REQUIREMENTS AND LONG-TERM DEVELOPMENT PLAN FOR FAST-SPECTRUM TRANSMUTATION FUELS IN THE U.S.

Douglas C. Crawford, Mitchell K. Meyer, Steven L. Hayes and **James J. Laidler**
Argonne National Laboratory, U.S.A.

Abstract

An objective of the Advanced Fuel Cycle Initiative in the United States is to develop technologies for transmutation of transuranic elements currently in spent light water reactor fuel. The advantages of fast-spectrum reactors, including accelerator-driven systems, are recognised. Because low-to-zero conversion-ratio designs are desired, fuels with little or no fertile uranium are required. Based upon institutional experience with fast reactor fuels, a set of requirements for the new fuels and a conceptual long-term development plan have been drafted to guide the development process. Many of the proposed requirements are similar to those that would be used for a sodium-cooled fast reactor; although such requirements are tentative, they provide a useful basis for initiation of the programme. The long-term development plan indicates that demonstration of a new fuel technology could be accomplished in less than 25 years, but successful technology development and convenient access to test facilities is assumed.

Introduction

The Advanced Fuel Cycle Initiative (AFCI) in the United States will, among other objectives, develop technologies for transmutation of transuranic elements currently in spent light water reactor fuel. The motivation for applying transmutation is improving the waste management strategy in the U.S. to reduce long-term costs of using geologic repositories and to reduce the waste management burden on future generations. At the time of this writing, the AFCI strategy remains transitory as newer and broader fuel cycle objectives are incorporated into the Initiative. However, the advantages of fast-spectrum reactors, including accelerator-driven systems, are recognised. Low-to-zero conversion-ratio concepts are targeted for development because such systems offer the quickest means to address transuranic elements that would otherwise require long duration of isolation by geologic disposal. The success of such concepts will depend on several technology advances, including the development of fuels with little or no fertile uranium. Although non-fertile fuels have been investigated previously, there was not sufficient work completed to establish such a fuel for any reactor system. Little of the non-fertile fuel work was applied to fast-spectrum systems, because those systems were primarily considered for creating fissile material and not for consuming it. Furthermore, development of non-fertile or low-uranium fuels is considered a technical challenge due to the complications to fabrication and performance that are exacerbated with increased proportions of transuranics in fuel (e.g., volatility of americium and its compounds, uncharacterised phase formation, and increased helium generation during irradiation).

The long-term nature of fuel development and the technical challenges inherent in the fuel compositions of interest for transmutation necessitate a review of anticipated fuel requirements and a long-term plan for fuel development. This paper presents the current versions of fuel requirements that have been assembled to guide the programme in the U.S. and a long-term fuel development plan to be considered with larger-context programme planning. The development plan is that envisioned to develop transmutation fuels through an Integrated System Demonstration (ISD).

Fuel development programme objectives

The long-term objective of AAA transmutation fuel development is the licensing of transmutation fuel[1] technologies. The primary programme tasks are to:

- Develop fuel designs and fabrication processes that satisfy transmutation mission demands, meeting requirements for system safety and for recycle technology compatibility.
- Acquire information to support safety analyses for fuel licensing and decisions based on technology economics or operational reliability.

Given successful completion of the first task, the second can be achieved through an Integrated System Demonstration (ISD). Therefore, development of fuel and target technology is driven by schedule and technology requirements for the Integrated System Demonstration.

---

1. In this document, the term "fuel" shall be used to mean fuel and target. In this context, "fuel" refers to actinide forms that add reactivity to the transmutation system, and "target" refers to actinide forms that do not add reactivity to the system. The approach to develop and qualify either type is essentially the same, allowing for a similar treatment in this document.

The tasks to be used to achieve the programme objectives can be guided by two sets of sub-objectives: one set to guide the fuel development tasks and another to guide the qualification and licensing tasks. Each are listed below.

Fuel development sub-objectives

- Specification of fuel designs, including chemical composition and form, geometric configuration, and design and materials of construction of fuel- and target-related components, such as cladding and assembly hardware, which meet performance requirements for the transmutation system (including safety and recycle requirements).
- Specification of fabrication processes that meet constituent loss and fuel cycle economics requirements.
- Measurement and correlation of fuel material properties.
- Identification of life-limiting fuel behaviour.
- Establishment of failure thresholds and assessment of failure consequences.
- Development of accurate models for fuel performance, with emphasis on life-limiting phenomena.
- Optimisation of fuel technology (including design and fabrication).

Fuel qualification and licensing sub-objectives

- Demonstration of consistent product quality from reference fabrication processes.
- Demonstration of acceptable and predictable fuel performance and of a core of transmutation fuels under nominal conditions and certain off-normal conditions.
- Establishment of margins to failure and demonstration of acceptable failure consequences for normal operation and for design-basis accident conditions.
- Assimilation of a fuel performance and property database to support safety analyses and the development of predictive fuel performance codes.
- Development and validation of integrated fuel performance codes to support licensing.

Fuel functions

Transmutation fuel rods and assemblies shall perform the following functions:

- Position the materials to be transmuted into the neutron flux of the transmuter.
- Provide for efficient heat generation and removal for economic energy production (if energy production is to be part of the mission).
- Provide a barrier to the release of fission products.
- Provide a convenient unit for insertion of fresh fuel into the core and for removal, handling and processing of spent fuel.

Fuel requirements

Currently, several transmutation system concepts are being evaluated to determine which are the most suitable for meeting U.S. needs. Included are reactors and accelerator-driven transmuters, with thermal-spectrum and fast-spectrum concepts each proposed for use in either a single-tier scheme or for use in combination in a dual-tier scheme. Because transmutation technology is in an early stage of development, many of the specific requirements for transmutation fuel are either unknown or will change from current assumptions over the next several years. However, many requirements can be deduced or assumed based on experience with similar reactor systems.

The currently envisioned requirements for fast-spectrum transmutation fuels are based, in part, on requirements for fuel for a Na-cooled fast reactor system and are described in this section.

Irradiation performance during normal service conditions

Requirements for irradiation performance are based on safety, economics, and operability considerations and are established for normal and off-normal conditions. Normal conditions are those encountered in the reactor during steady-state operation and during operational transients (e.g., during start-up and shutdown). Off–normal conditions are those encountered during anticipated and unlikely events, which will be determined through the reactor design evaluation process and analysed during safety evaluation for licensing. Requirements for normal conditions are addressed in this subsection, while those associated with safety and off-normal conditions are addressed in the next subsection.

Fuel rod breach rate: 3.3×10^{-4} In general, release of radionuclides from fuel rods into coolant is undesirable from perspectives of system operability as well as safety. Fortunately, some small number of fuel breaches can typically be tolerated without unacceptable exposure of workers to radiation from radionuclides in the coolant system. Although such exposures can be mitigated through careful maintenance and operating procedures and the use of personnel protective equipment, some restriction on radionuclide content in the primary system will be necessary. The amount of radionuclides that can released into the coolant will depend on the ability of support systems to clean the coolant and the degree to which operations necessarily expose personnel, each of which will be functions of the specific reactor design. The next factor to be successively considered in determining allowable fuel (or target) breach rates is the propensity of breached fuel to release radionuclides into the coolant. This will be affected by fuel rod design, coolant flow behaviour, the chemical reactivity of fuel and fission products with coolant, and fuel rod condition at the time of breach. Experience with Experimental Breeder Reactor II (EBR-II) metallic fuel had determined that a breach rate of 3.3×10^{-4} (less then one pin per EBR-II core loading) with 2-sigma confidence would be acceptable, and that rate is proposed for transmutation fuel.

Other requirements As transmutation core designs mature, more specific requirements will emerge for operating conditions such as linear heat generation rate and fast flux and for design parameters such as fissile density. Design criteria or performance limits can also be established to ensure that fuel performs reliably in service up to the given burn-up limit. Such criteria and limits might include limits on cladding damage fraction, cladding strain, fuel rod pressurisation, or cladding wastage. Because these criteria and limits are design specific and intended to ensure compliance with breach rate requirements, they are not incorporated as requirements themselves. Other criteria to be determined will be those necessary to ensure reliable performance through anticipated and operational transients – the latter of which might be challenging in an accelerator-driven system.

Safety and off-normal performance

In general, safety requirements for the fuel will ensure that these components accomplish the following system safety objectives:

- Provide operators with the ability to control the extent of the nuclear chain reaction.
- Contain hazardous radionuclides to prevent exposure of workers or the public, except as deemed acceptable by definition of design-basis accidents.

Specific safety objectives for fuel can then be defined as the following:

- Maintain fissionable materials in a known and predictable configuration at all times.
- Maintain a coolable geometry at all times.
- Provide the first barrier against radionuclide release except under design-basis accident conditions for which release through the first barrier would be acceptable.

Accomplishing these objectives will require certain fuel behaviour associated with anticipated and unlikely design-basis accidents. As such accidents are defined for the specific reactor designs, the evaluation of potential consequences will identify specific requirements to ensure that consequences are acceptable for postulated accidents.

Examples of Design-Basis Accidents that may need to be addressed include reactivity-insertion accidents leading to transient overpower (TOP) conditions and (LOF) events that arise when an initiating event disrupts the normal flow of coolant into the core or into a fuel assembly. TOP conditions typically involve higher-than-normal fission rates, which would induce higher-than-normal fuel temperatures and associated cladding and coolant temperature increases. The increase of temperatures could then lead to fuel melting or fragmentation, penetration of cladding by fission products or fuel, sudden release of retained fission gas from the fuel to the fuel rod plenum, or other deleterious phenomena. Therefore, safety requirements might include a minimum temperature margin to fuel melting or a limit to fuel or fission products released into coolant channels. LOF events typically result in increased cladding temperatures but have less impact on fuel temperatures than do TOP events, because they are usually followed by a SCRAM. Phenomena that can lead to fuel failure during such events include increased fuel rod pressure, stress rupture of softened cladding, and accelerated cladding wastage due to increased diffusion of fuel constituents or fission products into cladding. Safety requirements that address such concerns might include a minimum stress rupture lifetime of cladding.

Prior to the identification of specific requirements, certain phenomena and characteristics that contribute to consequences of design-basis accidents can be minimised, including the following:

- Mechanisms that place stress on cladding or other fission product barriers during transients (e.g., radial fuel swelling or sudden gas release).
- Fuel fragmentation.
- Reduction of cladding thickness by interdiffusion or corrosion.
- Fuel melting or formation of low-melting-temperature phases.
- Exacerbation of cladding breach that results in more severe breach configurations (which increase fuel/fission product release rate, coolant channel blockage, etc.).

Composition

Actinide content: The major consideration that impacts transmutation fuel composition is the desired transmutation rate. Exclusion of fertile ^{238}U will ensure the fastest possible destruction rate and will minimise the amount of material to be recycled through the transmutation system. However, excluding uranium from the fuel has implications for reactor control and fuel performance, so the U.S. is expanding consideration to low-uranium compositions, which are intended to provide some of the benefits of uranium-bearing fuel but still reduce the amount of conversion that adds to the fuel cycle burden. Currently it is assumed that plutonium contents will range from 20wt.% to 85wt.%, depending on the output from a first tier. The plutonium isotope and transplutonium isotope contents will vary, depending on the characteristics and deployment of a first tier. A homogenous mixture of all transuranics in fabrication and irradiation is assumed, although that requirement can be modified if fuel technology or separations technology warrant.

Fission product content: The fuel recycle processes, specifically pyroprocessing, under consideration in the U.S. will provide recycled fuel feed that contains some residual amount of fission products. The amounts of fission products that must be accommodated in the recycle fuel remain to be determined through separations R&D.

Burn-up and exposure limits

Burn-up: 30at.% (for non-fertile compositions): For a well-developed fuel with a well-established fabrication process, breach probability and consequences are, in large part, influenced by and correlated with burn-up. Therefore, burn-up limits are typically established to ensure that breach probability and consequences are acceptable. In the past, high burn-up potential, which requires high neutron exposure, for fast reactor fuel was desirable to reduce costs (per unit energy extracted from a quantity of fuel) associated with fuel handling and fuel recycle. Evaluations of fast reactor economics as in the 1980s indicated that average fuel burn-up values of about 15at.% would be necessary for a fast reactor fuel cycle to compete economically with the light water reactor fuel cycle, [1] and those values remained the target for the Integral Fast Reactor programme in the U.S. [2] In addition, maximum burn-up capability is desired for the transmutation mission in order to reduce the number of recycles required to completely transmute a quantity of material, because some amount of residue material will be lost to secondary waste streams during each recycle and re-fabrication pass.

Neutron exposure: 4×10^{23} n/cm^2 (E >0.1 MeV): Fuel assembly burn-up for fast reactor designs was initially limited by the performance of the fuel itself, but later was limited by the amount of neutron fluence that could be tolerated by the fuel cladding or fuel assembly ducts due irradiation-induced dimensional changes. In fact, burn-up of the most recent driver fuels for the EBR-II and the Fast Flux Test Facility (FFTF) was limited by duct dilations and distortions rather than by failure of the fuel rods. HT9-clad MOX fuel with HT9 ducts in the FFTF attained fluences of 3.9×10^{23} n/cm^2 with no observed performance concerns. (See, for example, [1] or [3]) Because HT9 is proposed as a reference cladding and duct material for transmutation, a limit of 4×10^{23} n/cm^2 (E >0.1 MeV) is proposed. Calculations of reactor core performance for a Na-cooled or lead-bismuth-eutecitic-cooled ADS indicate that the proposed fluence limit would result in 30 to 40at.% burn-up in a non-fertile, which is commensurate with the proposed burn-up limit. [4]

Fabrication and process requirements

Compatible with recycle technology: The ability of the transmutation system to perform its mission will be strongly dependent on the performance of the recycle technology. Therefore, the selected fuel design and the selected recycle technology must be mutually compatible. The selection and optimisation of these technologies will be based on considerations of economics, facility and fuel reliability, and waste management.

Fabrication considerations: The presence of residual fission products and actinides that emit high radiation fields will require that fuel fabrication for the fast-spectrum, second tier be performed using shielded equipment and/or operating spaces. Furthermore, radioactive contamination on the surface of the fabrication equipment and in the fabrication spaces will likely be high, preventing hands-on maintenance of the equipment. Therefore, fuel fabrication processes must be amenable to remote application, and the equipment amenable to remote operation and maintenance using remote manipulators. The as-fabricated fuel must meet the requirements of the Fuel Specification, as determined by measurable quality assurance parameters.

Fuel fabrication-related contributions to total fuel cycle cost: ≤20% – Although the transmutation mission is not necessarily intended to produce optimised profit, it must be as economic as possible. The 20% value that is selected is somewhat arbitrary until the transmutation system economics are better known, but is a good goal until then.

Fabrication losses of transuranic constituents to secondary waste: ≤20% – The success of the transmutation system will require that only small, acceptable amount of transuranic elements be discharged through secondary waste disposal. This implies that such losses due to adherence to fuel fabrication molds, dies, crucibles, etc. must be limited. Other such losses will necessarily be incurred with the recycle process. Therefore, fuel fabrication-related losses of transuranic elements will be limited to 20%, or less, of the total loss per each recycle pass.

Fuel development and qualification

The categories and phases that are used are based primarily on previous experience gained in successfully developing and qualifying several different driver fuels for the Experimental Breeder Reactor II and the reference fuel for the Integral Fast Reactor concept. It is recognised that a fuel development and qualification programme can be described in different ways, but a four-phase programme has proven convenient for the U.S. programme.

Phase 1. Fuel candidate selection

Objective: Identify fuel types and concepts with potential for meeting mission requirements

General considerations for selecting a fuel form include the purpose or mission for the reactor application (e.g., electricity sales, fissile production, or actinide transmutation), the power density and outlet temperatures, the source of the fissile material (e.g., fresh enriched uranium or recycled actinides), spent fuel management (e.g., once-through with repository disposal or recycle), and relevant previous experience. Because there is little experience with low-uranium and non-fertile fuels, selection of AFCI candidate fuel forms is based on experience with uranium-based analogues, with consideration to aspects such as fabrication, irradiation performance, and safety. Criteria considered for selection of candidates include the following:

- Relative amount of experience with uranium-bearing analogues.
- Suitability of established fabrication techniques for the envisioned application, or the potential for successful development of innovative techniques.
- High-burn-up capability of uranium-bearing analogues, with potential to address additional challenges due to non-fertile compositions and high minor-actinide contents.
- Acceptable safety-related behaviour of uranium-bearing analogues, with positive speculation regarding issues with non-fertile, high minor-actinide compositions.
- Suitability of proposed non-fertile composition and design for envisioned application, considering issues such as fuel-cladding compatibility, fuel-coolant compatibility and thermophysical properties.
- Compatibility with available or proposed recycle technology.
- Expected cost of fabrication and fabrication equipment.

The U.S. AFCI programme has selected metal alloy and nitride pellet forms as primary or reference fuels for transmutation, with others such as oxide or cermet forms to considered as alternatives (D.C. Crawford, S.L. Hayes, and M.K. Meyer, "Current U.S. Plans for Development of Fuels for Accelerator Transmutation of Waste", presented at the International Atomic Energy Agency Technical Committee Meeting on Core Physics and Engineering Aspects of Emerging Nuclear Energy Systems for Energy Generation and Transmutation, Argonne, U.S.A, 28 Nov-1 Dec 2000).

Phase 2. Concept definition and feasibility

Objective: Establish a reference fuel concept and design

In general, a successful fuel must be fabricable, it must have acceptable properties, it must be compatible with an acceptable disposal or recycle technology, and it must have acceptable in-service performance. Initial R&D efforts are therefore directed at determining viability of the selected fuel forms with respect to those characteristics.

Fabrication process development

Fabrication process development efforts are performed with the following objectives:

- Determine that fuel samples can be fabricated with identified techniques.
- Produce samples for characterisation and for irradiation testing.
- Evaluate need and potential for improvements to fabrication through process modification or development of innovative techniques.
- Perform conceptual design of fabrication processes to allow assessment of efficiency loss (e.g., batch yield or TRU loss), capital cost, and production cost.

Property measurement

Key properties are measured and/or assessed to identify any limiting characteristics and to support other R&D tasks, including irradiation testing, of the fuel designs. The following properties are emphasised initially, although others are typically identified for investigation:

- Thermophysical properties such as thermal conductivity and heat capacity.
- Physical properties such as density and hardness.
- Phase equilibria characteristics, including melting (i.e., liquidus and solidus) temperatures.
- Interdiffusion and compatibility of fuel constituents with cladding and coolants.

Irradiation testing

Initial irradiation testing of the candidate fuel forms is performed to provide a screening of different fuel concept options and to provide early indication of potential fuel behaviour challenges and to identify potentially life-limiting phenomena. Experience with nuclear reactor fuels has demonstrated that certain anticipated phenomena (e.g., fuel swelling or fuel/cladding chemical interaction) can impact the lifetime and reliability of a fuel design. Such behaviour cannot be reliably predicted with fuel performance codes that have not been previously modified and validated for the specific fuel composition and type. Therefore, early irradiation performance indications are important for the subsequent fuel development and design activities. Such phenomena to be investigated in initial irradiation tests, under steady state and transient conditions, include the following:

- Fuel swelling.
- Gas behaviour in the fuel, including retention and release of both fission gases and helium.
- Fuel constituent migration.
- Fuel phase stability.
- Fuel/cladding interdiffusion and chemical interaction.

Phase 3. Fuel design improvement and evaluation

Objectives

- Optimise the reference fuel design for performance, safety, and economics.
- Prepare a Fuel Specification and a Fuel Safety Case for a reactor core of the reference fuel.
- Establish a predictive fuel performance code (or codes).

Based on the results of Concept Definition and Feasibility R&D, reference and back-up fuel designs are selected for further improvement and evaluation as described below.

Fabrication process development and qualification

Fabrication techniques suitable to the particular mission are developed and demonstrated. Activities address the following objectives:

- Development of pilot-scale processes and parameters that meet specific fabrication requirements (such as avoiding volatile loss of americium and its compounds or minimising contamination of fabrication spaces).
- Design or development of fabrication tools (such as dies, crucibles or molds, that can be reused or that do not otherwise introduce sources of TRU loss).
- Design and construction of engineering-scale fabrication equipment (which might be used remotely within shielded hot cells if the fuel feed is to contain residual fission products after recycle).
- Qualification of engineering-scale fabrication processes by demonstrating repeatability of fuel fabrication within specification bounds.

Property measurement

Key properties are further assessed for the entire nominal range of operating conditions and for certain off-normal conditions. These properties are reviewed for quality control and complied into a controlled data format, such as a Fuel Properties Handbook. The following properties are considered necessary.

- Thermophysical properties such as thermal conductivity and heat capacity.
- Physical properties such as density and hardness.
- Phase equilibria characteristics, including melting (i.e., liquidus and solidus) temperatures.
- Interdiffusion and compatibility of fuel constituents with cladding and coolants.

Irradiation testing

Irradiation testing during the Design Improvement and Evaluation phase is performed for the following objectives:

- Provide performance data to inform the design improvement effort.
- Provide data to support the safety case for operation of the ISD facility using a full core/blanket of transmutation fuel.
- Establish performance limits and expected fuel lifetimes for nominal in-service conditions.
- Identify and assess safety-related behaviour and phenomena under off-normal conditions, such as transient overpower or transient undercooling.
- Determine the sensitivity of fuel behaviour to variations in fabrication parameters or in-service conditions.

Achieving the objectives of this particular phase will entail steady-state irradiation of 10 to 15 assemblies (on the order of 1 000 rods or more), wholly or partially filled with test fuel, using facilities with prototypic environments, followed by post-irradiation examination in shielded hot cells. Transient (off-normal) evaluation will require in-pile and out-of-pile testing of selected fuel rods (or other types of fuel elements) with well-defined previous steady-state irradiation histories. The conditions selected for the off-normal tests will be chosen to envelop postulated design-basis accident conditions for the ISD facility or the reference reactor design.

Model development

The understanding of fuel properties and behaviour is established through the development of predictive models. Specific modelling objectives are as follows:

- Models that accurately predict fuel material properties for all anticipated irradiation conditions.
- Demonstrated understanding of fuel fabrication phenomena.
- A Fuel Performance Code with predictive capability for fuel behaviour under nominal and off-normal in-service conditions that is validated against the available irradiation performance data.

Fuel specification

A Fuel Specification is derived from the results of the other activities of the Fuel Design Improvement and Evaluation phase and will specify the design(s) as optimised for considerations of recycle and fabrication, economics, safety, and system performance. Preparation of the ISD facility safety case will be based upon this specification.

Phase 4. Fuel qualification and demonstration

Objectives

- Demonstrate prototype-scale fuel production in conformance with the Fuel Specification.
- Qualify production-line fuel as the driver fuel for the ISD reactor by demonstrating fuel performance to be within the bounds of the ISD fuel safety case.
- Demonstrate the safety and reliability of a full core of reference fuel, and with fuel rods and assemblies, through successful operation of the demonstration reactor, accumulating reactor performance data and operating experience.
- Demonstration of acceptable fuel behaviour under design-basis accident conditions anticipated for a licensable reactor system.
- Validate the predictive fuel performance code or codes.

Safe and economic operation of a new reactor system can be established through successful operation of an Integrated System Demonstration (ISD), which constitutes the final phase of a fuel development programme and entails the operation of a scalable reactor using a core of reference fuel. The accumulated performance information for the fuel rods and assemblies, and for the reactor itself with a full core of the reference fuel, will provide the information necessary to license the first-of-a-kind system. The results of the ISD will validate assertions made in the licensing case, with specific results being embodied in documents that will support the licensing case for subsequently deployed systems.

As a practical matter, the operation of the ISD with a full core of the reference fuel is dependent upon a prior demonstration that fuel performance is bounded by the safety case for the ISD facility. This is accomplished through the Fuel Qualification Programme, which entails the irradiation, surveillance, and examination of a set of Lead Assemblies fabricated in accordance with the Fuel Specification using production line equipment. During ISD reactor start-up and conduct of the Fuel Qualification Programme, the reactor is operated with either a core of well-known driver fuel (such as UO_2 or U-Zr), or a core of reference driver fuel operated initially under conservative conditions. The Fuel Qualification Programme will entail irradiation of the Lead Assemblies at conditions selected to encompass the anticipated range of in-service conditions. If surveillance and examination indicate that fuel behaviour is within the bounds specified in the ISD facility safety case, then the fuel designs will be considered as qualified for ISD facility operation. At this point, the ISD reactor can be operated using the reference fuel in accordance with limiting conditions of operation identified in the safety case.

As the ISD is operated, specific design-basis accidents (DBAs) for subsequently-deployed units are selected for analysis in the licensing case. As part of the Integrated Fuel Cycle Demonstration (IFCD), selected fuel rods will be tested under specific DBA conditions (which will be selected with concurrence of the licensing agency) to provide validation of the assumptions and methodology employed in the safety case. The results of the ISD and IFCD will be incorporated into documents and codes that will support the licensing process for deployable transmutation systems. These documents and tools include the Transmutation Fuel Specification, the Transmutation Fuel Properties Handbook, and the Transmutation Fuel Performance Code. It is anticipated that the final form of these products will be influenced by the requirements of the licensing authority.

Acknowledgements

Contributing discussions with the following are gratefully acknowledged: K.M. Chidester and R.W. Margevicius of Los Alamos National Laboratory; L.C. Walters, D.L. Porter, and R.G. Pahl of Argonne National Laboratory; and D.J. Hill now of Oak Ridge National Laboratory.

REFERENCES

[1] R.D. Leggett and L.C. Walters, J. of Nucl. Mater., 204 (1993) 23-32.

[2] B.R. Seidel, L.C. Walters and Y.I. Chang, J. of Metals, v. 39. No. 4 (1987) 10-13.

[3] Baker, Bard, Leggett and Pitner, J. Nucl. Mater., 204 (1993) 109-118.

[4] R.N. Hill and H. Khalil, *Proceedings of the IAEA Technical Committee Meeting on Core Physics and Engineering Aspects of Emerging Nuclear Energy Systems for Energy Generation and Transmutation*, Argonne National Laboratory, Nov. 28-Dec. 1, 2000.