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Transmutation Fuel Campaign Description and Status

Global Nuclear Energy Partnership

Prepared for
U.S. Department of Energy
Transmutation Fuel Campaign

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SUMMARY

This report contains a technical summary package in response to a Level 2 milestone in the transmutation fuel campaign (TFC) management work-package calling for input to the Secretarial decision. At present, the form of the Secretarial decision package is not fully defined, and it is not clear exactly what will be required from the TFC as a final input. However, it is anticipated that a series of technical and programmatic documents will need to be provided in support of a wider encompassing document on GNEP technology development activities.

The TFC technical leadership team provides this report as initial input to the secretarial decision package which is being developed by the Technical Integration Office (TIO) in support of Secretarial decision.

This report contains a summary of the TFC execution plan with a work breakdown structure, high level schedule, major milestones, and summary description of critical activities in support of campaign objectives. Supporting documents referenced in this report but provided under separate cover include:

- An updated review of the state-of-the art for transmutation fuel development activities considering national as well as international fuel research and development testing activities.[1]
- A definition of the Technology Readiness Level (TRL) used to systematically define and execute the transmutation fuel development activities.[2]

1 W.J. Carmack and K.O. Pasamehmetoglu, "Definition of Technology Readiness Levels for Transmutation Fuel Development," Idaho National Laboratory, INL/EXT-08-13780, GNEP-FUEL-FUEL-TD-RT-2008-000051, January 2008.

2 W.J. Carmack and K.O. Pasamehmetoglu, "Review of Transmutation Fuel Studies," Idaho National Laboratory, INL/EXT-08-13779, GNEP-FUEL-FUEL-TD-RT-2008-000050, January 2008.

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1. INTRODUCTION

The Global Nuclear Energy Partnership (GNEP) mission is to expand the use of Nuclear Energy both domestically and internationally, address the nuclear waste management issue, and promote nuclear nonproliferation. One of the mission critical components of the GNEP Program is a research and technology development effort, which includes a focus on transmutation fuels. The Transmutation Fuel Campaign (TFC) is responsible for developing and qualifying fuel form(s) that can be used in destroying the transuranic (TRU) elements in the spent nuclear fuel (SNF).
Transmutation fuel is generically defined as fuel forms containing the TRU elements and encased in a cladding material that can sustain high-burnups. The TRU elements targeted for destruction are Plutonium (Pu), Neptunium (Np), Americium (Am), and Curium (Cm). Note that if Cm can be easily separated from the other TRU elements, the preferred method to deal with Cm is to let it decay to Pu and then transmute the decay product. However, a simple partitioning technology does not currently exist; therefore, it is assumed that Cm will be included in the transmutation fuel. A simplified depiction of the GNEP fuel cycle is shown in Figure 1, Summary of GNEP Baseline Fuel Cycle. This is the direct baseline approach where fast reactors are used for destruction of the TRU while recovering the energy value in these elements.

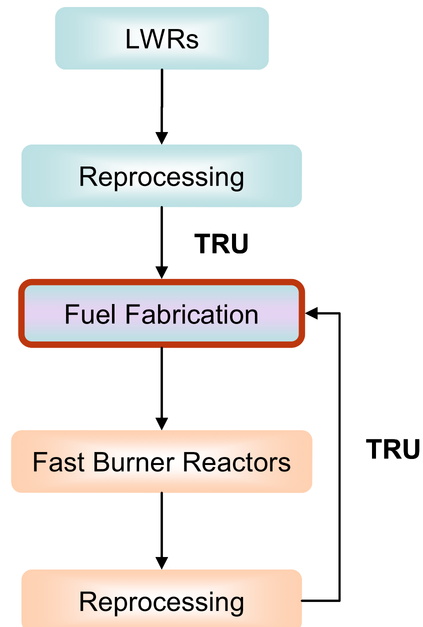

Figure 1. Summary of GNEP Baseline Fuel Cycle.

For the baseline approach, the TFC develops and qualifies transmutation fuels for fast reactors. The transmutation fuel can be designed to contain all the TRU elements together to be used in a fast reactor with a homogeneous core. Depending upon the separations and partitioning strategy, the transmutation objectives can also be achieved by two different types of fuels that can be used in a heterogeneous design. The driver fuel can be designed to contain Pu and perhaps Np blended with U. Minor actinides (primarily Am and possibly Np and Cm, depending upon the partitioning strategy) can be incorporated into secondary fuel (also referred to as MA targets).

Another transmutation option is recycling Pu into the Light Water Reactors (LWRs) in the form of Mixed Oxide (MOX) fuel. This option may be considered an intermediate step towards a fully-closed fuel cycle, prior to the introduction of a large number of fast reactors into the reactor fleet. A few passes in an LWR without the ultimate introduction of the fast reactors provide limited benefits in terms of GNEP principles of sustainability, repository utilization, and non-proliferation. However, this intermediate approach allows faster deployment of a closed fuel cycle, which ultimately requires a smaller fraction of fast reactors in the reactor fleet. The fuel type used for this initial step is likely to be the MOX fuel commonly used elsewhere, e.g., France. Thus, limited development is required for this fuel type, but a commercial-scale deployment using the products of the selected separations technology will be required. The TFC also includes the development activities for LWR MOX fuel deployment, if this choice is introduced into the GNEP deployment strategy.

By definition, the transmutation fuel covers a wide range of compositions that must be addressed during the development and qualification process. The following are the main reasons why the composition of the fuel cannot be maintained constant:

- Variable conversion ratio design for the burner reactor
- Age and burnup of the LWR fuel feed

- Compositional changes through multiple recycle in a fast reactor (especially if recycling into LWRs is introduced into the fuel cycle)
- Impurities in the fuel feed from the separation processes
- Burnup objectives for each pass through a fast reactor.

The development and qualification process must address the full range of compositions that are of interest to implement a closed fuel cycle. Furthermore, to optimize the fuel fabrication and fuel performance, consideration of multiple fabrication processes and advanced clad materials must be addressed during the development program.

The primary focus of the current report is the fast reactor transmutation based on the initial revision of the TFC Execution Plan.[c]

1.1 Transmutation Fuel Forms of Interest

As presented in the Idaho National Lab (INL) report INL/EXT-08-13779, “Review of Transmutation Fuel Studies,” initial studies confirm the feasibility of both metal and oxide fuel forms. The development of the pelletized oxide and metal fuels are slightly more advanced than the other ceramic or dispersion (either CERCER or CERMET) fuel forms. Comparing to the Technological Readiness Level (TRL) definitions discussed in INL/EXT-08-13780, “Definition of Technology Readiness Levels for Transmutation Fuel Development,” palletized oxide fuels and metal fuels containing minor actinides for transmutation applications are judged to meet the TRL 4 criteria. The analogue oxide and metal fuels (those containing U and Pu only without the MA additions also are further advanced than other fuel forms based on the available literature. Pelletized U-Pu oxide fuel fabricated with slightly different processes in various countries is judged to be at TRL 8. Metal fuel based on highly enriched uranium (HEU) also is at TRL 8 while the Pu containing version of the metal fuel is at TRL 7 (short of full core operations).

Based on these considerations and consistent with INL/EXT-08-13780, GNEP TFC is pursuing the development of both fuel types for a period of time until additional data is available to enhance the confidence level in the success of either form.

1.2 Transmutation Fuel Campaign Objective

The primary objective of the TFC is to qualify the transmutation fuel(s) for use in fast burner reactors over the entire range of compositions to obtain closure of the fuel cycle while maintaining the commercial competitiveness for nuclear energy.

A secondary objective is to sustain a long-term Research & Development (R&D) program to:

- Mitigate risk in case the initially selected options do not perform at the desired efficiencies
- Develop and maintain technologic capabilities for long-term competitiveness within the nuclear energy market.

If DOE chooses the LWR recycling option as an intermediate step towards a closed fuel cycle, the development of LWR fuel and/or target deployment strategy will become part of the primary objective. This includes incorporating the implications of this option into the transmutation fuel qualification program.

c. “Transmutation Fuel Campaign Execution Plan,” Revision 0, October 2008, GNEP-FUEL-PMO-PM-PL-2007-000326.

Within the context of the TFC, qualification means demonstration that the fuel will perform predictably and acceptably under normal operations and transient conditions. The qualification objective is achieved by:

- Rigorous testing for a limited number of fuel compositions, fabrication processes, and clad materials up to the level of lead-test assemblies
- An extensive modeling and simulation approach to quickly extend the empirical database to the entire range of variables that are needed to meet the GNEP objectives.

2. MAJOR TFC CATEGORIES AND WORK BREAKDOWN STRUCTURE

To achieve the objectives presented above, the TFC structure consists of three major categories:

- Integral Experiments
- Modeling and Simulation
- R&D Infrastructure.

Integral Experiments

Historically, nuclear fuel development has relied on an empirical approach. It is expected that such an empirical approach will be carried out to its full extent for a selected set of variables within the parametric range needed to achieve the GNEP objectives. Thus, a considerable amount of testing will be required for fuel fabrication and fuel performance under irradiation starting from bench-scale through engineering-scale as the campaign progresses.

Modeling and Simulation

The conventional modeling and simulation methodology relies heavily on an empirical trial-and-error approach. This must be revised due to the large range of variables that must be covered to qualify transmutation fuels. The scope of the TFC also includes the development and implementation of an advanced science-based approach to fuel qualification. The full power of advanced computational sciences will be utilized to supplement the empirical approach through an advanced modeling and simulation component.

R&D Infrastructure

New or upgraded research and development (R&D) facilities will be needed for fabrication, irradiation, characterization, and examination. Upgraded state-of-the art facilities are important because:

- The relevant U.S. infrastructure has degraded over the last few decades
- A science-based approach to fuel development demands a better examination and characterization infrastructure than currently available.

Some upgrades to existing facilities that will be used to support the TFC activities may be executed under a project structure, depending upon the scope of the work. These short-term projects are covered under this category.

The work breakdown structure (WBS) for the TFC was developed based on the key deliverables within the three major categories supporting the campaign’s objective. The WBS is summarized in Table 1 and described in the following sections.

Table 1. Transmutation Fuel Campaign WBS.

1.5.1. TRANSMUTATION FUEL CAMPAIGN

1. Transmutation Fuel Campaign Management and Integration
   1. National Program Integration
   2. Systems Engineering
   3. International Collaborations
2. Transmutation Fuel Fabrication and Characterization
   1. Metal Fuel Technology
   2. Oxide Pellet Technology
   3. Sphere-Pac/Vibro-Pac Technology
   4 Innovative Technologies
3. Core Materials
   1. Characterization/Fabrication
   2. Irradiation Performance
4. Fuel Irradiation Testing
   1. Irradiation Experiments
   2. Post-Irradiation Examination
5. Modeling and Simulation
   1. Code Development
   2. Model Development
   3. Phenomenological Testing
   4. Verification and Validation (V&V)
6. Fast Reactor Start-Up Fuel
   1. Test Fuel Fabrication and Characterization
   2. Qualification Verification Testing
7. R&D Project #1
   1. *TBD*
8. R&D Project #2
   2. *TBD*

2.1 TFC Management and Integration

Activities required to manage and coordinate the technical tasks of the TFC are included in this section.

2.1.1 National Program Integration

The TFC is a national program managed under the guidance of DOE. The management function includes defining and implementing the transmutation fuel related tasks and interfacing with the GNEP projects, other campaigns, the Technical Integration Office (TIO), the DOE management, and internal and external review groups.

2.1.2 Systems Engineering

Systems engineering directly supports the TFC Management and Integration, through scheduling, document management, requirements management, performance and progress tracking, and quality assurance functions. Design and process analyses in support of the requirements development also are included in this WBS element.

2.1.3 International Collaborations

GNEP is an international program with existing collaboration agreements and pending agreements with other countries. Transmutation fuel development is a major work package in all these agreements. The TFC will assist DOE in preparing and implementing the fuel-related international agreements; attend the relevant international working group meetings; and comply with the TFC-related financial and technical obligations specified in the international agreements.

2.2 Transmutation Fuel Fabrication and Characterization

At present multiple fuel types and forms are being considered for transmutation fuels. The primary fuel types considered for the initial qualification are metal and oxide fuels, but research on other fuel types will continue. In addition, fuel types and forms need to accommodate both homogeneous and heterogeneous recycling schemes.

2.2.1 Metal Fuel Technology

The activities cover the fabrication process development for metal transmutation fuels for both homogeneous and heterogeneous recycling schemes, consistent with the imposed requirements. Also included are fabrication and characterization of the metal fuel samples for irradiation and out-of-pile testing.

2.2.2 Oxide Pellet Fuel Technology

The activities cover the fabrication process development for oxide transmutation fuel pellets for both homogeneous and heterogeneous recycling schemes, consistent with the imposed requirements. Also included are fabrication and characterization of the oxide fuel samples for irradiation and out-of-pile testing.

2.2.3 Sphere-Pac/Vibro-Pac Fuel Technology

The commonly used ceramic fuels are based on ceramic pellets. However, for process simplification and potential cost-savings when dealing with remotely fabricated fuels, the TFC also is considering the sphere-pac or vibro-pac technology for oxide fuels. The activities cover the fabrication process development for sphere-pac/vibro-pac oxide transmutation fuels for both homogeneous and heterogeneous recycling schemes, consistent with the imposed requirements. Also included are fabrication and characterization of the fuel samples for irradiation and out-of-pile testing.

2.2.4 Innovative Technologies

The activities cover the fabrication process development at the bench-scale research level for fuel forms and types that are candidates for the second or third generation transmutation fuels (including fuel types for fast reactors other than sodium-cooled reactors). Typical examples are nitride, carbide, or dispersion fuels with a ceramic or metal matrix. Also included are fabrication and characterization of the innovative fuel samples for irradiation testing and out-of-pile testing.

2.3 Core Materials

Materials R&D is conducted within two campaigns in GNEP: the TFC and the Fast Reactor Technology Campaign. The out-of-core materials, which require American Society of Mechanical Engineering (ASME) code compliance, are included in the Fast Reactor Technology Campaign. Replaceable structural materials in the core (cladding, ducts and associated hardware) are covered under the TFC. Because of high-burnup requirements for the transmutation fuels, advanced alloys and composite clad structures (liners) are being investigated as part of the fuel development program. Interfacing with the materials related activities within other campaigns (especially with the Fast Reactor Technology Campaign) and projects is also a key function of this WBS element.

2.3.1 Characterization/Fabrication

The activities cover the fabrication process development and the definition of the technical specifications for core structural materials, consistent with the imposed requirements. Also included are the fabrication and characterization of the samples for irradiation testing and out-of-pile testing.

2.3.2 Irradiation Performance

The activities cover the design of irradiation experiments for structural material samples and coupons, the post-irradiation analysis of the samples, and the measurement of the relevant structural properties.

2.4 Fuel Irradiation Testing

This WBS element is responsible for in-pile testing of the transmutation fuels.

2.4.1 Irradiation Experiments

The activities include preparation of the test plans, the safety documentation for reactor insertion, the insertion into the reactor, and the irradiation testing. Domestic reactors that will be used for irradiation are the ATR and the HFIR; therefore, the activities must be closely coordinated with the reactor operations. In addition, if built, facilities such as the Material Test Station and/or ATR Fast Flux Booster may be used for irradiation experiments. Transient testing in the Annular Core Research Reactor (ACRR) and the Transient Reactor Test Facility (TREAT) are also being considered as part of the irradiation program. Also included are preparing the test plans, safety documentation, and fuel transfers for irradiations performed in foreign test reactors.

2.4.2 Post-Irradiation Examination

The activities include post-irradiation exams (PIE) performed according to the requirements and the test plan. Specific equipment or process development to meet the PIE objectives of a given test also are covered under this WBS element.

2.5 Modeling and Simulation

This WBS element is responsible for the development of the models and codes to be used in the transmutation fuel qualification.

2.5.1 Code Development

The activities cover the development of the computer codes that integrates the phenomenology for fuel fabrication and fuel performance. It is expected that the codes developed for predicting the fuel behavior will take full-advantage of the modern architectures for high-performance computing recently developed by the Advanced Simulation and Computing (ASC) program. An important feature of the new codes will be the capability of bridging over multiple temporal and spatial scales related to different phenomenology pertinent to fuel behavior. The recent advances made in computational sciences under the prevue of the DOE Office of Science also will be incorporated into these activities.

2.5.2 Model Development

The activities cover the development and assessment of various physics models required for closure of the transport equations integrated in the performance and fabrication codes. The closure models include thermo-physical, chemical properties, and radiation damage and may span a large temporal and spatial scale. The relevant work performed under DOE- Office of Science will be closely coupled with these activities.

2.5.3 Phenomenological Testing

Besides the integral experiments discussed above, there is a need for phenomenological testing (also referred to as a Separate-Effects Test [SET]). These tests may be in the form of short duration irradiations or out-of-pile testing targeted for specific phenomena. These special tests will be used for developing and benchmarking the closure models and a strong integration of this testing into the modeling development effort is critical to improvement of the physics contained within the closure modeling effort.

2.5.4 Verification and Validation (V&V)

Because the codes will ultimately be used for establishing the safety basis for fuels qualification along with design of fuel fabrication facilities, a rigorous V&V program is essential. Past experience shows that starting the V&V planning early in the code development process and integrating it into the program is important for success (Reference: LA-UR-07-1865).

2.6 Fast Reactor Start-Up Fuel

To complete the transmutation fuel qualification, it is expected that a fast reactor will be available for testing the transmutation lead test assemblies (LTAs). The TFC assumes that the startup fuel for the fast reactor will be based on current technology that produces a commonly used fuel form.

2.6.1 Start-Up Fuel Fabrication and Characterization

The various options for startup fuel fabrication will be evaluated and the results provided to DOE. Included in this scope is the identification of the characterization requirements for different fabrication options. This activity covers the development of the technical specifications for the fabrication process to ensure the final product is identical to the previously qualified fuel. The technical specifications will be partly based on the testing requirements developed under Qualification Verification Testing.

2.6.2 Qualification Verification Testing

Even though an existing fuel form will be used as the start-up fuel for the fast reactor, it is likely that some verification testing will be required to ensure that the fuel fabricated for the reactor is identical to the previously used fuels. Initially, the verification testing requirements will be defined in collaboration with the regulatory agency. Subsequently, once fuel fabrication is initiated at a selected site, the actual experiments will be included in this activity.

2.7 Infrastructure Projects

Under the TFC, there may be a number of projects initiated to provide the temporary infrastructure needed to support the fuel development program objectives. These projects typically deal with improvements or refurbishment of existing facilities. Each project will operate with an execution plan and a defined WBS. The following are examples of infrastructure projects likely to be conducted under the TFC.

PIE and Characterization Equipment. DOE provided funding in FY-07 to the INL to develop state-of-the art characterization and PIE capability to support the fuel development needs. This is primarily a refurbishment project of the applicable existing facilities at the INL to accommodate installation and operation of the new equipment.

Metal Fuel Fabrication Hot-Cells. In order to fabricate TRU fuels at quantities that support the experimental program, a hot-cell facility to remotely fabricate metal fuel is needed. The preparation of a hot-cell facility, until it is available for fuel fabrication, will be managed as a project.

Oxide Fuel Fabrication Hot-Cells. In order to fabricate TRU fuels at quantities that support the experimental program, a hot-cell facility to remotely fabricate oxide fuel pellets is needed. The preparation of such hot-cell facility, until it is available for fuel fabrication, will be managed as a project.

3. HIGH-LEVEL SCHEDULE AND MAJOR MILESTONES

A notional schedule for the TFC is provided in Figure 2. While developed for the homogeneous recycling option, this schedule also applies to the option of heterogeneous recycling, since the driver fuel and MA target development activities will be conducted in parallel. A list of the major milestones and the critical dates relevant to the transmutation fuel development and demonstration are provided in Table 2.

These high-level schedules are provided as a guide to the detailed implementation plans. The schedules will be revised annually based on GNEP program directions and budget commitments. A critical date for program direction is the Secretarial decision in FY-08. A more detailed description of some of the activities and milestones are provided below.

3.1 Down-selection of the fuel form for initial transmutation applications

The selection between metal and oxide fuel for initial transmutation application depends on many factors, including factors totally outside the prevue of the TFC.

Reactor Design – Metal or oxide fueled reactor cores have different performance characteristics for steady-state operations and, more importantly, under transient conditions (safety characteristics). Thus, given both fuel forms can be shown to meet the fabrication and performance requirements, the selection may depend on the reactor design philosophy.

Separations Technologies – The selection of the separations technology and partitioning philosophy also has a major influence on the fuel selection. For instance, electrochemical process is the preferred technology for metal fuels while it can be used for oxide fuel as well. Aqueous processes that appear to be more technologically mature are also applicable to oxide fuels. Group TRU separation favors electrochemical technologies while additional partitioning of the TRU is likely to require aqueous based techniques. Thus, the fuel selection is not totally independent than the separation and partitioning technology selections.

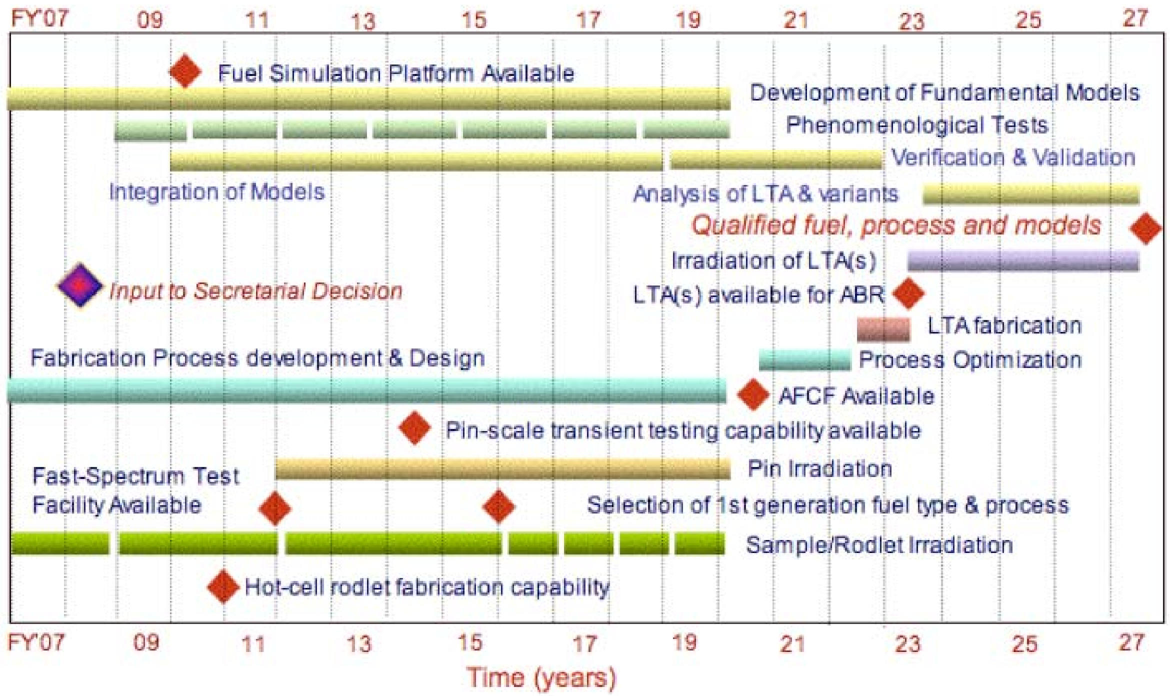

Figure 2. Notional TFC Schedule for Development of Transmutation Fuels, including Minor Actinide (MA) Targets.

Table 2. Transmutation Fuel Development and Demonstration Major Milestones and Critical Dates.

MILESTONE	DATE
Initial revision of the campaign execution plan (yearly updates)	1st Qtr FY-08
Initial version of 5-year implementation plan (yearly updates)	2nd Qtr FY-08
Transmutation fuel technical assessment input for Secretarial Decision	3rd Qtr FY-08
Fuel modeling and simulation platform/architecture available	1st Qtr FY-09
Hot-cell fabrication facilities available for primary fuel forms	1st Qtr FY-11
Domestic fast-spectrum irradiation test facility available	3rd Qtr FY-11
Selection of the initial transmutation fuel type for qualification	1st Qtr FY-14
AFCF assembly fabrication module available	2nd Qtr FY-20
Fuel performance and fabrication codes completed	2nd Qtr FY-20
LTAs available for insertion into the fast reactor	2nd Qtr FY-23
Fuel codes V&V completed	2nd Qtr FY-23
Initial LTA irradiation completed	1st Qtr FY-27
Fuel qualification completed	1st Qtr FY-28

Based on the review provided in INL/EXT-08-13779, both metal and oxide fuels are believed to be feasible for transmutation applications. The TRL for each fuel form is judged to be equal at TRL 4. There is additional development needed and some additional performance issues need to be addressed, especially to achieve relatively high burnup levels (>100 MWd/kg). The technical risk to achieve the performance objectives appears manageable. If all other factors are equal, the major differentiating factor between oxide and metal fuel technologies is associated with the remote fabrication. Therefore, under the TFC, the selection milestone is set to FY-14, three years after the availability of hot-cell fabrication capabilities for both the metal and oxide fuels. This allows adequate testing of the remote fabrication processes and associated losses, characterization (quality control techniques), and the implications on the availability and economics at commercial scale.

In addition, data on irradiation performance in a prototypic irradiation environment (fast spectrum irradiation) on these fuels will be collected for direct comparison. Small scale transient testing data aimed at failure threshold and mechanisms will be available for selection.

Based on these considerations, it is believed that after completion of TRL 5 (see INL/EXT-08-13780), a technically based selection with minimal residual risk can be made for the fuels. Obviously, the inputs from the reactor design and separations campaign are equally as important in the selection evaluations.

3.2 Hot-Cell Fabrication Capabilities

One of the major issues with the transmutation fuels/targets is the need for remote fabrication in hot-cells. The fabrication processes along with the quality control techniques need to be tested in a remote fabrication test bed before the implications on availability, economics, and fabrication loss quantifications can be assessed. As an intermediate-scale before engineering-scale demonstration, TFC depends on a laboratory-scale testing using existing hot-cells retrofitted for metal and oxide fuel fabrication. The fabrication-scale used at laboratory scale is assumed to be on the order of 1 kg HM/year using equipment and processes adequate for the laboratory scale. It is assumed that, through simple engineering scaling or advanced modeling and simulation, laboratory scale testing will directly support the design and operations of the subsequent engineering scale demonstration for the fabrication of the selected fuel type. In order to maintain the schedule shown in Figure 2, the hot-cell fabrication capabilities must be available no later than the beginning of FY-11. These hot-cells will support TRL 5 and TRL 6 activities in the development program (see INL/EXT-08-13780).

3.3 LTA Fabrication Capabilities

To complete the fuel qualification (TRL 7), irradiation of a number of LTAs is needed. To achieve that objective, an assembly-scale fabrication capability is needed. The assembly-scale fabrication using prototypic processes completes the engineering-scale demonstration for the fuel fabrication.

Under GNEP, the LTA fabrication is envisioned to take place in the Advanced Fuel Cycle Facility (AFCF), which is one of the major projects. AFCF is being conceptualized with a throughput on the order of 100 kg TRU/year, which is adequate for fabricating multiple LTAs per year. Either green-field or brown-field facilities are being considered for AFCF. AFCF design, construction, and operation are not under the prevue of TFC, but TFC is responsible for developing and defining the technologies and processes to be deployed in AFCF for assembly fabrication.

3.4 Irradiation Testing Capabilities

The fuel development program must rely considerably on irradiation testing, even with the envisioned extensive support by the modeling and simulation activities. If there were a dedicated fast test reactor to support the TFC, the irradiation testing program would have been simplified considerably. Such a test reactor would be used to perform targeted experiments at various geometric-scales and for various phenomenologies to advance to TRL in concert with the modeling and simulation activities. The lack of such a dedicated fast test reactor complicates the irradiation testing program.

To complete the TRL 5 and TRL 6 activities, testing needs are divided into representative environment and prototypic environment. Representative testing needs will be fulfilled using thermal spectrum test facilities, such as the ATR and HFIR where large number of samples can be irradiated using a thermal-flux filtering technique while meeting the thermal conditions of the fuel as closely as possible. Even if the thermal conditions (boundary conditions and power generation rates) can be closely matched, there are two major issues with these tests:

- Radial fission density distribution which affects the radial power density distribution and temperature profiles; and
- Damage rates and helium/hydrogen production rates in the clad material.

Because of these issues, the results of the experiments conducted in a thermal test reactor must be verified using a fast spectrum testing capability before the results can be extrapolated to predict the fast spectrum performance of the fuel. Currently, there are two possibilities for obtaining fast spectrum data to supplement the thermal reactor testing data.

- One possibility is the Material Test Station (MTS) proposed to be built at the end of the LANSCE accelerator at Los Alamos National Laboratory. This approach relies on producing fast neutrons through spallation with a sufficiently high flux for meaningful testing over a small irradiation volume. The spallation produced neutron spectrum is harder than a fast reactor spectrum, but it is believed to provide meaningful data to supplement the thermal reactor testing. With a concentrated effort, this facility may be available in 3 to 4 years for small-scale fast spectrum testing. Because of geometric limitation, such a facility cannot be used prototypic pin designs, but it will be invaluable to provide phenomenological data to supplement the thermal reactor testing and modeling and simulation efforts.
- While they are not readily accessible for testing large volumes of fuel pins or rodlets, foreign fast test reactors also are needed for targeted tests. Collaborative oxide and metal fuel tests are currently ongoing in the French Phenix reactor (see INL/EXT-08-13779). Efforts are underway to perform similar collaborative tests in the Japanese JOYO reactor and the Russian BOR60 reactor. Obviously, large-scale with large-throughputs are hampered in such reactors because of the National priorities of the owner countries and the limitations associated with transport of fresh and irradiated fuel samples. Larger pilot-scale reactors such as MONJU in Japan and BN600 in Russia also are candidates for doing pin-scale testing under limited set of conditions covered by their safety bases.

3.5 Transient Testing Capabilities

Transient testing of any new fuel form will be required to demonstrate acceptable behavior during anticipated transient and design basis accidents and to establish operational constraints. Under the TFC execution plan, there are four primary goals in the transient testing of fuel pins.

- <u>The first goal is primarily exploratory</u> and is aimed at some initial assessment for the transmutation fuels of interest compared to more traditional fuels where a large transient database is available. The objective is to relate new, TRU-bearing fuels back to the historical database of transient performance. Transient testing of traditional compositions, compared to compositions, which include substantial quantities of the minor actinides, will reveal the major differences in transient fuel behavior due to the presence of the minor actinides.
- <u>The second goal of transient testing is comparative</u> among candidate fuel forms. The objective is to identify any disqualifying behaviors and/or to highlight differences in transient testing performance between candidate metallic and oxide fuel forms during transient scenarios. These data are important for the fuel form down selection decision. The advanced fuels tested so far in the Advanced Fuel-Cycle Initiative (AFCI) fuel development program have had high success rates (i.e., no failures) during limited steady state irradiation in ATR (and similar tests conducted for abroad for

transmutation fuels). However, fuel behavior during transients and at the margin limits of operating conditions present more challenging environments for fuel and must be understood.

- The third goal of transient testing is to establish the design- and safety-basis. The objective is to provide feedback to reactor designers and fuel designers regarding transient conditions and fuel performance. Fuel designers must understand the possible reactor transients (i.e., design basis accidents) in order to subject fuel to appropriate conditions during transient testing. Reactor designers must understand fuel response during transient conditions in order to design the reactor to prevent or mitigate the severity of an accident.
- The forth goal is confirmatory. Once the fuel design is completed, the transient testing is used on prototypic fuel design to demonstrate the established safety basis for the design basis transient of interest.

Transient testing can be performed in- or out-of-pile, depending upon the transient conditions of interest. While transients dealing with decay heat removal are typically dealt with using out-of-pile experiments, transients dealing with reactivity insertion must be tested in-pile. Transient irradiation tests are important to provide internal fission heating in the fuel that cannot be replicated in ex-pile furnace tests because temperature profiles and thermal gradients due to internal fission heating are important to certain fuel behavior phenomena.

Based on the TRL descriptions for the fast reactor transmutation fuel (see INL/EXT-08-13780), the development and demonstration is done in three major phases:

- Proof-of-concept (covering TRL 1 through 3)
- Proof-of-principle (covering TRL 4 through 6), and
- Proof-of-performance (covering TRL 7 through 8).

As discussed in Reference 1, INL/EXT-08-13780, in-pile transient testing of transmutation fuel will be required in the proof-of-principle phase during steps corresponding to TRL 5 and 6, prior to insertion of lead-test assemblies into a prototypic reactor. Early phase transient testing is performed to demonstrate fundamental understanding of the behavior using representative conditions and later phase transient testing is required to provide confirmation of acceptable and predictable fuel performance during anticipated accident or off-normal scenarios.

The requirements for transient testing of fast reactor transmutation fuel can be divided into three general categories:

A. Geometry/Dimensions,
B. Irradiation Conditions (including control system capabilities), and
C. Measurement Capabilities.

Additionally, transient testing requirements may differ for different types of advanced reactor fuels. The U.S. is investigating a variety of advanced reactor designs, utilizing both thermal and fast spectra and innovative fuels. Different reactor designs will have different transient conditions and representative and bounding accident (off-normal) scenarios.

In general, any transient testing capabilities developed in the U.S. should be able to accommodate as wide a range of transient conditions as possible to meet the needs of as many fuel types as possible. Unless a very specific fuel cycle is chosen early on, additional investment in the early design and construction phases may provide significant additional capabilities that will avoid the need for multiple facilities at a later date.

3.5.1 Transient Testing Requirements

Transient testing requirements for fast reactor transmutation fuels are described according to the phase of fuel development.

3.5.1.1 Fundamental Understanding of Transient Behavior (TRL 5)

Early transient testing should be focused on phenomenological studies of the fuel and interactions within the fuel or between fuel and cladding or other reactor materials. Early tests can provide insight into the fundamental behavior of fuel forms and their constituents. Early transient tests also provide important information regarding the effects of minor actinides (or other composition differences) compared to traditional fuel compositions. The testing under this category also is important in its support of the advanced modeling and simulation efforts by focusing on phenomenologically targeted tests.

Geometry/Dimensions

In the applied research phase, transient tests would consist of simple capsule-type experiments. Existing steady-state irradiation samples in ATR are in the form of miniature rodlets. Overall fuel rodlet length is approximately 6 in.

Irradiation Conditions

Early phase steady-state irradiation testing does not require fully prototypic irradiation conditions. The same should apply to transient testing. The goals of transient testing in this phase are to provide screening tests to determine intrinsic transient overpower response to identify any disqualifying fuel behavior.

Irradiation conditions for initial phase transient testing should include a range of overpower ramp rates and peak powers and should replicate the range of test conditions present in the historical database. Transient testing in this phase can likely be performed preferably in a flowing sodium loop but, in some cases, in simple capsules without sodium coolant. However, simulations of the heat removal rate of any proposed test assembly should be performed and compared to expected prototypical fast reactor conditions. The test assembly, even in the initial phase, should match the heat removal rate conditions as reasonably as possible.

In any phase, it is important to know the appropriate conditions (e.g., power, temperature, coolant flow rate) during the irradiation test. However, during the initial phase, the test conditions will not be required to exactly match a reactor accident scenario (the reactor design has not yet been finalized). Therefore, the reactor control system may not be required to be able to simulate a prototypical accident scenario.

Measurement Capabilities

One of the goals of transient testing during the initial phase is to identify the failure threshold for TRU-bearing fuels. Pre-failure fuel motion is one key indicator leading to fuel failure. The ability to measure fuel motion during transient testing is critical to identifying the onset of fuel failure. If the ability to measure in-situ fuel motion in unavailable, many transient tests must be performed with appropriate PIE to determine whether or not a specific fuel failed and the test repeated over a range of transient energy input conditions and fuel burnup conditions.

3.5.1.2 Prediction and Confirmation of Transient Fuel Performance (TRL 6)

During the prediction and confirmation phase, prototypic fuel rods and assemblies must be irradiated in representative transient environments under the full range of relevant normal and off-normal conditions. The precursor steady-state irradiations in this phase must be done under prototypic conditions. The results of this phase must be sufficient to support a Fuel Specification and Fuel Safety Case. If the experiments are done in support of the LTA qualification, reference fuel is fabricated from production supply sources and irradiated to design conditions in a prototypic environment. Transient testing requirements for the qualification tests are similar to the tests done for prediction and confirmation.

Geometry/Dimensions

Transient testing in the prediction and confirmation phase must be able to accommodate full-scale fuel rods and at least partial assemblies and, possibly, full assemblies. The active fuel region of the transient test reactor must be at least as long as the active fuel region of the TRU-bearing fuel.

Irradiation Conditions

Irradiation conditions in the prediction and confirmation phase must be able to replicate the anticipated transient conditions and design basis accidents of the proposed fast reactor design. Accurate heat removal rates will require flowing sodium loops to provide prototypical cooling.

Measurement Capabilities

Transient testing must be able to detect in-situ pre-failure and post-failure fuel motion and behavior. A neutron hodoscope (i.e., real time neutron radiography) was previously used for this purpose. Pre-failure fuel motion is an important indicator of fuel failure and post-failure fuel motion and fuel interaction with the cladding and coolant dictate the severity of the transient.

3.5.2 Summary of Transient Testing Needs

Early phase transient testing aimed at fundamental understanding of the transient behavior can likely be performed with simple capsule-type tests and miniature fuel samples (e.g., rodlets). Such tests should be performed over a wide range of conditions and can utilize a variety of components and constituents to simulate transient conditions. For example, simplified some transient tests could be performed in static-gas filled capsules or even flowing gas capsules. However, transient testing during Prediction, Confirmation and Qualification phases must be conducted under prototypical conditions. This must be done utilizing flowing sodium loops to produce the correct heat removal rates and fuel-coolant interactions during fuel release.

The ability to measure in-situ fuel motion is key to understanding fuel behavior and fuel failure predictors. Additionally, fuel motion during and after release from the cladding dictates the severity of the transient.

Simulating the correct transient is important. This is accomplished by the transient reactor control system. The reactor control system must be able to simulate the requested transient pattern, which may be simplified for early phases of the testing and must simulate design basis accidents for qualification of the LTAs.

Post-irradiation examination is also an important consideration. Some fuel samples will be disrupted during transient testing. If fuel is not examined at or near the transient reactor site, the fuel must be stabilized without affecting the transient test results before it can be shipped.

3.6 Modeling and Simulation Capabilities

The general capabilities that will be developed as part of the Modeling and Simulation (M&S) activities are as follows:

- Data Storage and Archives: Repositories will be maintained to contain product configurations, data used in development and validation, V&V suites, and reference input (meshes and product input files such as production fuel models). The TFC may use other repositories that meet the necessary requirements, e.g., a data repository. The objective of these repositories is to define the pedigree of any part that may be used in a prediction.
- Software quality and configuration tracking: Products shall be maintained under configuration control. This includes not only the major products but also all utilities, scripts, and other software or information contained in the repositories that could affect product results.

- Documentation: Because of the vast amounts of information that will be produced over the lifetime of the TFC, it is necessary that a systematic approach be part of the process. This should include archival storage and also online documentation of the various products employed.
- Uncertainty quantification: This will be employed in both the V&V aspects of product development.
- V&V will be completed as part of product delivery.

3.6.1 Fuel Performance M&S Capabilities

The M&S objectives for fuel performance (given fuel and cladding type, fuel element design, and power history) are as follows:

- The ability to predict the fuel element safety margin during normal reactor operation and design-basis accidents. Safety margin is defined as the margin between the nominal thermomechanical state of the fuel element and its design limits
- The ability to predict the time that a fuel-element-cladding breach will occur
- The ability to improve clad/duct performance through microstructural manipulation of advanced steels.

To meet these objectives, the capabilities provided in Table 3 are needed.

3.6.2 Advanced Oxide Fuel Fabrication

Fabrication of ceramic fuel pellets is typically done by conventional ceramic processing. The fabrication steps include feedstock blending, powder milling, introduction of additives (binder, plasticizer, and lubricant), pellet pressing, binder burnout, and sintering under a controlled atmosphere, and, usually, grinding of the final pellet to within geometric specifications. From this complex processing of a multicomponent system, a consistent fuel pellet must be produced with controlled (either homogeneous or heterogeneous) microstructure, geometry, density, and oxygen stoichiometry, while maintaining low defect and impurity levels. The M&S objectives for oxide fuel fabrication are as follows:

- The ability to characterize microstructural evolution as a function of composition (including stoichiometry) and sintering temperature
- The ability to ensure proper final pellet geometry
- The ability to optimize the fabrication process to produce consistently acceptable fuel pellets.

To meet these objectives, the capabilities provided in Table 4 are needed.

The combination of these models will enable efficient process design and optimization, which will be highly desirable (if not required) for fabrication of mixed-oxide fuels bearing minor actinides in a hot-cell-based process line. Integration of these models should allow, for instance, design of a process that yields a net-shape sintered pellet such that pellet grinding (which will be a major source of waste and contamination) can be minimized or eliminated.

Table 3. Fuel Modeling and Simulation capability needs.

M&S Capability	Why Capability is Needed
Temperature distribution throughout the fuel element.	Maximum fuel and cladding temperatures are set by the design limits of the fuel element. To predict the safety margin, the code must constantly check the nominal temperatures against the design limits.
Stress-strain state, dimensions of the fuel and cladding, and the fuel-cladding mechanical interaction.	Maximum cladding strain is set by the design limits of the fuel element. To predict the safety margin, the code must constantly check the nominal cladding strain against the design limit. Fuel dimensions affect core criticality, which influences reactor control. Cladding dimensions affect coolant flow in the subassemblies.
Irradiation effects in fuel, such as change in actinide and fission product inventory, fission gas release, constituent redistribution, oxygen redistribution, restructuring, solid and gaseous fission product swelling, cracking, densification, and creep.	Irradiation alters fuel material properties impeding heat transfer in the fuel element and causing the fuel to operate at a higher temperature to generate the same amount of energy. Maintaining the fuel temperature within the design limit while coping with irradiation-induced degradation of the fuel and cladding is the main fuel safety challenge. Irradiation effects cause the decrease of the fuel melting temperature.
Irradiation effects in cladding such as irradiation-induced creep, swelling, hardening, and embrittlement.	Irradiation effects in cladding reduce cladding load bearing capacity. Irradiation induced creep and swelling contribute to the cladding strain.
Thermal creep of the cladding.	Thermal creep is a primary failure mechanism of some cladding types and a key contributor to the cladding strain.
Cladding wastage due to fuel-cladding chemical interaction and coolant-cladding chemical interaction.	Cladding wastage reduces cladding thickness, thus reducing cladding load bearing capacity. Fuel-cladding chemical interaction results in low-melting products, thus reducing maximum allowed fuel operating temperature.
Cladding failure criteria.	Cladding failure criteria must be determined in order to predict cladding breach.

Table 4. Oxide fuel fabrication modeling and simulation needs.

M&S Capability	Why Capability is Needed
Fuel composition.	Fuel composition modeling would be used to improve the efficiency of fuel development R&D, in which pellet composition, microstructure, density, and stoichiometry are varied for fuel performance irradiation tests.
Green pellet pressing model to yield density/stress distributions in a pellet as a function of pressing parameters, such as die profile and type, pellet L/d ratio, pressing pressure, load dwell time, and powder flow characteristics.	The pressing model will facilitate control of green density (for controlled shrinkage in subsequent steps), design of die geometries for optimized sintered pellet size and shape, and mitigation of residual stresses in green pellets, which lead to flaws such as lamination and end-capping (especially in pellet geometries that include a dish and/or chamfer).
Furnace model. To show thermodynamic aspects of furnace atmosphere control to set oxygen activity for various fuel compositions. To be calibrated to a specific fabrication furnace to efficiently establish sintering profile parameters. To predict the variation in the final pellet specifications (in coordination with the sintering model).	Furnace modeling will inform the need to control furnace temperature ramp rates and uniformity as well as the need to control the oxygen activity for sintering kinetics and adjusting the final oxygen to metal ratio [O/M] in the fuel.
Sintering model. To show shrinkage, densification, and microstructural evolution as a function of fuel composition and furnace time, temperature, and atmosphere. To account for thermal and species transport during sintering, including phase stability (both thermodynamic and kinetic). To account for starting stoichiometry of the green pellet.	The sintering model will be key to establishing desired pellet microstructures, compositions, and densities that are suitably stable when irradiated. This model will also predict the final geometry of the sintered pellet. Integration of the pressing and sintering models will permit identification of preferred powder characteristics, e.g., starting O/M, particle size, and flow properties, thus helping to generate a specific feedstock specification.
Phase diagrams for the given ranges of the fuel compositions.	Fuel microstructure evolution and mobility of the constituents are determined by phase diagrams of the fuel. A large experimental program would be required to determine phase equilibrium in a six component system even for a narrow compositional range. A program of modeling combined with experimental validation will be necessary to make significant progress.

3.6.3 Metallic Fuel Fabrication Modeling and Simulation Requirements.

The ultimate goal of the metallic fuel fabrication M&S is to develop a modeling and simulation tool to aid in the design and scale-up of fuel fabrication systems and to optimize fuel fabrication parameters that result in low TRU loss and optimal microstructures.

The key predictive capabilities for metal fuel fabrication M&S are provided in Table 5.

Table 5. Metal Fuel Fabrication Modeling and Simulation needs.

M&S capability	Why capability is needed
Flow and solidification of the melt during the casting process.	This capability is necessary to aid in the design of a casting system, to optimize casting process parameters such as pressure differential and temperature, to minimize TRU loss through appropriate process parameters, and to ensure that selected processes are scalable to meet the production requirements for commercial deployment.
Fuel microstructure evolution during the casting process.	This capability will allow efficient fabrication of the fuel that meets reactor safety requirements without performing extensive fuel fabrication development work by trial-and error testing.
Temperature history throughout the casting charge.	TRU loss and microstructure evolution in the cast fuel are temperature driven; therefore, accurate prediction of the temperature distribution at all times during casting is paramount.
Phase diagrams for the given ranges of the fuel compositions.	Fuel microstructure evolution and volatility of the constituents are determined by phase diagrams of the fuel. A large experimental program would be required to determine phase equilibrium in a six component system even for a narrow compositional range. A program of modeling combined with experimental validation will be necessary to make significant progress.