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ScienceDirect
Journal of Nuclear Materials 371 (2007) 232–242
journal of nuclear materials
www.elsevier.com/locate/jnucmat

An approach to fuel development and qualification

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Abstract

Some of the rationale for nuclear energy technology development in the US has been lost or forgotten over the past two decades with the lack of a focused reactor development program. But the emergence of new R&D programs points to a need to understand how best to plan for a long-term fuel development program. The rationale for such a program is not easily found in the literature, so the authors have suggested a structure and rationale. The approach is described as four phases, with emphasis on selecting a reference fuel concept, evaluating and improving the fuel to develop a fuel specification for a reference design, obtaining data to support a licensing safety case for the fuel, and final qualification of the fuel for a specific application. Because a fuel program requires long-lead-time irradiation testing, bringing a fuel design from the initial concept through licensing might take over 20 years.

1. Introduction

Emergence of nuclear energy R&D programs in the US (e.g., the Generation IV initiative [1,2], the Advanced Fuel Cycle Initiative [3], and perhaps the recently announced Global Nuclear Energy Partnership for which plans are just now being formulated [4]) and elsewhere has motivated consideration of reactor fuels for new applications [5,6]. To support long-range planning in the recent programmatic environment, it has been necessary to consider and describe the process needed to bring a new fuel type to implementation. Because the rationale used previously was not fully described in the literature, the authors attempt to do so here.

The fuel development approach described is based on experience with, or observations of, developing and improving fuels at various stages of technical maturity, reflecting previous and current efforts with fuels for gas-cooled reactors [7,8], fast reactors [9–12], research reactors [13], and even light water reactors [14]. Other descriptions may also be valid, but the structure and rationale here has recently been used to identify the tasks and sequencing that best serve US program needs. Whether all the elements of the full and generic program described here are necessary for a given application depends on the needs and technical maturity of the fuel technology being addressed. For example, fuel

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0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.05.029

development underway now for high-temperature gas reactors is building on considerable work performed in the 1970s and 1980s [7], allowing that program [8] to begin in what is described here as Phase 3; on the other hand, although fuel development efforts for low-conversion ratio, sodium-cooled fast reactors certainly builds on previous fast reactor fuel experience, the substantial departure of these fuel compositions from the previous experience base requires some effort at a level described here as Phase 1 and Phase 2 [9]. So, the reader is reminded that work performed in previous efforts often meets the needs of what is described in this paper for a new fuel concept or design, and not every fuel development program requires the same time or investment reflected in this generic description.

An important component of this approach is the rationale presented for fuel qualification. In the authors' experience, specialists have differing perspectives on the objectives and means of qualifying a fuel for use, some of which confuse objectives of testing with objectives of qualification; so here we offer our perspective.

The approach is driven by objectives discussed below. We describe the approach in terms of four phases, distinguished by specific objectives and nature of activities. These four phases are delineated, in part, to achieve certain technical readiness levels [15], which are described for application to reactor fuel development.

2. Fuel development and qualification objectives

Simply stated, an effort to develop a fuel design to the implementation stage typically must provide the following:

1. A specification for the fuel design(s), including chemical composition and form, geometric configuration, and design and materials of construction of related components, such as cladding and assembly hardware or compacts and elements.
2. A database of fuel properties and irradiation behavior to sufficiently reduce the safety and reliability uncertainty for use of the fuel design.

Achieving the first of the objectives will define the fuel design such that it can be produced by, for example, a fuel vendor. Achieving the second of these objectives brings the fuel design to a sufficient stage of technical readiness such that the safety risk associated with its use is acceptable to regulators and the operational/economic risk is acceptable to a reactor operator. Uncertainties in fuel behavior or properties are incorporated into the licensing safety analyses, quantitatively when possible, and those uncertainty values can lead to limits on operating conditions necessary to assure safe operation; the determination of those limits is a balance between safety and economic risk. Uncertainties in fuel reliability typically do not introduce safety risk, but often introduce operational/economic risk. For example, reactor operation with breached fuel barriers (such as cladding or particle coating) might lead to release of radionuclides into the reactor coolant, with unacceptable implications for radiation exposure to workers or maintenance schedules; management of those implications can impact reactor operating schedules with financial consequences for the operator.

Given a fuel design that meets objectives for safety and reliability, the objectives of fuel qualification is simply stated as follows:

> Demonstration that a fuel product fabricated in accordance with a specification behaves as assumed or described in the applicable licensing safety case, and with the reliability necessary for economic operation of the reactor plant.

As discussed in a later section, qualification, as defined here, addresses a specific use or application of the fuel design.

3. Technical readiness levels

Many technologies, including reactor fuels, are developed through a sequence of activities, often iteratively. To measure and indicate technical progress with a fuel concept or design, we can apply a technical readiness level (TRL) scale. The TRL scale was derived from a model used by NASA to assess the readiness of space technologies during development [15]. The US Department of Energy Advanced Fuel Cycle Initiative (AFCI) program in the US adopted the technical readiness level (TRL) scale as a means to indicate the degree of development of transmutation technologies. A similar adaptation can be applied to fuel development more generally, as described in Table 1. The subsequent discussion makes use of this TRL scale.

Table 1
Proposed application of technical readiness levels to reactor fuel development and qualification

TRL	TRL Function	Generic Definition	Fuel Development-Specific Definition	Fuel Dev. Phase
1	Technology Down-Selection	Basic principles observed and formulated	Technical review leading to identified technical options. Identification of criteria for candidate selection	1
2		Technology concepts and/or applications formulated	Fuel candidates selected from options, based on selection criteria	
3		Analytical and experimental demonstration of critical function and/or proof of concept	Calculational analysis and lab-scale experimentation and characterization addressing feasibility, including: fabrication process development, property measurement, and ex-pile tests	2
4	Final Process Selections and integration	Component and/or bench-scale validation in a laboratory environment	Establish proof of concept. Fabrication of irradiation testing samples in accordance with QA requirements. Design parameters and features established Performance phenomena identified with proof-of-concept irradiation testing	
5		Component and/or breadboard validation in a relevant environment	Irradiation testing of prototypic rods/compacts under nominal representative conditions (e.g., fission densities, fuel and cladding temperatures, cladding damage rates) is performed and assessed	3
6	Full-scale integrated testing	System/subsystem model or prototype demonstration in relevant environment	Prototypic rod/compact and assembly/element irradiation in representative environment, under full range of relevant normal and off-normal conditions. Representative compositions Design parameters investigated Information is sufficient to support a Fuel Specification and a Fuel Safety Case (which, in turn, support larger System Demonstration to achieve TRL7)	
7		System prototype demonstration in prototypic environment	Fabrication of reference fuel derived from production supply sources irradiated to design conditions and utilization Irradiation in representative environment Prototypic design. Prototypic fabrication processes. Representative compositions	4
8	Full-scale demonstration	Actual system completed and qualified through test and demonstration		
9		Actual system proven through successful mission operations		

4. Description of approach

4.1. Phase 1. Fuel candidate selection

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

Selection of a fuel form for a reactor application will consider the application requirements as well as previous experience. In the early days of nuclear technology, designers had very limited information regarding potential fuel materials, so fuel candidate selections were based on knowledge of materials science and presumptions about what characteristics would be important for irradiation performance. Development work and experience since that time, however, provides a considerable knowledge base from which to propose fuels for new applications.

In general, a successful fuel must be amenable to fabrication, it must have acceptable thermomechanical, thermophyiscal and physiochemical properties, it must be compatible with an acceptable disposal or recycle technology, and it must have acceptable in-service performance. Selection of a candidate fuel form considers requirements derived from the reactor application (e.g., electricity generation, fissile production, actinide transmutation, or space propulsion), the desired power density and outlet temperatures, the expected neutron damage, the source of the fissile material (e.g., fresh enriched uranium or recycled actinides), spent fuel management, and relevant previous experience. Criteria for selection then often include the following:

- Ability to accommodate desired fuel compositions.
- Experience with similar fuel types or analogues.
- Suitability of established fabrication techniques, or the potential for successful innovative techniques.
- Anticipated performance capabilities (e.g., temperature, burnup, or fluence).
- Anticipated safety-related behavior (which may be quite speculative at an early stage).
- Suitability of design, considering issues such as fuel-cladding compatibility, fuel-coolant compatibility, and thermomechanical, thermophysical, and physiochemical properties.
- Compatibility with envisioned back-end fuel cycle technology.
- Expected cost of fabrication.

Completion of Phase 1 achieves TRL 2 as described in Table 1.

4.2. Phase 2. Concept definition and feasibility

Objective: Establish a reference fuel concept and design.

Initial R&D efforts are therefore directed at determining viability of the selected fuel forms; i.e., whether it can be fabricated, whether key properties are acceptable, and whether there are problematic performance issues.

Fabrication process development: Known and established fabrication techniques, or variants of such techniques, are used to fabricate samples of the candidate fuel forms. Some applications may require new or novel techniques, for example, if conventional techniques do not meet requirements for process loss. Fabrication process development efforts are performed with the following objectives:

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

Property measurement: Key material 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 emphasized initially, although others might be identified for investigation:

- Thermophysical properties such as thermal conductivity and heat capacity.
- Physical and mechanical properties such as density and perhaps hardness.
- Phase equilibria or stability characteristics, such as liquidus, solidus, and/or dissociation temperatures.
- Interdiffusion and compatibility of fuel constituents and fission products with cladding and coolants.
- Thermomechanical properties of cladding.

Irradiation testing: Initial irradiation testing is performed to screen different fuel concepts and to identify potential fuel behavior challenges and life-limiting phenomena. The types of tests, which could be used, are described conceptually in Appendix. Experience with nuclear reactor fuels has demonstrated that certain anticipated phenomena can impact the lifetime and reliability of a fuel design but cannot be reliably predicted with fuel performance codes that have not been modified and validated for the specific fuel composition and type. Therefore, early irradiation performance indications are important for subsequent development and design activities. Such phenomena to be investigated in initial irradiation tests, under steady-state and transient conditions, include the following:

- Fuel dimensional changes, through swelling or irradiation growth.
- Gas behavior in the fuel, including retention and release of fission gases and other gases generated under irradiation (e.g., helium if the fuel contains high amounts of americium or curium; or carbon monoxide in the case of UO_2 TRISO fuel).
- Fuel constituent migration.
- Fuel phase stability.
- Interdiffusion and chemical interaction of fuel or fission products with cladding or coating constituents.
- Dimensional change or degradation of cladding/coating properties from neutron exposure at temperature.

The laboratory-scale experiments and measurements of Phase 2 are typically sufficient to achieve TRL 3, by demonstrating that intrinsic properties and characteristics (such as thermal conductivity, melting temperatures, and feasibility of fabrication) are sufficient for fuel concept feasibility. TRL 4 can be achieved with simple proof-of-concept performance tests, such as fabrication and nominal-condition irradiation testing of a small number of test samples.

4.3. Phase 3. Fuel design improvement and evaluation

Objectives:

- Optimize the reference fuel design for performance, safety, and economics.
- Prepare a fuel specification and a licensing safety case for a reactor core of the reference fuel.
- Establish a predictive fuel performance code (or codes).

Based on results of concept definition and feasibility R&D, selected fuel concepts are evaluated and improved. In this phase, life-limiting phenomena are further investigated for implications for fuel design and operation limits. A reference design is established and information regarding its fabrication, properties, and performance is collected. The results are embodied in a fuel specification, and the understanding of fuel properties and behavior is established through the development of predictive models, which are incorporated in a predictive fuel performance code. These efforts support the preparation of a licensing safety case. Typical activities are described below.

Fabrication process development and demonstration: Fabrication techniques suitable to the particular mission are developed and demonstrated, with activities addressing the following objectives:

- Development of pilot-scale processes and parameters that meet specific fabrication requirements (such as avoiding process loss or minimizing contamination of fabrication spaces).
- Design or development of fabrication tools (such as reusable dies, crucibles or molds, to reduce sources of process loss).
- Design and construction of engineering-scale fabrication equipment; such equipment might be intended for remote use within shielded hot cells if the fuel feed is to contain residual fission products after recycle.
- Demonstrating repeatability of fuel fabrication within specification bounds.

Property measurement: Key properties are further assessed in detail, with measurements and with use of property models, for the entire nominal range of operating conditions and for certain off-normal conditions. These properties are measured or estimated, reviewed for quality assurance, and compiled into a controlled data format, such as a Fuel Properties Handbook. The following properties are considered necessary, but others might be assessed as well.

- 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 and fission products with cladding, coatings and coolants.
- Thermomechanical properties of cladding or coatings.
- Changes in relevant properties with fast neutron damage and/or burnup.

Irradiation testing: Irradiation testing during the design improvement and evaluation phase is a relatively large effort, performed for the following objectives:

- Provide performance data to inform the design improvement effort.
- Provide data to support the licensing safety case.
- Establish performance limits and expected fuel lifetimes for nominal in-service conditions.
- Identify and assess safety-related behavior and phenomena under off-normal conditions, such as transient overpower or transient undercooling.
- Determine the sensitivity of fuel behavior to variations in fabrication parameters (within and outside of ranges given by fuel specification) or in-service conditions.

Achieving the objectives of this particular phase requires a significant amount of irradiation space in test facilities with prototypic environments followed by post-irradiation examination in shielded hot cells. Irradiation tests that achieve the objectives of this phase are conceptually described in Appendix. For a new fast reactor fuel, depending on relevant previous experience, steady-state testing might entail irradiation of 10–15 assemblies (on the order of 1000–3000 rods), wholly or partially filled with test fuel. Smaller variations to established fuel designs, such as those for research reactor fuel or light water reactor fuel usually require less irradiation testing. For example, work with research reactor fuel is being addressed with small-scale and prototypic specimens sufficient to demonstrate the variability of fuel behavior with composition or fabrication parameters, and over 200 'mini-plates' have been tested in recent years. Development of TRISO particle fuel for high-temperature gas reactors has required irradiation of hundreds of thousands of particles in 50 or more compacts through this phase.

Post-irradiation examination is important to document the state of the fuel following irradiation (beyond that which can be inferred from on-line measurements) and provide physical evidence of breach and incipient failure mechanisms that will be used as feedback to the fuel development process. Because the behavior of life-limiting phenomena are difficult to predict analytically in materials systems as complex as reactor fuels, it is essential to observe and characterize these effects as directly as possible – until modeling capabilities advance sufficiently to make such predictions possible. Transient (off-normal) evaluation will require in-pile and out-of-pile testing of selected fuel elements (e.g., fuel rods) 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 reference reactor application or to provide sufficient phenomenological data for safety model validation. Post-irradiation examination following transient testing will be essential to properly characterize fuel behavior under the transient conditions.

Model development: Understanding of fuel properties and behavior is established through the development of predictive models. These models can be developed using state-of-the-art computational techniques and validated using available experimental data. The models are incorporated into a fuel performance code, which is validated against irradiation performance data and used to support the safety case for the operation of the reference fuel. Specific modeling objectives are as follows:

- Demonstrated understanding of phenomena that are operative during fuel fabrication processes.
- Accurate prediction of fuel material properties as a function of fast neutron damage and/or burnup for all anticipated irradiation conditions.
- A fuel performance code (or codes) with predictive capability for fuel behavior under nominal and off-normal in-service conditions that is validated against the available irradiation and transient testing performance data.

Fuel specification: The fuel specification will be derived from the results of the other activities of the Fuel Design Improvement and Evaluation phase and will describe all aspects of fuel design that are important to achieve the required in-reactor performance and meet requirements for fuel safety and reliability. Preparation of the licensing safety case will be based upon this specification.

TRL 5 is achieved in this phase with successful irradiation of reference-design fuel, fabricated in accordance with a quality assurance plan appropriate for the R&D nature of this phase of the program, under a range of representative conditions and which fully reveal all fuel performance phenomena of interest. TRL 6 is achieved with completion of a defendable safety case (with predictive fuel performance models) for use of the fuel under design conditions; this requires satisfactory results from irradiation tests and safety tests of reference-design fuel under the full range of anticipated conditions and relevant design-basis accident conditions, including near 2-sigma fuel and cladding temperatures and under relevant off-normal conditions and sufficient collection of properties data to reduce uncertainties in safety analysis to acceptable values.

4.4. Phase 4. Fuel qualification and demonstration

Objectives:

- Demonstrate engineering-scale or full-scale fuel production in conformance with the fuel specification (i.e., qualify the fabrication process).
- Qualify production-line fuel by demonstrating fuel performance to be within the bounds of the licensing safety case.
- Confirm acceptable fuel behavior under design-basis accident conditions anticipated for a licensable reactor system.
- Demonstrate the safety and reliability of a core or partial core of reference fuel, accumulating reactor performance data and operating experience.
- Validate the predictive fuel performance code or codes.

Acceptable fuel performance must be demonstrated in a manner to validate the assumptions in the safety case. A fuel qualification program entails the irradiation, surveillance, and examination of a set of Lead Assemblies fabricated in accordance with the fuel specification using production-line equipment. It is important to note here that although the irradiation tests in Phase 3 should cover all expected operating conditions and provide a solid basis for the licensing safety case, that effort does not qualify the fuel for use. The purpose of a qualification program is to establish that fuel produced according to specification, with a specified quality assurance and control program, will behave as expected in the licensing safety case when the reactor is operated within the licensing basis; it verifies that the fuel supply and the applied quality control measures meet licensing-based expectations.

The fuel qualification irradiation conditions are selected to encompass the anticipated range of in-service conditions. As-irradiated fuel (rods, plates, compacts or blocks) is selected with concurrence of the licensing authority for testing under specific DBA conditions to validate the assumptions and methodology employed in the safety case. If fuel behavior is within the bounds specified in the licensing safety case, then the fuel designs will be considered as qualified for operation of that reactor, in accordance with limiting conditions of operation identified in the safety case. The types of irradiation tests to accomplish this are described conceptually in Appendix. Completion of this phase brings the technology to TRL 7, if accomplished using a set of lead assemblies, or to TRL 8 if accomplished with core batches or whole cores. TRL 9 is achieved with some amount of experience in a full-scale or commercial-scale reactor, sufficient to accurately quantify financial risk of further deployment.

5. Comments on schedule

Typically, the complete development and licensing of a new fuel requires 20–25 years. The schedule-setting aspect of this effort is the lengthy course of necessary irradiation testing and post-irradiation examination, with associated long-lead times. Yet these tests remain necessary, as they are the only viable assessment of fuel performance potential and limitations. Based on previous experience, such an irradiation testing sequence can be envisioned and is illustrated in Fig. 1. The sequence and scheduling indicated in the figure assumes that fuel technologists have convenient access to test reactors, including one that can provide a prototypic neutron spectrum, neutron flux, and coolant environment, and that a demonstration reactor will be constructed (or is otherwise available) for an integrated system demonstration. Of course, the actual time required will depend on the nature of the technical challenges, the technical readiness of the fuel concept when the effort begins, the availability of funds and experimental facilities, and the degree to which requirements for the fuel change

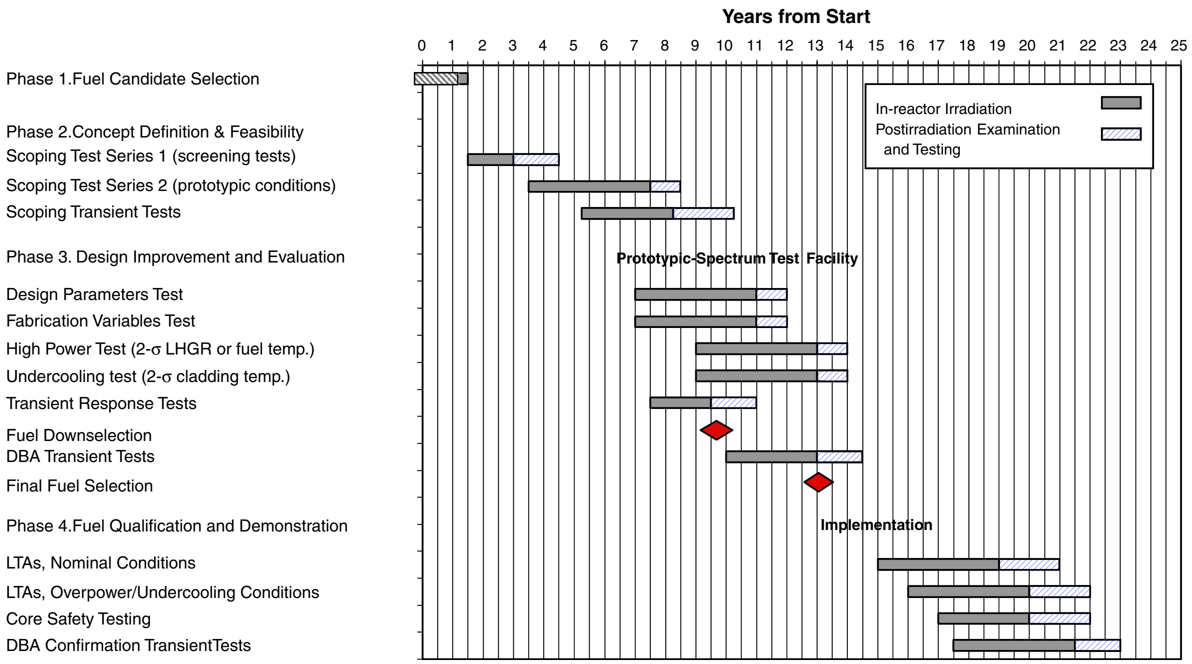

Fig. 1. Conceptual schedule for fuel development and qualification.

during the development process. Recent experience indicates that new fuel designs are more likely to be proposed on the basis of something previously investigated, so the time required for those new designs might be reduced to 15 years.

6. Summary

Some of the rationale for nuclear energy technology development in the US has been lost or forgotten over the past two decades with the decrease in R&D activity, and with the lack of a focused reactor development program in particular. But the emergence of new R&D programs points to a need to understand how best to plan for a long-term fuel development program. The rationale for such a program is not easily found in the literature, so the authors have suggested a structure and rationale. The approach is described as four phases, with emphasis on selecting a reference fuel concept, evaluating and improving the fuel to develop a fuel specification for a reference design, obtaining data to support a licensing safety case for the fuel, and final qualification of the fuel for a specific application. Because a fuel program requires long-lead-time irradiation testing, bringing a fuel design from the initial concept through licensing might take over 20 years.

Acknowledgements

Contributing discussions with the following are gratefully acknowledged: R.N. Hill of Argonne National Laboratory; L.C. Walters and R.G. Pahl, formerly of Argonne National Laboratory; D.R. Bennett of Los Alamos National Laboratory; and D.J. Hill, now of Idaho National Laboratory.

Appendix. Description of conceptual irradiation tests

Because irradiation testing is an important part of developing, demonstrating, and qualifying a new fuel form, a conceptual view of necessary or typical irradiation tests is presented here.

Irradiation tests for Phase 2, concept definition and feasibility

Scoping fuel test series I. If a fuel type or composition for which there is no previous experience is to be selected as reference, then it will be desirable to quickly gain some initial indication of irradiation performance characteristics or to address critical issues that have been identified early. Experience has shown that fuel development budgets often do not have sufficient resources for expensive testing early in a program, so less-expensive test means are used. Such tests are typically performed in capsules or miniature fuel elements (rods, compacts, or mini-plates) using established irradiation vehicles. The choice of test reactor is determined by considerations of cost and schedule, and certain prototypical conditions might be ceded for the purpose of achieving limited objectives within cost and schedule constraints. With such testing, it is important to understand the applicability of results due to non-prototypicality. This test series can be comprised of multiple capsules or irradiation vehicles and address a range of fuel compositions and/or form options. Samples of fuel from this test series will be available for scoping transient tests, described below.

Scoping fuel test series II. (This test series might also be considered part of Phase 3.) If initial scoping tests indicate that a fuel type has promise, then assessing its performance under prototypic conditions (i.e., typical steady-state temperature, heat generation, neutron spectrum, and coolant conditions) is important for further development. This second set of scoping tests should include representative rod bundles, plate arrays, or prototypic compacts, and will be used to assess life-limiting phenomena and to evaluate the burnup potential of the fuel design. The number of assemblies or irradiation vehicles to be inserted into the test reactor will depend on the number of variables to be assessed in the experiments, which depend on the fuel form under study. This test series will also serve the important function of providing irradiated test fuels for use in transient fuel testing.

Scoping transient tests. Safe reactor operation will require benign and predictable behavior of fuel under design-basis accident conditions. Therefore, the response of a fuel to transient conditions is an important consideration in selecting and developing a fuel type. While the transient performance of a fuel is often neglected early on, experience has shown that substantial modifications to core design can result from the need to accommodate fuel response to transients; thus, an early indication of transient fuel behavior is warranted. Tests of different fuel types and designs under various transient conditions, including transient overpower and undercooling, should be conducted to identify any problematic behavior (e.g., drastic radial fuel swelling that might rupture fuel cladding, or fuel softening that might lead to slumping). Early identification of such behavior will allow mitigation by design or could even lead to abandonment of a fuel option. These scoping tests are intended to be lower-cost, consisting of furnace tests or overpower tests of irradiated fuel contained in capsules, depending on the transient conditions to be addressed. Fuel irradiated from the Scoping Fuel Test Series I and II can be used as test fuel for these transient tests.

Irradiation tests for Phase 3, fuel design improvement and evaluation

Design parameters test series. After a reference fuel concept has been established, the design parameters test series will gather performance information for different parameters expected to impact fuel lifetime and operating limits (e.g., fuel-cladding gap or plenum volume). In addition, these tests can be used to help establish burnup limits for the reference fuel for a start-up core. (Burnup limits after start-up are re-evaluated based on actual performance and reliability results, which can provide the basis for a different burnup limit, if warranted.) Such information will be used to optimize the fuel design, leading to a reference design. This test series could consist of one to four fuel assemblies irradiated in a test reactor with a prototypic irradiation environment, including neutron spectrum, neutron flux, and coolant flow conditions.

Fabrication variables test series. After a reference fuel design has been established, the fabrication variables test series will be used to assess how minor deviations from the fuel specification affect fuel performance, lifetime and operating limits. Aspects to be assessed include variations in fuel composition, including amounts of impurities, and variations in fuel dimensions near the reference values. Such information will be used to establish tolerances on these and other parameters in the fuel specification, with the objective of relaxing tolerances as much as possible to minimize fabrication costs. In addition, these tests will help establish the effect of variability in fuel product characteristics on fuel reliability. This test series will consist of one to four fuel assemblies irradiated in a test reactor with a prototypic irradiation environment, including neutron spectrum, neutron flux, and coolant flow conditions. These tests are typically used to help establish initial burnup limits and other operational constraints for the reference fuel.

High power test and undercooling test. The safety analysis for operation of a core of reference fuel will necessarily have uncertainty in calculated values of fuel temperature and heat generation. Furthermore, application of operating limits might be further impacted by uncertainties in measurements of plant conditions (e.g., assembly outlet temperatures or local heat generation rates). Therefore, it is important to determine how fuel will perform if it is operating at the more aggressive limits of probable values and whether fuel lifetime will be impacted. For that reason, special irradiation tests are performed with fuel powers and cladding temperatures artificially influenced such that some number of test rods, plates, or particles operate at or near upper bounds of probability (e.g., near two-sigma values). This can be accomplished by using assembly flow orifices, increased fissile enrichment (for a uranium-bearing fuel), or placement of assemblies in peak core positions. Typically, at least one assembly each is used to assess fuel performance at high power conditions and high cladding temperature conditions, respectively.

Design-basis and beyond-design basis accident tests. As core designs for the applicable reactor are further developed, design-basis accidents (DBAs) and Beyond-Design-Basis Accidents (BDBAs) to be addressed in the licensing process are typically identified, and the conditions they induce on fuel are determined. Transient tests that simulate those DBA conditions can be performed parametrically to determine conditions at which fuel elements breach and the behavior of the fuel after breach (e.g., the degree to which fuel and fission products are released into the coolant and whether such release induces further damage, such as flow blockage), of the temperature-dependent release of fission products from TRISO fuel particles and compacts. Alternatively, rather than using a parametric approach, it is possible that selected tests can be performed for the purpose of validating models of safety-related phenomena. Transient overpower tests (e.g., simulating reactivity insertion scenarios) are conducted with irradiated fuel using test loops with coolant under prototypic flow and heat transfer conditions. Transient undercooling tests with irradiated fuel might be performed in a transient test reactor in similar test loops or might otherwise be addressed using furnace tests in shielded hot cells. These tests establish margin to fuel breach for specific DBA and BDBA conditions and allow assessment of the consequences of such events, including derivation of source-term quantities.

Irradiation tests for Phase 4, fuel qualification and demonstration

Fuel irradiation in Phase 4 is different from the testing activities in Phase 3, as the Phase-4 activities are demonstrating design-basis use of the fuel, which is based on the results of Phase 3.

Lead use assemblies (LUAs), nominal conditions. As the applicable reactor becomes available, lead use assemblies (LUAs) of the production-line fuel are inserted into the core. These assemblies are intended for exposure beyond the established fuel burnup limit, with interim and final examinations used to assess whether fuel behavior is consistent with the licensing safety case. The set of LUAs might consist of four to ten assemblies, each intended to represent an important combination of characteristics that might be encountered in the core under nominal conditions (e.g., encompassing various combinations of power, coolant flow, and coolant temperature – all of which impact fuel and cladding temperatures and burnup rate). Irradiation to breach, or some other burnup value beyond the design value, provides indication of margin to breach. (Establishing an actual margin to breach may require a larger number of rods, plates, or compacts.)

Lead use assemblies, overpower and/or undercooling conditions. As it is being established that nominal-condition LUAs perform as predicted, it may also be necessary to address performance of the production-line fuel at the aggressive ends of the probability range of conditions. Such assemblies would likely be configured to artificially restrict assembly flow and/or increase power through increased fissile enrichment.

DBA/BDBA confirmation testing. After irradiated production-line fuel becomes available, the failure thresholds, behavior, and source-term derivations under DBA conditions are determined and/or confirmed using specific DBA tests in transient test reactors and in hot cell furnace tests. The number and configuration of tests are determined as the behavior issues that require confirmation are identified.

Core safety testing. An objective of some reactor development programs might include demonstration of integral reactor safety while operating with a core of the production-line fuel. Such demonstration would likely involve reactor operational transients as well as tests that simulate DBA events and/or conditions to some degree. Such a demonstration becomes part of a fuel qualification plan and provides information to support licensing of subsequent reactor units. The specifics of a core safety test program are determined when important issues that are properly addressed through such testing are identified.

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