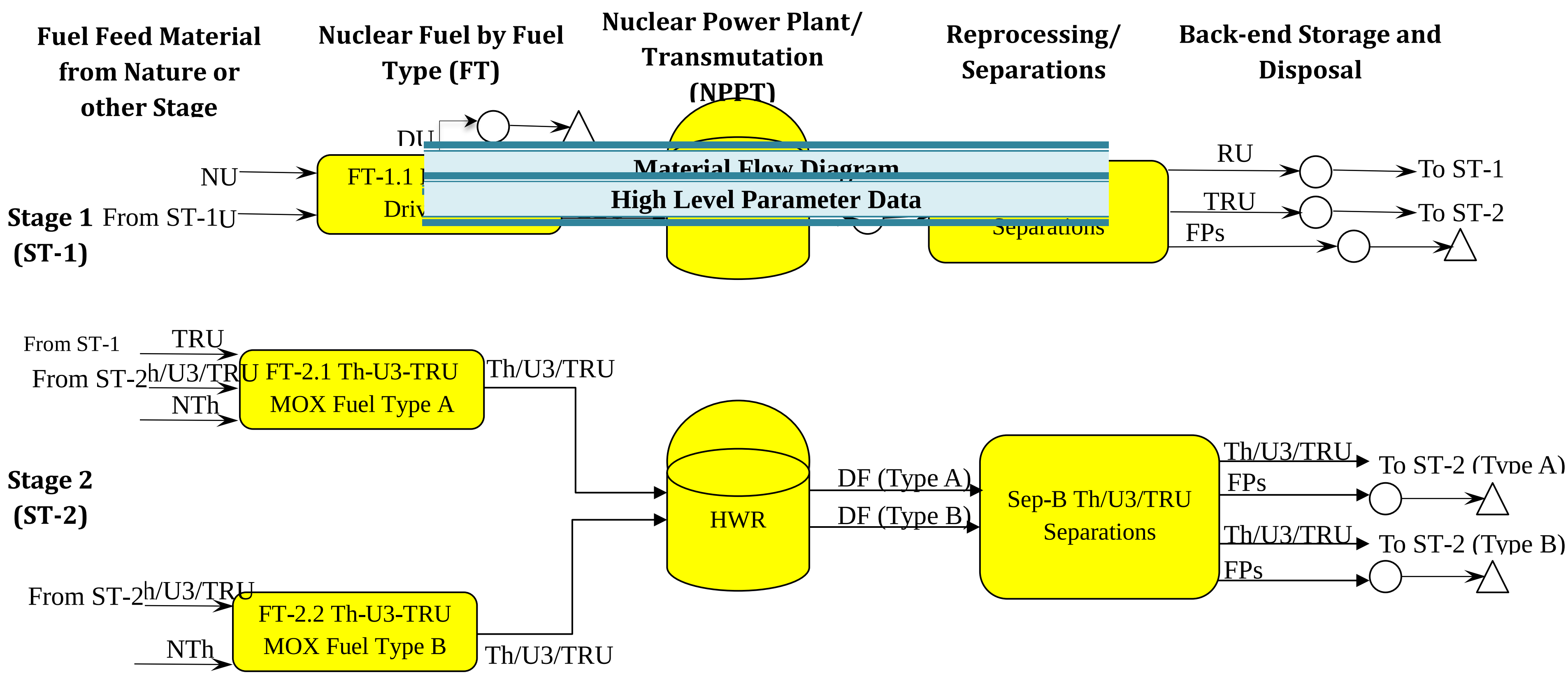
Note: If possible, reference with distribution limitations should be avoided.

For the Ellis paper, the FCDP actually relied on unpublished data that supported that publication, rather than information presented in the publication itself. However, this is the closest publicly available document to the actual methodology that was used.

A6 – FCDP 5 System Datasheet and Supplementary Information

Summary Description

Fuel Cycle Option No.	EG-25 (MC-C-T/T-UTh-U3-Y (with TRU))	**Roadmap Strategy**	Full Recycle	**Recycle Strategy**	Continuous Recycle
Fuel Cycle Option Title	PWR-LEU-Oxide to HWR—Th/TRU-MOX				
Revision number	**Revision remarks**				
Rev. 0.0 Rev. 0.1 Rev 0.2	Initial Revision Switched Template Version to Rev 0.4 and Addressed Multiple Internal Reviewer Comments from ORNL Addressed Multiple External Reviewer Comments from ANL and INL				
High-level Objective(s)	16) Produce electricity 17) Provide or enhance ability to use natural resources 18) Can utilize existing thermal reactor infrastructure 19) Manage waste disposal by partitioning or transmuting actinide isotopes				
No. of Stages 2	**Stage Description**				
Stage 1 UOX fuel (driver) PWR	LEU oxide driver fuel is irradiated in a PWR. The driver fuel is enriched to 4.41% and the burnup is 50 GWd/MTIHM. Discharged fuel is stored and then reprocessed. Recycled uranium is sent to Stage 1 for re-enrichment and re-use (the accumulation of U-236 necessitates the enrichment increase of 0.2% relative to reference PWR fuel). Transuranic elements (including plutonium) are also recovered and sent to Stage 2. Fission products are stored and then sent to a disposal site.				
Stage 2 RU-Pu MOX fuel (driver) ThOX fuel (blanket) HWR	TRU from Stage 1 is combined with recycled Stage 2 fuel and natural thorium to make a mixed (thorium/uranium-233/TRU) oxide (MOX) fuel type for a heavy water reactor. There is also another fuel type for the heavy water reactor comprised of recycled thorium/uranium-233/TRU combined with natural thorium. All actinides are recycled for re-use within the respective fuel type. The combined burnup of the two HWR fuels is 30 GWd/MTIHM. Fission products from both fuel types are stored and then sent to a disposal site.				
Prepared by	Timothy Ault (VU)	**Rev. 0 Date**	10-24-16		
	Timothy Ault (VU)	**Rev. 1 Date**	01-04-17		
Internally Reviewed by	Joshua Peterson	**Approval Date**	01-13-17		
Externally Reviewed by	TK Kim (ANL) Brent Dixon (INL	**Approval Date**	TBD		
Accepted by	FCDP coordinator	**Acceptance Date**	TBD		



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium DF = Discharged Fuel PWR = Pressurized Water Reactor = Nuclear Waste Disposal

DU = Depleted Uranium FP = Fission Products HWR = Heavy Water Reactor = Nuclear Material Storage

LEU = Low-enriched Uranium Th = Thorium UOX = Uranium Oxide = Nuclear Material Transport

Technology category	Parameter	Stage Number 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	PWR	HWR		
	Core Configuration	PWR with UOX Driver Fuel	HWR with Th/U3/TRU Fuel Type A and Th/U3/TRU Fuel Type B		
	Core Thermal Power, MWth	3000	3000		
	Net Thermal Efficiency, %	33	33		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	33.389	30		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	27.02	72.98		
	Reference(s)	1, 2	3, 4		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	2.1	2.2		
Nuclear Fuel	Fuel Technology Identifier		PWR-UOX	HWR–MOX(1)	HWR-MOX(2)		
	Purpose		Driver	Driver/Target	Driver		
	Chemical Form		Oxide	Oxide	Oxide		
	Physical Form		Pin Bundle – Ductless	Pin Bundle – Ductless	Pin Bundle – Ductless		
	Average Discharge Burnup, GWd/t		50	32.7	28.5		
				30.0 (combined)			
	Fuel Composition	Initial Nuclear Material(s)	LEU	Th/U3/TRU	Th/U3/TRU		
		(U-235+ U-233)/Total U, %	4.41	60.20	57.66		
		Th/Total HM, %	0	93.38	97.11		
		TRU (incl. Pa)/Total HM, %	0	4.01	0.10		
	Non-fissionable Target materials		n.a.	n.a.	n.a.		
	Non-fissionable Target Charge Rate, kg/GWe-yr		n.a.	n.a.	n.a.		
	Non-fissionable Target Transmutation Fraction, %		n.a.	n.a.	n.a.		
	Fabrication Losses, %		0.2	0.2	0.2		
	Separation Process(es) Used as Source		n.a.	A, B	B		
	Enrichment Tailing, %		0.25	n/a	n.a.		
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	1.0	1.0		
	Fuel Residence Time in Reactor, EFPY		4.10	2.74	2.74		
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	5.0 for All	5.0 for All		
	Technology Readiness Level (TRL)*		TBD	TBD	TBD		
	Brief Justification of TRL:		TBD	TBD	TBD		
	Reference(s)		1, 2	3,4	3, 4		

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	Parameter	Reprocessing/Separation Processes				
		A	B	C		
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD	TBD	TBD		
	Separation	RU, TRU, FPs	Th/U3/TRU, FPs	Th/U3/TRU, FPs		
	Fuel Type Used as Source	1.1	2.1	2.2		
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99% for U, TRU. All others (1% U, TRU and 100% FP) are treated as waste	Recovery of 99% for Th/U3/TRU. All others (1% Th/U3/TRU and 100% FP) are treated as waste	Recovery of 99% for Th/U3/TRU. All others (1% Th/U3/TRU and 100% FP) are treated as waste		
	Technology Readiness Level (TRL)**	TBD	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD	TBD		
	Reference(s)	1, 2	1, 2	1, 2		

Note: 1) Additional information included in the Material Flow Diagram.
2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data

Note: Some columns may not add to precisely zero due to the rounding of certain values to the nearest 0.1 metric tons.

Stage		**1**			**2**						**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sec**	
Electricity, GWe-yr		27.02			72.98						100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU	-4,578.6									-4,578.6
	Th				-97.1						-97.1
Products from fuel or NPPT technology	DU	+4,531.9									+4,531.9
	LEU	+598.0	-598.0								+0.0
	Th				+2,579.6	-2,579.6					+0.0
	U3				+73.3	-73.3					+0.0
	TRU				+39.7	-39.7					+0.0
	DF		+598.0	-598.0		+2,692.6	-2,692.6				+0.0
Products from Rep/Sep technology	RU	-552.6		+552.6							+0.0
	Th				-2,487.7		+2,487.7				+0.0
	U3				-73.4		+73.4				+0.0
	TRU			+8.9	-39.8		+30.9				+0.0
	FP			+30.8			+74.4				+105.2
Loss		+1.2	+0.0	+5.7	+5.3	+0.0	+26.2				+38.4
References		1, 2			3, 4						

n) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

o) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

References

Reference	Distribution Restrictions
19. DeHart, M. “SCALE-4 Analysis of Pressurized Water Reactor Critical Configurations: Volume 1- Summary”, Oak Ridge National Laboratory Report ORNL/TM-12294/V1, 1995	None
20. Cerne, S., Hermann, O., and Westfall, P. “Reactivity and Isotopic Composition of Spent PWR Fuel as a Function of Initial Enrichment, Burnup, and Cooling Time”, Oak Ridge National Laboratory Report ORNL/CSD/TM-244, 1987	None
21. Chen M., Zhang Z., Meng Z., Cottrell, C., and Kuran, S. “CANDU Flexible and Economical Fuel Technology in China”, Pacific Basin Nuclear Conference 2014, Vancouver, BC, Canada, August 24-28, 2014	None
22. Ellis, R. “Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program”, Transactions of the American Nuclear Society, Vol. 97, 2007	None

Note: If possible, reference with distribution limitations should be avoided.

For the Ellis paper, the FCDP actually relied on unpublished data that supported that publication, rather than information presented in the publication itself. However, this is the closest publicly available document to the actual methodology that was used.

"Supplementary" Mass Flow Data: Separate Fuel Type Tracking

Note: This version of the mass flow data table has been provided to track the separate flows of "Type A" (FT-2.1) and "Type B" (FT-2.2) fuels in Stage 2. It therefore does not follow the usual guidelines for mass flow data table guidelines and is intended purely to provide supplementary information about the fuel cycle. Some columns may not add to precisely zero due to the rounding of certain values to the nearest 0.1 metric tons.

Stage		**1**			**2.1 "Type A"**			**2.2 "Type B"**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sec**	
Electricity, GWe-yr		27.02			27.97			45.01			100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU	-4,578.6									-4,578.6
	Th				-28.7			-68.4			-97.1
Products from fuel or NPPT technology	DU	+4,531.9									+4,531.9
	LEU	+598.0	-598.0								+0.0
	Th				+883.4	-883.4		+1,696.2	-1,696.2		+0.0
	U3				+24.7	-24.7		+48.6	-48.6		+0.0
	TRU				+37.9	-37.9		+1.8	-1.8		+0.0
	DF		+598.0	-598.0		+946.0	-946.0		+1,746.5	-1,746.5	+0.0
Products from Rep/Sep technology	RU	-552.6		+552.6							+0.0
	Th				-856.5		+856.5	-1,631.2		+1,631.2	+0.0
	U3				-24.8		+24.8	-48.7		+48.7	+0.0
	TRU			+8.9	-38.0		+29.1	-1.8		+1.8	+0.0
	FP			+30.8			+26.6			+47.9	+105.3
Loss		+1.2	+0.0	+5.7	+1.9	+0.0	+9.1	+3.5		+17.0	+38.4
References		1, 2			3, 4						

p) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr

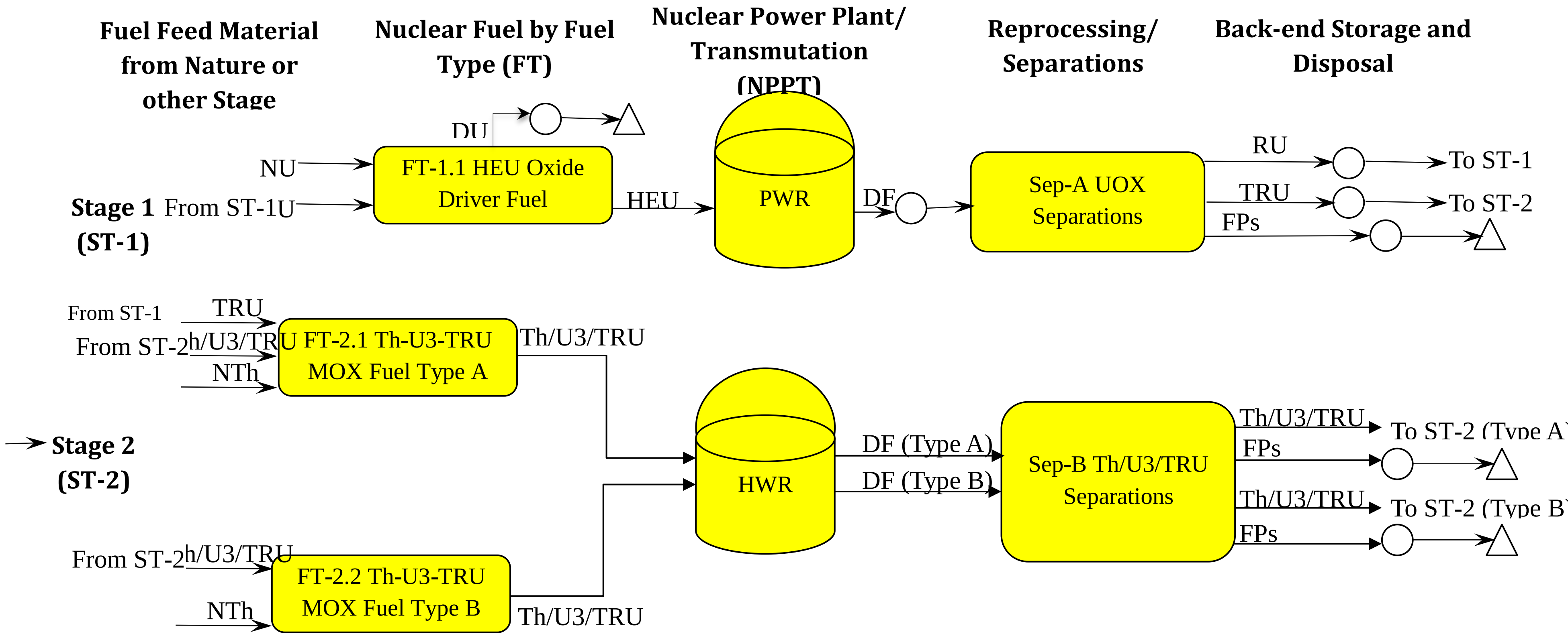
A7 – FCDP 6 System Datasheet and Supplementary Information

Summary Description

Fuel Cycle Option No.	EG-25 (MC-C-T/T-UTh-U3-Y (with HEU and TRU)	**Roadmap Strategy**	Full Recycle	**Recycle Strategy**	Continuous Recycle
Fuel Cycle Option Title	PWR-HEU-Oxide to HWR—Th/TRU-MOX				
Revision number	**Revision remarks**				
Rev. 0.0 Rev. 0.1 Rev 0.2	Initial Revision Switched Template Version to Rev 0.4 and Addressed Multiple Internal Reviewer Comments from ORNL Addressed Multiple External Reviewer Comments from ANL and INL				
High-level Objective(s)	20) Produce electricity 21) Provide or enhance ability to use natural resources 22) Can utilize existing thermal reactor infrastructure 23) Manage waste disposal by partitioning or transmuting actinide isotopes				
No. of Stages 2	**Stage Description**				
Stage 1 UOX fuel (driver) PWR	HEU oxide driver fuel is irradiated in a PWR. The driver fuel is enriched such that the U-238 vector does not exceed 10% (leading to 68.73% U-235) and the burnup is 100 GWd/MTIHM. Discharged fuel is stored and then reprocessed. Recycled uranium is sent to Stage 1 for re-enrichment and re-use, leading to a 21.21% accumulation of U-236. Transuranic elements (including plutonium) are also recovered and sent to Stage 2. Fission products are stored and then sent to a disposal site.				

Stage 2 RU-Pu MOX fuel (driver) ThOX fuel (blanket) HWR	TRU from Stage 1 is combined with recycled Stage 2 fuel and natural thorium to make a mixed (thorium/uranium-233/TRU) oxide (MOX) fuel type for a heavy water reactor. There is also another fuel type comprised of recycled thorium/uranium-233/TRU combined with natural thorium. All actinides are recycled for re-use within the respective fuel type. The combined burnup of the two HWR fuels is 30 GWd/MTIHM. Fission products from both fuel types are stored and then sent to a disposal site.		
Prepared by	Timothy Ault (VU)	**Date**	10-24-16
	Timothy Ault (VU)	**Rev. 1 Date**	01-04-17
Internally Reviewed by	Joshua Peterson (ORNL)	**Approval Date**	01-13-17
Externally Reviewed by	TK Kim (ANL)	**Approval Date**	TBD
Accepted by	FCDP coordinator	**Acceptance Date**	TBD

Material Flow Diagram



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium DF = Discharged Fuel PWR = Pressurized Water Reactor △ = Nuclear Waste Disposal

DU = Depleted Uranium FP = Fission Products HWR = Heavy Water Reactor ○ = Nuclear Material Storage

HEU = High-enriched Uranium Th = Thorium UOX = Uranium Oxide → = Nuclear Material Transport

High Level Parameter Data

Technology category	Parameter	Stage Number 1	2	3	4
Nuclear Power Plant/ Transmutation (NPPT)	NPPT Technology Identifier	PWR	HWR		
	Core Configuration	PWR with UOX Driver Fuel	HWR with Th/U3/TRU Fuel Type A and Th/U3/TRU Fuel Type B		
	Core Thermal Power, MWth	3000	3000		
	Net Thermal Efficiency, %	33	33		
	Capacity Factor, %	90	90		
	Specific Power Density, MW/IHMMT*	100	30		
	Technology Readiness Level (TRL) **	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD		
	Electrical Energy Generation Sharing, %	39.51	60.49		
	Reference(s)	1, 2	3, 4		

* IHMMT: Initial Heavy Metal Metric Ton

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided

Technology category	Parameter		Fuel Type Number (1st digit denotes Stage No.)				
			1.1	2.1	2.2		
Nuclear Fuel	Fuel Technology Identifier		PWR-UOX	HWR–MOX(1)	HWR-MOX(2)		
	Purpose		Driver	Driver/Target	Driver		
	Chemical Form		Oxide	Oxide	Oxide		
	Physical Form		Pin Bundle – Ductless	Pin Bundle – Ductless	Pin Bundle – Ductless		
	Average Discharge Burnup, GWd/t		100	28.4	30.9		
				30.0 (combined)			
	Fuel Composition	Initial Nuclear Material(s)	LEU	Th/U3/TRU	Th/U3/TRU		
		(U-235+ U-233)/Total U, %	68.73	57.86	57.32		
		Th/Total HM, %	0	95.26	97.14		
		TRU (inc. Pa)/Total HM, %	0	2.01	0.09		
	Non-fissionable Target materials		n.a.	n.a.	n.a.		
	Non-fissionable Target Charge Rate, kg/GWe-yr		n.a.	n.a.	n.a.		
	Non-fissionable Target Transmutation Fraction, %		n.a.	n.a.	n.a.		
	Fabrication Losses, %		0.2	0.2	0.2		
	Separation Process(es) Used as Source		n.a.	A, B	B		
	Enrichment Tailing, %		0.25	n/a	n.a.		
	Fuel Fabrication Time and Lag before Use in NPPT, years		1.0	1.0	1.0		
	Fuel Residence Time in Reactor, EFPY		2.74	2.74	2.74		
	Post Irradiation Time (Decay and Separation if applicable) before Fabrication/Disposal, years		5.0 for All	5.0 for All	5.0 for All		
	Technology Readiness Level (TRL)*		TBD	TBD	TBD		
	Brief Justification of TRL:		TBD	TBD	TBD		
	Reference(s)		1, 2	3,4	3, 4		

Note: Repeat table if additional columns are required for additional fuel types.
* TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Technology category	**Parameter**	**Reprocessing/Separation Processes**				
		A	B	C		
Reprocessing/Separations	Potential Reprocessing/Separations Approach	TBD	TBD	TBD		
	Separation	RU, TRU, FPs	Th/U3/TRU, FPs	Th/U3/TRU, FPs		
	Fuel Type Used as Source	1.1	2.1	2.2		
	Recovery Efficiency (%) & Descriptive Information†	Recovery of 99% for U, TRU. All others (1% U, TRU and 100% FP) are treated as waste	Recovery of 99% for Th/U3/TRU. All others (1% Th/U3/TRU and 100% FP) are treated as waste	Recovery of 99% for Th/U3/TRU. All others (1% Th/U3/TRU and 100% FP) are treated as waste		
	Technology Readiness Level (TRL)**	TBD	TBD	TBD		
	Brief Justification of TRL:	TBD	TBD	TBD		
	Reference(s)	1, 2	1, 2	1, 2		

Note: 1) Additional information included in the Material Flow Diagram.

2) Repeat table if additional columns are required for separation of additional fuel types.

† Net plant efficiency – fraction of material that ends up in recycled material or intended waste stream (e.g. excess recovered uranium)

** TRL will be evaluated by Evaluation Screening Team (EST), but input may be provided.

Mass Flow Data

Note: Some columns may not add to precisely zero due to the rounding of certain values to the nearest 0.1 metric tons.

Stage		1			2						Sum [b)]
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sec	
Electricity, GWe-yr		39.51			60.49						100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU	-13,230.5									-13,230.5
	Th				-86.7						-86.7
Products from fuel or NPPT technology	DU	+13,174.6									+13,174.6
	LEU	+437.3	-437.3								+0.0
	Th				+2,153.2	-2,153.2					+0.0
	U3				+61.5	-61.5					+0.0
	TRU				+17.1	-17.1					+0.0
	DF		+437.3	-437.3		+2,231.8	-2,231.8				+0.0
Products from Rep/Sep technology	RU	-382.2		+382.2							+0.0
	Th				-2,070.8		+2,070.8				+0.0
	U3				-61.6		+61.6				+0.0
	TRU			+4.7	-17.1		+12.4				+0.0
	FP			+46.4			+65.2				+111.6
Loss		+0.9	+0.0	+3.9	+4.4	+0.0	+21.7				+30.9
References		1, 2			3, 4						

q) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

r) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Transition and Scenario Analysis Data
(Provide references, if any, and brief description)

References to any transition or scenario analysis data:

References

Reference	Distribution Restrictions
23. DeHart, M. “SCALE-4 Analysis of Pressurized Water Reactor Critical Configurations: Volume 1- Summary”, Oak Ridge National Laboratory Report ORNL/TM-12294/V1, 1995	None
24. Cerne, S., Hermann, O., and Westfall, P. “Reactivity and Isotopic Composition of Spent PWR Fuel as a Function of Initial Enrichment, Burnup, and Cooling Time”, Oak Ridge National Laboratory Report ORNL/CSD/TM-244, 1987	None
25. Chen M., Zhang Z., Meng Z., Cottrell, C., and Kuran, S. “CANDU Flexible and Economical Fuel Technology in China”, Pacific Basin Nuclear Conference 2014, Vancouver, BC, Canada, August 24-28, 2014	None
26. Ellis, R. “Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program”, Transactions of the American Nuclear Society, Vol. 97, 2007	None

Note: If possible, reference with distribution limitations should be avoided.

For the Ellis paper, the FCDP actually relied on unpublished data that supported that publication, rather than information presented in the publication itself. However, this is the closest publicly available document to the actual methodology that was used.

“Supplementary” Mass Flow Data

Note: This version of the mass flow data table has been provided to track the separate flows of “Type A” (FT-2.1) and “Type B” (FT-2.2) fuels in Stage 2. It therefore does not follow the usual guidelines for mass flow data table guidelines and is intended purely to provide supplementary information about the fuel cycle. Some columns may not add to precisely zero due to the rounding of certain values to the nearest 0.1 metric tons.

Stage		**1**			**2.1 “Type A”**			**2.2 “Type**	
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**
Electricity, GWe-yr		39.51			20.13			40.36	
Feed or product of nuclear materials (metric ton) [a)]									
Natural resource	NU	-13,230.5							
	Th				-25.7			-61.0	
Products from fuel or NPPT technology	DU	+13,174.6							
	LEU	+437.3	-437.3						
	Th				+747.0	-747.0		+1,406.2	-1,406.2
	U3				+21.4	-21.4		+40.1	-40.1
	TRU				+15.8	-15.8		+1.3	-1.3
	DF		+437.3	-437.3		+784.1	-784.1		+1,447.8
Products from Rep/Sep technology	RU	-382.2		+382.2					
	Th				-722.8		+722.8	-1,348.1	
	U3				-21.4		+21.4	-40.2	
	TRU			+4.7	-15.8		+11.1	-1.3	
	FP			+46.4			+21.2		
Loss		+0.9	+0.0	+3.9	+1.6		+7.6	+2.9	
References		1, 2			3, 4			3,4	

s) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

t) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

A8 – Interim Publication on Year 1 FCDP Insights Presented at the Global 2015 International Fuel Cycle Conference (“Analysis of Multi-Stage Thorium Fuel Cycle Options for Improved Resource Utilization and Plutonium Inventory Management”)

This publication was presented at a conference. Readers are invited to check the Global 2015 website publications or to contact Steven Krahn at (steve.krahn@vanderbilt.edu) for more information.

A9 – Interim Publication on Year 2 FCDP Results, Presented at ANS Annual Meeting 2016 (“Analysis of Synergistic Fuel Cycle Options with Thorium and Heavy Water Reactors”)

This publication was presented at an American Nuclear Society conference. Readers are invited to check the American Nuclear Society’s website for conference publications or to contact Steven Krahn at (steve.krahn@vanderbilt.edu) for more information.

Literature Appendices ("B")

B1 - Submitted Manuscript on Thorium Literature Trends

This manuscript has been submitted to *Annals of Nuclear Energy* for review at the time of this writing. Readers are invited to check Elsevier's website for *Annals of Nuclear Energy* or to contact Steven Krahn at (steve.krahn@vanderbilt.edu) for more information.

B2 – Interim Publication on Findings of Thorium Literature Review at the ANS Annual Meeting 2016 ("Insights and Trends from a Literature Assessment of the Thorium Fuel Cycle")

This publication was presented at an American Nuclear Society conference. Readers are invited to check the American Nuclear Society's website for conference publications or to contact Steven Krahn at (steve.krahn@vanderbilt.edu) for more information.

B3 – Thorium Literature Database Users Guide

Project Context

A renewed interest in nuclear technology for electricity generation began to arise at the turn of the 21st century, sparking the conceptual design of a number of advanced reactor and fuel types. One of these concepts includes the use of thorium 232 as a fertile material to be bred into the fissile nuclear fuel, uranium 233. Those advocating for the use of thorium cite a number of potential benefits such as thorium's abundance relative to uranium, its ease of access via byproduct mining, the potential for decreased minor actinide and plutonium generation, as well as the possibility of improved proliferation resistance.

However, the pros and cons of the thorium fuel cycle are still being heavily debated by the nuclear community in order to determine the best course of action. During this current period of indecision, Vanderbilt has received a grant from the Department of Energy's Nuclear Energy sector to develop of database of literature written in the past 50-60 years specifically on the thorium fuel cycle. As current reactor designs are improved and advanced reactors move closer to commercialization, this database is to be used as a tool to assist in decision making as the blueprint for thorium fuel usage continues to evolve. This literature database includes material on most prominent reactor types (both commercially used, and designs currently under development), as well as information on a variety of pertinent topics such as nuclear physics, safeguards, resources and recovery, reprocessing and waste, etc.

Database Guidance

The following guide is intended to assist database users in navigation of key features, as well as to help with understanding some of the nuances and exceptions that exist in the entries. It will also help future contributors to the database to add new literature items in accordance with the database structure. As a reader moves through the various tables of the database, he or she can search for a particular piece of literature by citation to provide more detail on the topic at hand. To facilitate the search process, the database entries have been individually organized into these fields:

- ID
- Chapter
- Title
- Author(s)
- Publication Month
- Publication Year
- Report Number
- Resource Type
- Publication Owner
- Research Organization(s)
- Research Organization Category
- Country of Publication
- Language
- Abstract
- Abstract Origin
- Keywords
- Keyword Origin

Each field represents a different column in the database. For many pieces of literature, populating each of these fields is straightforward. However, some entries are not readily amenable to the input requirements of the database. To facilitate future additions to the database, the field entries for new pieces of literature should be populated according to the following definitions and guidelines:

ID – a unique ID following the numbering system XX-XXXX, where the last four numbers stand for the datum within a chapter and the first two stand for the chapter and are numbered as follows:

- 10 – Resources and Recovery
- 20 – Fuels
- 30 – Physics and Nuclear Data
- 41 – Light Water Reactors
- 42 – Heavy Water Reactors
- 43 – Liquid-Metal-Cooled Reactors
- 44 – Molten-Salt-Cooled Reactors
- 45 – Gas-Cooled Reactors
- 46 – Externally Driven Systems

- 50 – Reprocessing and Waste Management
- 60 – Safeguards
- 70 – Overviews and Impacts

Chapter – Indicates the Chapter or literature category in which the piece of literature is referenced (e.g. if the literature's ID begins with 42, the Chapter field would read "Heavy Water Reactors"). The possible chapters are those named in the bulleted list at the end of the description of the ID field.

Title – Names the title of the piece of literature. When subtitles are included without separation by character (comma, colon, semicolon, etc.), separate the main title from the subtitle by a comma and a space (e.g., Preparation of Metals by Magnesium-Zinc Reduction, Part II, Reduction of Thorium Dioxide).

Author(s) – Names the author(s) of the piece of literature in the format "First_Initial Last_Name" with multiple authors separated by a comma and a space. If an author has a suffix such as "junior", there is no comma placed between his last name and his suffix, with a period following the suffix (e.g., "D. Roberts, R. Smith, J. Williams Jr., S. Whitlock"). Additionally, if an individual author is not named and the work is instead attributed to a collective organization, a note "See Research Organization(s)" is inserted instead.

Publication Month – Names the month in which the piece of literature was published. If only a publication year is given, but no Publication Month, January is assigned as a default. If no year is given with the piece of literature, a value of "Unknown" is assigned to both Publication Month and Publication Year.

Publication Year – Indicates the year in which the literature was published. If no year is given with the piece of literature, a value of "Unknown" is assigned to both Publication Year and Publication Month.

Report Number – Indicates the official report number included in the piece of literature, as assigned by either the author(s) or research organization. The report number is to be entered exactly as it is found on the piece of literature (including any punctuation). If no report number is given, a value of "None" is assigned.

Resource Type – Names the specific format in which the piece of literature was written. The possible entries are as follows:

- Technical Report
- Conference Paper
- Journal Article
- Thesis or Dissertation
- Viewgraph
- Other

Publication Owner – In the event that this database is made publicly available (e.g., on a website), it may be necessary to denote ownership of certain publication types. In most cases, the information in the database is publicly available, but the actual literature attachments (most as PDFs) may not be sharable. Many items (especially government-based reports) have been released from any classified or copyrighted labels; however, others (especially articles from subscription-oriented journals) do not fall under this category, and thus must be managed carefully prior to release of the database.

At the time being, this category is labeled ***EMPTY***, but it should be addressed if and when the database is made publicly available (e.g., on a website).

Research Organization(s) – Names the organization(s) that was/were responsible for writing and conducting research for the piece of literature. In the case of multiple organizations, list them in the order that they appear on the document, separated by commas. If the research organization has changed names since the time of publication, update to the current name of the organization (e.g. Idaho National Engineering and Environmental Laboratory changed to Idaho National Laboratory in 2005). If the piece was written by an individual not associated with a particular organization, write “Independent Consultant”.

Research Organization Category – Names the type(s) of entity/entities under which the research was conducted. When a publication consists of contributors from multiple organization categories, name the contributors’ organization categories in the respective order that the contributors are listed in the Research Organization(s) section, separated by commas (e.g. if the Research Organizations are “Oak Ridge National Laboratory, Vanderbilt University” then the Research Organization Category would be listed as “National Laboratory, University”. If no research organization exists (as in the case of an independent consultant), assign a value of “Other”. If an organization is government funded with the phrase “National Laboratory” included in the title, then it is marked as National Laboratory; if not, it is marked a Government Agency. Possible field entries include:

- National Laboratory
- Corporation (for-profits and non-profits)
- University
- Government Agency (Note: this includes agencies that represent more than one country, such as the International Atomic Energy Agency)
- Other

Country of Publication – Names the country in which the piece of literature was originally published, or the multinational conglomeration responsible for publishing (e.g. European Commission). If a group of international entities responsible for publication are not in an organized, named conglomeration/consortium, simply assign a value of “International”. In the case of countries/territories of publication that no longer exist (e.g., USSR, Yugoslavia, Czechoslovakia, etc.), do not attempt to update the information based on present geopolitical configurations, as this information may have an effect on how the information in the piece of literature is interpreted.

Language – Names the language in which the piece of literature is primarily written in its given form; for example, if a paper has abstracts in both French and English but the main body of the report is written in English, then the field entry would be “English”.

Abstract – Provides a short synopsis of the purpose and/or discoveries of the conducted research described in the piece of literature. The priority is to use abstracts or brief executive summaries directly in their “word-for-word” form, if they are available. If only a prolonged executive summary or introduction is available, the next priority is to strategically truncate this information into a manageable abstract-length field entry. Finally, when neither of these options is available, an abstract will be prepared by the database creators which reflects the key points of the literature item. If the literature item is written in a language that is not English, enter a value of “Translation needed”. A flag distinguishing between these options is signaled by the “Abstract Origin” field, described next.

Abstract Origin – Denotes whether the abstract of the piece of literature was taken exactly as it appears in the literature, whether the abstract in the database is a truncated version of the one that appears in the literature, or whether the abstract in the database was derived from the literature. These three options (Exactly, Truncated, Derived) are the only permissible field entries.

Keywords – Lists keywords of the piece of literature to help facilitate searches. The priority is to use keywords provided by the literature if they are available. Otherwise, appropriate keywords are selected by the database creators based on key points of the literature item, using language directly from the text wherever possible. . If the literature item is written in a language other than English, enter a value of “translation needed”. A flag distinguishing between these options is signaled by the “Keyword Origin” field, described next.

Keyword Origin – Denotes whether the keywords listed were derived from the literature, or if they were provided as a list somewhere in the paper. These two options (derived, provided) are the only permissible field entries.

If an entry has not yet been made for the Abstract, Abstract Origin, Keywords, and Keyword Origin categories, assign a value of ***EMPTY*** to the section.

B4 – List of Identified Thorium Fuel Cycle Literature

<u>Resources and Recovery</u>

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Thorium Fuel Cycle Technical Track and Proceedings Appendices ("C")

C1 – Introductory Paper for the Thorium Track ("The Context, Structure, and Objectives of the Thorium Fuel Cycle Technical Track")

INTRODUCTION

In 2013, Vanderbilt University (VU) and Oak Ridge National Laboratory (ORNL) were awarded a NEUP grant to analyze an array of multi-stage[3] thorium fuel cycles (Th FCs) under the US Department of Energy (DOE)'s Nuclear Energy University Program (NEUP). The project, which began in early 2014, consists of the development of fuel cycle data packages (FCDPs)[4] for six Th FCs, the creation of a Th literature database, and the development

[3]A stage is defined under the FCDP program as an individual reactor configuration and its corresponding fuel fabrication and reprocessing facilities.
[4] A fuel cycle data package consists of a system overview with a description of relevant technologies, key technical parameters, mass flow information with references to detailed isotopic information, and references for each of the aforementioned areas [9].

and management of an extended technical track on the Th FC at the American Nuclear Society (ANS) Winter Meeting 2014.

The technical track on the Th FC (henceforth referred to as the Th Track) is structured with three objectives in mind:

- To produce a summary of the latest information on the performance, progress and requirements of the Th fuel cycle.
- To identify alternative Th FCs that are candidates for future FCDPs to be prepared by this project, as well as data sources for those candidate FCs.
- To identify key gaps in knowledge/data to assist DOE in prioritizing future R&D on Th fuels and their associated fuel cycles.

To achieve these objectives, the Th Track has been organized into five technical sessions, consisting of four paper sessions (Overview of Technical Programs; Thorium Resources, Recovery, and Fuel Fabrication; Thorium Reactors; Thorium Fuel Reprocessing and Waste Management) and one panel session. These sessions are intended to span the constituent parts of the Th FC and elucidate the current status of Th FC technology development.

This paper will briefly summarize the VU-ORNL project under NEUP and then expand on the structure and objectives of the Th Track.

PROJECT BACKGROUND

In Fiscal Year 2013, DOE called for proposals in the fuel cycles portion of the NEUP workscopes (under heading FC-5.1) to develop FCDPs for multi-stage FCs in entirely the thermal or fast spectrum which would reduce the actinide content of nuclear waste [1]. DOE's prioritization of actinide reduction reflects the rapidity with which the amount of such materials is increasing; between 1990 and 2012, the global plutonium (Pu) inventory approximately doubled [2-3]. In addition, minor actinides (MAs) constitute an additional 7% of the total amount of transuranic elements (TRU) [4]. The use of mixed-oxide (MOX) in reactors can slow the rate of Pu accumulation to a degree, but the presence of uranium (U) means that Pu will still be generated to some extent [5]. A more effective measure to counter the rate of Pu accumulation may be the use of a thorium (Th) fuel system. Unlike U-238, both Th-232 and its fissile counterpart U-233 are many neutron captures away from Pu-239 and other TRU elements, resulting in only minimal TRU production. Furthermore, Th fuels may be mixed with Pu in FCs which lowers the Pu inventory [6].

Given Th's potential role in the future of Pu/TRU mitigation and the relatively large amount of work to be done in consolidating data on the Th FC, VU-ORNL submitted a winning application to develop FCDPs for six multi-stage, thermal Th FCs. The project will take place over a three-year span. Early stages of the work will include a literature review (already ongoing) in preparation for both the first FCDP and populating a literature database.

Taking into account DOE's to desire to have all "stages" use thermal spectrum reactors, VU and ORNL surveyed past applicable reactor and FC development efforts. This led to the tentative identification of six FCs for consideration[5]:

- 2-stage, U/Th light water reactor (LWR) → U/Th high-temperature gas reactor (HTGR) (breed-to-burn)
- 3-stage, low-enrichment uranium (LEU) LWR → Th/Pu heavy water reactor (HWR) → Th/U-233 HTGR (generate Pu, breed U-233, and burn)
- 3-stage, LEU LWR → Th/Pu LWR → Th/U-233 LWR (generate Pu, breed U-233, and burn)
- 3-stage, LEU LWR → Th/Pu HWR → Th/U-233 HTGR w/ MA Targets (generate Pu, breed U-233, and burn while eliminating MAs)
- 3-stage, LEU LWR → Th/Pu HWR → Th/U-233 LWR w/ MA Targets (generate Pu, breed U-233, and burn while eliminating MAs)
- 2-stage LEU/Th HWR → Th/U & Th/Pu MOX HWR (generate Pu and U-233 and burn both)

[5] It should be noted that none of these options are 'full recycle' systems, since all have at least some SNF that is sent to waste [10].

The FC selections may change in response to newly available information or evolving DOE priorities. The FCDPs will ultimately be made available in the publically-accessible Fuel Cycle Option Catalog maintained by Sandia National Laboratory [8]. For FCDP development, it is expected that there may be some data that will not be directly available in the literature. In this case, calculations or technical judgment will be used to fill the gaps based on the information that is available.

While extensive literature has been produced on the Th FC, it has not been consolidated. To address this need, another component of the project is to develop a database of Th technical and programmatic literature. ORNL was a focal point for much of the Th FC research and development that was done in U.S. in the 1960s and 1970s, and the ongoing literature review is being facilitated by ORNL's document archive of Th FC material and relevant available expertise. One objective of the Th literature database is to make available some material that is not currently accessible in electronic form.

The project will adhere to appropriate DOE standards for quality assurance. All major deliverables will undergo internal peer review. In addition, an industry partner, the Electric Power Research Institute (EPRI), will provide external peer review as well as an industry perspective throughout project development.

THE THORIUM FUEL CYCLE TECHNICAL TRACK (ANS WINTER 2014 MEETING, ANAHEIM, CA)

One of the major components of the VU-ORNL NEUP project on Th FCs is to organize a technical track on the thorium fuel cycle. This is being implemented by organizing the Th Track. The concept of the Th Track was partly inspired by the successes of Thorium Fuel Cycle Symposia held in the 1960s [7,8]. The Th Track is intended not only to capture the current status of Th FC development but also to pinpoint data gaps to be filled by future research. Planning for the Th FC Track has been informed by the successes of the technical sessions on the Th FC held at the *Global 2013: International Fuel Cycle Conference* [9].

Organizers of the Thorium Track

The thorium track represents a multi-national, multi-organizational effort to bring together the leading researchers and developers of Th FC technology. The following parties have contributed to the organization and implementation of the Th Track:

- Steven Krahn, Vanderbilt University (Chair)
- Andrew Worrall, Oak Ridge National Laboratory (Co-Chair)
- Raymond Wymer, ORNL-Retired (Honorary Chair)
- Blair Bromley, Atomic Energy of Canada Ltd.
- Allen Croff, Vanderbilt University
- Charles Forsberg, Massachusetts Institute of Technology
- Jess Gehin, Oak Ridge National Laboratory
- Julian Kelly, Thor Energy
- T.K. Kim, Argonne National Laboratory
- Andrew Sowder, Electric Power Research Institute
- Temitope Taiwo, Argonne National Laboratory
- Michael Todosow, Brookhaven National Laboratory
- Luc Van Den Durpel, AREVA
- P.K. Wattal, Bhabha Atomic Research Centre

Paper Session: Overview of Thorium Programs

The Th Track begins with a session that highlights programmatic aspects of national, industrial, and international organizations concerning the Th FC. These papers will highlight what has been accomplished to-date as well as future Th FC program endeavors. The diversity of the organizations represented in this session will provide a well-rounded-perspective on the Th FC.

Paper Session: Thorium Resources, Recovery, and Fuel Fabrication

This session will focus on the "front end" of the fuel cycle, including thorium mining, refining, fuel fabrication, and associated activities. This includes, but is not limited to, thorium recovery experience, fuel fabrication experience and challenges, prospective thorium resources (including byproduct production), and thorium-based fuel designs.

Paper Session: Thorium Reactors

This session will address topics pertaining to thorium reactor design and configuration. The session will address a range of reactor concepts which will highlight niche applications for thorium fuels as well as indicate overall characteristics and trends of their use.

Paper Session: Thorium Fuel Processing and Waste Management

To round out the technological status of the thorium fuel cycle, this session will emphasize developments in the "back end" of the fuel cycle, with emphasis on reprocessing and the implications of thorium fuel cycles to waste management. This session will also include presentations addressing the proliferation and security considerations of the Th FC.

Panel Session: Preferred Thorium Fuel Cycles and Identification of Data Gaps

After the paper sessions, which have been designed to span the entirety of the thorium fuel cycle, a panel session will be held to consider information from the paper sessions and offer expert views on Th FCs that appear more (or less) promising, where thorium fuel cycle data/technology gaps exist, and how those data gaps might be filled. The findings which result from this panel should be useful in prioritizing subsequent thorium research and development for any number of relevant organizations. The panel session will also serve as a forum for discussing mechanisms and venues for future information exchanges on thorium fuel cycle options. The findings of the Th Track in general will serve to inform the selection of FCs for FCDP development in the later years of the project.

The chairs from the other four paper sessions will provide a short report/summary of the highlights of their respective sessions. After the summaries, each panel member will be allowed make a 5-10 minute statement or presentation of their views, emphasizing the most significant data gaps present in their area of expertise. After all panel members have spoken, the session will be opened to questions from the audience and from written questions submitted in the four paper sessions.

RESULTS

The collaborative VU-ORNL NEUP project will elucidate the information available to pursue Th FC research and development. Deliverables in the form of FCDPs, the proceedings of the Th FC Track, the Th FC literature database, and project reports will provide the technical community with widely accessible forms of documentation on Th.

The Th Track will have immediate value to those attending and presenting by presenting a consolidated view of the status of the Th FC. Key data gaps will be identified for subsequent resolution, which will help to focus the scope of future Th FC collaborations. Arrangements have been made to publish full papers based on the Th Track as a special edition of the ANS journal *Nuclear Technology*. In addition to serving as a NEUP deliverable to DOE, this method of publication will ensure the findings of the Th Track will be available to the public for future Th FC research endeavors.

ACKNOWLEDGEMENTS

This work is supported by the U.S. Department of Energy, under the Nuclear Energy University Program. The work will be carried out as Project No. DE-NE0000735, "Development of Fuel Cycle Data Packages for Thorium Fuel Cycle Options".

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C2 – Introduction to the Thorium Fuel Cycle Special Edition of Nuclear Technology ("The Reemergence of the Thorium Fuel Cycle: A Special Edition of Nuclear Technology")

Thorium was intensively studied from the 1960's to 1980's in the U.S. and elsewhere as a potential basis for advanced, future nuclear fuel cycle options. After demonstration of feasible thorium-based concepts, the U.S. decided instead to pursue liquid metal, fast breeder reactors using uranium and plutonium. Worldwide interest in the thorium fuel cycle continued at a reduced level, with India having invested the most resources into continued development. Recently, the thorium fuel cycle has been the subject of renewed interest partly due to a speculated substantial growth in nuclear energy worldwide (hence putting potential additional strain on uranium reserves), and partly due to the pursuit of advanced reactor concepts with improved safety and economics, that also have the potential to utilize thorium. This renewed interest often addresses new possibilities using thorium in the modern era, but it can be difficult to discern between actual characteristics of the new thorium concepts and misconceptions propagated by non-technical advocacy and detractor groups. It is therefore a good time to discuss experience with the thorium fuel cycle to-date, provide an even-handed description of its inherent attributes, and identify data gaps that have yet to be resolved.

This special edition represents a spectrum of recent thorium-related work, across a number of fuel cycle disciplines, and also provides some new perspectives on current and past international thorium fuel cycle operations. The resulting conversation builds on a renewed dialogue on thorium, beginning with three technical sessions on the thorium fuel cycle at the Global 2013: International Fuel Cycle Conference during September/October 2013 in Salt Lake City, UT, USA (summarized in [1]), and continuing with a special "Thorium Fuel Cycle Technical Track" at November 2014's American Nuclear Society Winter Meeting in Anaheim, CA, USA, during which 44 papers were presented. The 12 constituent papers of this special edition build on the dialogue that occurred at the 2014 ANS Winter Meeting. Topics covered in this special edition include thorium recovery, strategies for thorium's use in a variety of reactor technologies, fuel reprocessing, waste management, safeguards considerations, and nuclear safety.

The renewed interest in thorium is supported in part by a resurgence of major programs related to thorium-based nuclear fuel cycles. India has described plans for a three-stage nuclear energy strategy that integrates thorium-based fuels: Stage 1 involves natural-uranium-burning heavy water reactors to produce plutonium and stockpile it for further use; Stage 2 uses the stockpiled plutonium in fast breeder reactors with thorium blankets to produce uranium-233 (and additional plutonium) and recycles plutonium back to the fast reactor; Stage 3 uses recovered U-233 (from Stage 2) in advanced heavy-water moderated, light-water-cooled reactors. Currently, Stage 1 is operational, Stage 2 is in advanced testing, and Stage 3 is in advanced design [2]. China is planning to build two experimental molten salt reactors: the first, which is to commence operation in 2017, will use spherical pebble fuel and LiF-BeF_2 molten salt as the coolant. The second molten salt reactor (scheduled to commence operations in 2020) will use thorium-based fluid fuel and include fuel salt processing, operating on modified once-through and then fully closed fuel cycles [3]. China is also considering the use of Canadian-designed fuels in heavy water reactors which have the potential to incorporate thorium [4]. Thor Energy (Norway) is conducting experiments focused on fuel manufacturing, materials, and nuclear performance of PuO_2-ThO_2 and UO_2-ThO_2 ceramic fuels. Test pins composed of thorium-uranium and thorium-plutonium oxide mixtures are currently being irradiated in the Halden test reactor, and additional testing of thorium-based oxide fuel pins is planned [5].

Differences in the major technical features of the thorium/U-233 fuel cycle and present fuel cycles based on U-235 and plutonium (Pu) present implications for facility design and operation, and waste disposal. Thorium is fertile but does not contain natural fissile isotopes, so external fissile material is required to produce U-233 at the onset of fuel cycle implementation. Thorium-based fuels offer higher conversion ratios than uranium-based fuels in thermal reactors, since U-233 has a relatively low neutron capture (non-fission) cross section compared to U-235 or Pu-239, produces about 5% more neutrons per thermal fission, and Th-232 has a higher neutron capture cross section than U-238. Differences extend to individual fuel cycle operations as well. Natural thorium recovery is simplified by its isotopic purity (avoiding conversion and enrichment requirements), but it can require significant reagent quantities to purify chemically. Thorium fuel fabrication is complicated by higher shielding requirements, especially for reprocessed thorium-based fuels due to the energetic gamma-emitters of the U-232 decay chain. Reprocessing of thorium fuels generally requires larger reagent concentrations than for uranium/plutonium fuels, and process efficiencies can be lower. An excellent summary of thorium-based fuel physical and chemical properties can be found in [6]. Comparison of the hazards posed by thorium and uranium spent fuels is highly dependent on parameters such as timeframe, geology, and extent of reprocessing, and this frequent source of erroneous information is addressed in this special edition. Historically, thorium fuel cycles have been described as proliferation-resistant due to their external gamma radiation field (from the U-232 decay chain), although today these advantages are generally agreed to be overstated; the particular technical challenges of safeguards in thorium-based systems are introduced in another paper of this special edition.

We hope that this special edition will facilitate informed discussion of the thorium fuel cycle among researchers, nuclear industries, and power utilities by providing concise, up-to-date perspectives on the experiences with and capabilities of thorium.

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