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Technology Readiness Levels for the Development of Accident Tolerant Fuel Pellets

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1. Introduction

The objective of accident tolerant fuels (ATFs) research is developing innovative fuels that can mitigate the consequences of accidents. Several concepts has been suggested and developed for ATFs[1]. ATF fuel technologies will be developed and commercialized through a sequence of long-lead and expensive activities. In order to fully mature ATF concepts and successfully implement ATF technologies in the commercial power plants, it would be important to understand the development status of proposed concepts, define research gap and priority, and gauge the time and effort remaining.

Technology Readiness Levels (TRLs)[2] are a systematic metric/measurement system that assesses the maturity of a particular technology and compares consistently the maturity between different types of technology. Fuel-specific TRLs definition will allow a common understanding of the development status of proposed ATF concepts across all countries participating in ATF development and the effort needed on the different ATF candidates.

This paper will address the preliminary definition and criteria of TRLs for ATFs development and assess the evaluation and verification processes required for relevant technology to move to a higher TRL.

2. Definition of Technology Readiness Levels (TRLs) for fuel development [3-7]

The fuel development process would be described in 4 phases. In phase 1, fuel concepts and candidates are selected. The mission of phase 2 is to establish a reference fuel concept and design and to verify a fabrication and performance feasibility. Phase 3 is a fuel design improvement and evaluation phase. Fuel qualification and demonstration should be achieved in phase 4.

There are two elements used to evaluate the maturity of a new fuel type in terms of readiness for deployment:

A. Fabrication Process Maturity
B. Fuel Performance Maturity

The TRL is defined on a scale from 1 through 9, where last level of 9 corresponds to fully mature and largely commercialized technologies. A TRL definition that provides a balance between these two elements is essential.

A main attribute to gauge the fabrication process maturity for ATFs is the quantity of materials used for fabrication process and testing. The quantity can be measured as batch size and/or throughput rate.

Fuel performance maturity is associated with the acquiring database of fuel properties and irradiation behavior to reduce sufficiently the uncertainty of safety and reliability for use of the fuel design. There are two important parameters of test environment and size of campaign that must be considered to gauge the maturity of fuel performance.

3. Definition of Specific Activities for ATF pellet development

In order to complete the development and licensing of a new fuel, the lengthy course of irradiation testing and post-irradiation examination is necessary. Bringing a fuel design from the initial concept through licensing might take over 20 years. The following describes specific activities for corresponding TRLs. All the activities in a given level must be completed before advancing to the next level.

- **TRL 1**: Identification of fuel type and concepts

TRL 1 is the level of identification of fuel types and concepts which have potential to satisfy the desirable attributes of accident tolerant fuels.

Thus far, following concepts has been proposed.

- · Pellet performance (thermal conductivity): Metallic microcell UO_2, UO_2-SiC.
- · Fission products retention capability: Ceramic microcell UO_2, Fully ceramic micro-encapsulated fuel (FCM).
- · Uranium loading density: Uranium nitride composites, U_3Si_2.

- **TRL 2**: Select fuel candidates

In TRL 2, fuel candidates are selected based on criteria of compatibility with current fleets of LWRs industry, economy, performance capability, safety related behavior under accident condition, and fuel cycle.

- **TRL 3**: Evaluation of fabrication feasibility and fundamental properties.

It should be demonstrated that the fuels can be fabricated with identical techniques. Fundamental properties of the samples produced by developed technique should be measured. The fundamental properties include thermal conductivity, thermal expansion, heat capacity, density, hardness, deformation behavior, melting, chemical interactions between fuel constituents, dissociation, and compatibility of fission products with cladding and coolants.

- **TRL 4**: Fabrication improvement, in-pile and out-of-pile test for screening

The irradiation test to screen and to identify potential candidates is an important task. The irradiation test starts with small sized rodlets. The typical in-reactor performances are fuel pellet dimensional changes through densification or swelling, gas behavior in the fuel including retention and release of fission gases and other gases generated under irradiation, fuel constituent migration, fuel phase stability, and inter-diffusion and chemical interaction of fuel or fission products with cladding.

Efforts for development of fabrication process are bridging the gap between lab-scale and engineering-scale fabrication process. Conceptual design of engineering-scale and full-scale fabrication processes is performed..

Property measurements are out-of-pile tests under selected DBA/BDBA condition. The fuel behaviors of high temperature steam oxidation and fuel-cladding chemical interaction at high temperature are typical examples required to be assessed.

- **TRL 5**: Irradiation test with pins for in-reactor performance and engineering-scale process

Irradiation test with pins is essential to provide performance data to inform the design improvement effort, support the licensing safety case, establish performance limits and expected fuel lifetimes, identify and assess safety-related behavior and phenomena under off-normal conditions, and determine the sensitivity of fuel behavior to variations in fabrication parameters or in-service conditions.

The fabrication process development is related on the engineering-scale processes and parameters that meet specific fabrication requirements.

In the case of 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

- **TRL 6**: Fuel performance modelling and full-scale integration of fabrication processes

Tasks are focused on the full-scale integration of fabrication processes and modeling the fuel performance by gathering and combining data from TRLs 2-5.

Engineering-scale fabrication equipment are designed and constructed. Repeatability of fuel fabrication within specification bounds should be demonstrated.

Key properties are measured or estimated, reviewed for quality assurance, and compiled into a controlled data format.

Post-irradiation examination is conducted to provide sufficient phenomenological data under the full range of anticipated conditions and relevant DBA/BDBA conditions for performance and safety model validation. Post irradiation examination following transient testing is essential to characterize fuel behavior under the transient conditions. Transient testing of fresh and irradiated pins and bundles are performed to establish accident behavior and failure thresholds.

Fuel performance model is developed. The model can accurately predict the fuel material properties as a function of 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 is (or are) developed.

Fuel specification is 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 7**: Irradiation tests of lead test assemblies in commercial reactors

Most important task is an irradiation test of the lead test assemblies (LTAs) in commercial reactors. In order to that, engineering-scale or full-scale fuel production in conformance with the fuel specification should be demonstrated.

The objectives of irradiation test with lead assemblies are to qualify production-line fuel by demonstrating fuel performance to be within the bounds of the licensing safety case and confirm acceptable fuel behavior under normal and accident conditions anticipated for a licensable reactor system.

By using the performance data from irradiation test of LTAs, the predictive fuel performance code or codes are validated.

- **TRL 8**: Demonstrate the safety and reliability in a commercial reactor

TRL 8-9 are the levels of full-scale demonstration. The developed fuel assemblies gradually occupy a core or partial core of the commercial reactor to demonstrate the safety and reliability of a core or partial core of reference fuel. Those activities accumulate reactor performance data and operating experience.

- **TRL 9**: Practical use in a commercial-scale reactor

TRL 9 is a practical use in a commercial-scale reactor. Some amount of experience in a commercial-scale reactor can provide sufficient data to accurately quantify financial risk of further deployment.

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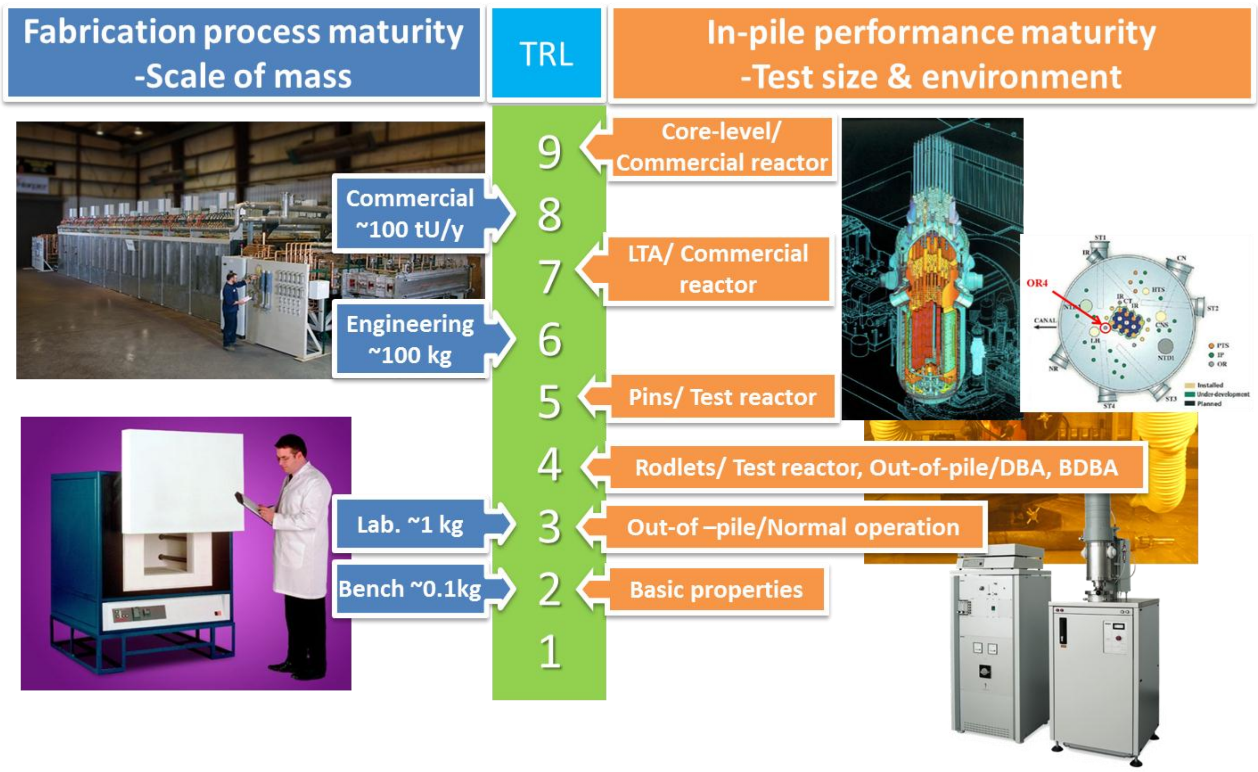

Fig. 1. Technology Readiness Levels on Fuel R&D- Maturity Definition