ELECTRIC POWER RESEARCH INSTITUTE

Program on Technology Innovation: Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability

2017 TECHNICAL REPORT

Program on Technology Innovation: Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale, and Time-Dependent Technical Information Availability

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NOTE

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Abstract

Public and private sector interest and investment in advanced nuclear reactor technologies is growing as utilities and other energy suppliers seek options for scalable, dispatchable, concentrated, and non-emitting energy sources. Flexible energy generation technologies are needed to support such an energy future. Furthermore, if advanced nuclear energy technologies—advanced reactors—are to be compelling and commercially relevant, flexibility will likely represent an important, if not essential, design attribute. In keeping with EPRI's nuclear innovation mission—and with its research portfolio increasingly focused on enhancing the flexibility, resilience, and integration of electricity and energy infrastructures—this report provides additional understanding of advanced reactor flexibility attributes. In specific, it examines the basis for proposed attributes and potential metrics to facilitate understanding of the developed attributes. The report addresses the following topics:

- A refined set of sub-criteria and attributes for flexibility criteria
- Development of a proposed modified technology readiness level (TRL) scale tailored to evaluation of advanced reactor technology
- A summary of technical information anticipated to be available at each TRL
- A consistent set of key design documents for advanced nuclear reactors and the information each would contain
- Guidance with respect to when each proposed flexibility attribute can be reasonably evaluated

The flexibility attributes that are useful for evaluating reactors at low TRLs are limited in number; therefore, the evaluation of advanced reactors at low TRLs is unlikely to be definitive. Meanwhile, test and demonstration reactors can provide the information needed to fully evaluate many flexibility attributes, but the scarcity of these reactors means that data of this quality are also limited for advanced reactor designs.

Despite the limited utility of flexibility attributes for evaluating reactor options at low TRLs, these attributes can be useful to advanced reactor developers by informing them of design goals and specifications early in the development process.

Keywords
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PRIMARY AUDIENCE: Advanced reactor technology developers, vendors, and potential owner-operators (including utilities)

SECONDARY AUDIENCE: Other stakeholders with an interest in understanding attributes of advanced reactor technologies

KEY RESEARCH QUESTION

Advanced nuclear generation technologies offer compelling options for meeting future energy needs by taking advantage of new fuels and fuel cycles, lower reactor pressures, higher outlet temperatures, and advanced energy conversion technologies. Most technologies have been demonstrated at some scale and span a wide range of technological maturity landmarks—from proof-of-concept to actual operation at commercial scale.

Flexible energy generation technologies are needed to provide an option-rich energy future. If advanced nuclear energy technologies—advanced reactors—are to be economically competitive and relevant players in this future, flexibility will likely represent an important, if not central, design attribute. EPRI seeks to answer the fundamental question, "How can advanced nuclear reactor designs use and expand flexibility attributes in order to compete in a future elec tricity and energy landscape in which opportunities and constraints are as numerous as they are uncertain?"

RESEARCH OVERVIEW

Developed energy markets need to adapt large, aging infrastructures to maintain adequate energy and capacity, while addressing future uncertainty in policy and markets, disruptive competition from new sources of energy, and increasing regulation. Developing energy markets face the challenges and opportunities associated with "clean slates"—deploying new generation assets and infrastructures without the benefits of or constraints from existing ones. Flexibility is the ability to justify or adapt deployment and operation under challenging or uncertain external conditions and constraints and is about increasing revenues and reducing financial risks.

This report represents a further elaboration of an expanded concept of flexibility presented in the 2016 EPRI report, *Program on Technology Innovation: Interim Progress on Two White Papers Supporting Advanced Reactor Commercialization: Expanding the Concept of Flexibility and Exploring the Historical Role of Public-Private Partnerships* (3002008046).

Results include the following: a refined set of sub-criteria and attributes for flexibility criteria; development of a proposed modified technology readiness level (TRL) scale tailored to evaluation of advanced reactor technology; a summary of technical information anticipated to be available at each TRL; a consistent set of key design documents for advanced nuclear reactors and the information each would contain; and guidance with respect to when each proposed flexibility attribute can be reasonably evaluated.

KEY FINDINGS

- Examination of the attributes available in the early stages of maturation reveals that consideration of just a few underlying aspects of advanced reactor designs may provide a good indication of which design might be preferred for additional research and development (R&D) investment.
- Attributes that are not useful for evaluating advanced reactor options at lower TRLs are still useful for establishing design goals throughout the research, development, and demonstration (RD&D) process.
- Test and demonstration reactors play an important role in generating information to support full evaluation of many flexibility attributes.
- The flexibility attributes that are useful for comparing reactors at low TRLs are limited in number.
- Flexibility alone is not an end in itself; over-emphasizing flexibility, without regard to other important attributes in a balanced manner, could impact the economic competitiveness efforts.

WHY THIS MATTERS

Early and meaningful engagement of advanced reactor developers regarding flexibility criteria and sub-attributes provides many potential, far-reaching benefits including

- A common approach to developing a consistent set of key design documents and the information they would contain
- Guidance for development of design requirements and specifications
- Identification of unaddressed gaps and risks
- Early buy-in from potential technology customers

HOW TO APPLY RESULTS

This report provides a foundation for streamlining the concept of a flexibility criterion as well as associated sub-criteria and attributes for comparing advanced nuclear reactor designs. The report also facilitates development of a TRL scale specific to advanced reactors that can be used to assess the maturity level of advanced reactors. Finally, the report summarizes information that should be in available at each of the several stages of advanced reactor design.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI has established an advanced reactor technical advisory group (TAG) under the Advanced Nuclear Technology Program to provide a forum for exchanging information and obtaining input on the direction and nature of EPRI’s strategic focus on advanced reactor technology.

- Related EPRI work includes *Program on Technology Innovation: Interim Progress on Two White Papers Supporting Advanced Reactor Commercialization: Expanding the Concept of Flexibility and Exploring the Historical Role of Public-Private Partnerships* (report 3002008046).
- EPRI is seeking international collaboration opportunities with governments, utility members, and advanced reactor developers/vendors. The goal is to inspire new lines of thinking to inform prioritization of and investment in relevant technology development while ensuring alignment of that development with societal and market needs.

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Definitions

- CD: Conceptual Design
- CTE: Critical Technology Element
- DoD: Department of Defense
- DOE: Department of Energy
- DOE-EM: Department of Energy, Office of Environmental Management
- DOE-NE: Department of Energy, Office of Nuclear Energy
- EA: Environmental Assessment
- EIS: Environmental Impact Statement
- EPRI: Electric Power Research Institute
- FCO: Fuel Cycle Option
- FD: Final Design
- GAO: Government Accountability Office
- GEN-IV: Generation IV
- GFR: Gas-cooled Fast Reactor
- GIF: Generation IV Forum
- INCOSE: International Council on Systems Engineering
- IRL: Integration Technology Level
- LA: Licensing Application
- LWR: Light Water Reactor
- NAS: National Academy of Sciences
- NASA: National Aeronautics and Space Administration
- NERAC: Nuclear Energy Research Advisory Committee
- NRC: Nuclear Regulatory Commission
- NWTRB: Nuclear Waste Technology Review Board
- PCD: Preliminary Conceptual Design
- PD: Preliminary Design
- R&D: Research and Development

- RD&D: Research, Development, and Demonstration
- RDD&D: Research, Development, Demonstration, and Deployment
- SCWR: Supercritical Water Reactor
- SRL: System Readiness Level
- TMP: Technology Maturation Plan
- TRA: Technology Readiness Assessment
- TRL: Technology Readiness Level

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Section 1: Introduction

1.1 The Importance of Flexibility

The commercial environment for new nuclear deployment is changing. Developed energy markets need to adapt large, aging infrastructures to maintain adequate energy and capacity, while addressing future uncertainty in policy and markets, disruptive competition from new sources of energy, and increasing regulation. Developing energy markets face the challenges and opportunities associated with "clean slates", i.e., deploying new generation assets and infrastructures without the benefits of or constraints from existing ones. Meanwhile, the established and proven technology, dominated by large light water reactor (LWR) designs, is struggling to compete in many markets globally on the basis of overnight costs, construction duration, levelized cost of electricity (LCOE), and other key economic factors.

Flexibility is a well-established and recognized feature applicable to existing reactor technology in the context of flexible power operation—a term generally used to describe any operational mode in which the plant electric power output is varied in response to regional electrical grid demands (EPRI, 2014c). To prepare for a future electricity and energy landscape in which opportunities and constraints are as numerous as they are uncertain, utilities and other stakeholders are looking for technology options that will provide reliable, resilient and integrated generation and delivery of electricity and energy (EPRI, 2017). Flexible energy generation technologies are needed to provide an option-rich energy future. If advanced nuclear energy technologies – advanced reactors – are to be compelling and relevant players in this future, flexibility will likely represent an important, if not central, design attribute. And this flexibility will likely extend beyond the traditional use of the term.

1.11 Flexible Operation of Current Reactor Technology

Most nuclear power plants have operated as base-load units, and as a result, their operation and maintenance have been optimized for continuous, full-power operation. However, units in France and Germany have routinely operated flexibly for decades, and plants in North America are increasingly called upon to reduce power output in response to seasonal load demands and increasing variable generation. This trend is expected to continue with increasing penetration of renewable generation and anticipated retirement of older fossil units (EPRI, 2014c; 2015).

1.12 Flexibility for Advanced Generation IV Reactors

Advanced reactors[1], often termed Generation IV (GEN IV), are being developed that employ fuels, coolants and materials that extend performance and safety margins beyond those of the commercially available Generation II and III reactors that are currently operating or are under construction world-wide. These enhancements include the potential for new markets and missions. The Generation IV International Forum (GIF)[2] has prioritized six families or systems of advanced reactor designs for development and commercialization in its Technology Roadmap (GIF, 2002; 2014). GIF recognizes the economic benefits included multiple missions and diversified end users for advanced GEN IV reactors, including:

1. Electricity generation
2. Hydrogen production, co-generation, and other non-electricity applications, and
3. Actinide management.

EPRI has sponsored the development of a decision framework and tools to support the structured assessment and evaluation of advanced nuclear technology options, including reactor and fuel cycle technologies (EPRI, 2011). Through a series of workshops that incorporated expert elicitation, criteria for use in structured decision-making were developed (EPRI, 2012; 2013a; 2013b; EPRI, 2014b; EPRI, 2016a).

The resulting top-level criteria identified for evaluation of advanced nuclear energy systems are:

1. Waste management
2. Safety
3. Economic competitiveness
4. Resource utilization
5. Flexibility

The first four criteria are familiar terms to most in the nuclear industry and standard definitions are provided in EPRI (2016). The fifth, flexibility, was included to capture attributes that extend beyond the traditional "flexible operation" sense of the term described above. In the course of defining and

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[1] The terms "GEN IV" and "advanced" are often used interchangeably when referring to reactor technologies beyond current Generation III/III+ designs, with most employing coolants other than water. However, the term GEN IV also carries the stricter, more limited definition established under GIF in 2002 for six reference designs and four goals. Therefore, the term "advanced reactor" will be used preferentially when discussing the more general set of non-LWR reactor technology options.

[2] The Generation IV International Forum is a cooperative framework comprising 14 countries and other partnering organizations to promote international collaboration on R&D for advancing development of GEN IV reactor technologies (https://www.gen-4.org/).

refining this expanded use of the term flexibility, defining more granular sub-criteria and attributes for advanced nuclear reactors proved challenging for a number of reasons:

1. The previously developed set of flexibility sub-criteria, attributes, and metrics proved to be too detailed and information-intensive to be practical for use in comparing advanced nuclear reactor preferences.
2. There was a surprising lack of a generally accepted scale of technology readiness levels (TRLs) tailored to advanced reactor technology assessment needs and a uniform paradigm for classifying stage of design.
3. There was limited understanding of what technical information would be available as a function of design maturity, corresponding TRL, and design phase.

1.2 Purpose and Scope

In a previous report, EPRI provides a detailed basis for the proposed flexibility sub-criteria and associated technology attributes, as well as potential metrics for evaluating each sub-criteria against those attributes (EPRI, 2016b). However, a major impediment in applying the flexibility attributes and metrics developed in EPRI (2016b) is that for the early design stages, much of the needed information is not available. As a result of this finding, this technical report addresses the following:

- Refining the set of sub-criteria and attributes for the flexibility criterion (Section 2).
- Developing a scale of proposed technology readiness levels (TRLs) expressed in terms directly relevant to advanced nuclear reactors and the technical information that would be available at each TRL – including information in key design documents such as a conceptual design report – which is addressed in Section 3. The proposed scale and information availability is based on the results of a literature search to identify scales and information availability in other industries.
- Analyzing each attribute of the flexibility sub-criteria in the context of the information available at each TRL level to determine the earliest (lowest) TRL at which each attribute criteria can be evaluated and implications of the result to comparison of advanced reactors (Section 4).

This report expands and refines the concept of flexibility in the context of related confounding issues by:

- Streamlining the concept of a flexibility criterion and associated sub-criteria and attributes for comparing advanced nuclear reactors as well as providing the basis for deployment specifications;
- Defining a proposed TRL scale for advanced nuclear reactor development and the information that must be available to achieve each TRL;
- Defining a consistent set of key design documents for advanced nuclear reactors and the information they would contain; and

- Providing guidance with respect to when each proposed flexibility attribute can be reasonably evaluated by comparing the information expect to be available at each TRL to the information required to adequately evaluate each flexibility attribute.

Addressing these issues yielded two notable products: a TRL scale specific to advanced reactors that can be used to assess the maturity level of advanced reactors and a summary of the information that should be in available at each of the several stages of advanced reactor design. These two products provide a framework for evaluating advanced nuclear energy systems as future commercial options.

Section 2: Definition of Flexibility Criteria for Evaluating Advanced Reactors

The first four of the five criteria and related sub-criteria introduced in Section 1 have been used to evaluate reactor and fuel cycle options have been defined and described elsewhere (EPRI, 2014b; EPRI, 2016b), and therefore are not discussed further. This report focuses on the development of an expanded flexibility criterion or set of criteria.

2.1 Development of Expanded Flexibility Criteria

Through a series of expert elicitations, including a workshop held in October 2015 (EPRI, 2016a), flexibility was confirmed as an important and useful attribute. While it does represent a set of options associated with deployable technologies as well as potential technology RD&D platforms, flexibility alone is not an end in itself. Over-emphasizing the flexibility, without regard to also considering other important attributes in a balanced manner, could impact the economic competitiveness efforts for commercial adoption (EPRI, 2016b).

2.2 Definition of Flexibility Sub-Criteria and Attributes

As a high-level criteria, flexibility is composed of multiple aspects and features that increase its complexity. To help with simplification, the expanded flexibility concept is developed using a hierarchy of flexibility criteria. Reactor design and evaluation reactors involves evaluating expert preferences for each of the lowest-level criteria (called "attributes" in this report), and the relative importance of each attribute. Then, reactor preferences for each of the next level criteria, which are called "sub-criteria" in this report, are determined by combining attribute preferences to help determining the relative importance of each sub-criterion. Finally, reactor preferences for the flexibility criterion are determined by evaluating the relative importance of the sub-criteria and mathematically combining this with the attribute preference-importance previously established for each sub-criterion. A previously applied process, used for evaluating the flexibility criterion to inform RD&D, design, or deployment decisions is described in Gardiner et al. (2015).

A set of sub-criteria that can be used to evaluate the flexibility of various advanced reactors and attributes that expand on the interpretation of each sub-criterion have been proposed (EPRI, 2016a; Sowder et al., 2016). The hierarchy of sub-criteria and attributes for the flexibility criterion is shown in Table 2-1 and are described in the remainder of this section.

Table 2-1
Flexibility sub-criteria and attributes

Flexibility Sub-Criteria	Attributes
Operational	Maneuverability Compatibility with Hybrid Systems Diversified Fuel Use Island Mode Operation
Deployment	Scalability Siting Constructability
Product	Electricity Process Heat Radioisotopes

2.2.1 Operational Flexibility Definitions

The operational flexibility sub-criterion considers the ability of an advanced reactor system to be operated under a range of conditions. Most commonly, operational flexibility is equated to the ability of a power plant to adjust to grid conditions and support power quality via load following and grid frequency control, i.e. by the "maneuverability" attribute of the power plant (NEA, 2011; Kee, 2015; IAEA, 2013).

However, there is increasing recognition of other desirable attributes of operational flexibility. One example is the flexibility of an advanced reactor to integrate with technologies such as topping cycles and energy storage technologies, i.e., the "compatibility with hybrid systems" attribute to address challenges posed by the increasing use of renewable energy technologies (Studarus, 2014). A second example is the ability of a reactor to use various types of nuclear fuel as economic or technological conditions change: the "diversified fuel use" attribute. Finally, consideration is being given to operating nuclear reactors in locations where they may not be connected to the electrical grid which leads to the importance of the ability of a reactor to operate in island mode. These, four attributes of operational flexibility are defined as follows:

- *Maneuverability*: The ability of the advanced reactor system (reactor and power conversion) to change power level and corresponding outputs in terms of extent and rate to match changing operational requirements and external conditions, including electrical load following and contributing to grid frequency control.

- *Compatibility with Hybrid Systems*[3]: The ability of the advanced reactor system to operate in concert with other energy-related technologies such as topping cycles and energy storage.
- *Diversified Fuel Use*: The ability of the advanced reactor system to operate using a variety of fuel designs, fuel structural materials (e.g., cladding), and fuel compositions.
- *Island Mode Operation*: The ability of the advanced reactor system to operate in isolation from local, regional or national electricity distribution networks, either on a routine or exceptional basis.

These attributes are intended to focus on the inherent extent to which advanced nuclear reactors have these attributes and not the economic implications of operational flexibility, which are addressed under the Economic Competitiveness criterion.

2.2.2 Deployment Flexibility Definitions

The deployment flexibility sub-criterion addresses the ability of an advanced nuclear reactor to be licensed, financed, sited, and built under a range of external conditions. Attributes of deployment flexibility are:

- *Scalability*: The ability of an advanced reactor system to be sized to match energy demand, and to meet other local and regional requirements or to have the ability to be resized to increase energy output to meet changes to accommodate any growth in demand. Essentially, this attribute addresses the extent to which there are technical limits on the minimum or maximum size of a particular reactor and fuel cycle technology.
- *Siting*: The extent to which an advanced reactor can be licensed, constructed, and operated where desired, after all safety concerns are properly addressed. Safety is a very important factor in siting, as any below ground construction or emergency planning zone constraints will greatly impact any siting considerations. Some reactor features that could increase siting flexibility are smaller size (physical or power) or higher operating temperatures (which generally increase the feasibility of dry cooling technology).
- *Constructability*: The relative ease with which advanced nuclear systems can be built on schedule and within budget. Examples of reactor features that might improve constructability are the extent to which systems, structures and components are amenable to factory assembly and modular deployment.

2.2.3 Product Flexibility Definition

Product flexibility considers the ability of an advanced nuclear system to fulfill more than one mission by being able to produce multiple or higher-quality

[3] "Hybrid systems" are sometimes defined to include the ability of a nuclear reactor to produce multiple forms of energy such as electricity and heat. This aspect is considered under the Product Flexibility sub-criterion.

products. Definitions of three fundament product flexibility attributes for advanced nuclear are:

- *Electricity*: The ability of an advanced reactor to efficiently convert thermal power to electricity. In general, thermal efficiency increases with reactor outlet temperature.
- *Process heat*: The ability of an advanced reactor to produce desired quality and quantity of heat appropriate for a given end use or industrial application.
- *Radioisotopes*: The ability of an advanced reactor to produce and allow extraction of desirable radioisotopes. Examples include production of tritium, Co-60, noble gases, Ir-192, and Mo-99.

Section 3: Technology Readiness Levels and Information Availability for Evaluating the Flexibility of Advanced Reactor Designs

A metric that is used to measure how close technologies are to being ready for deployment (maturity) is the Technology Readiness Level (TRL). The TRL is a numerical value denoting how far a technology has progressed through RDD&D steps ranging from basic research to deployment at industrial scale. TRLs are frequently established through a Technology Readiness Assessment (TRA) process.

TRLs can be a useful mechanism for evaluating advanced nuclear reactor designs. Analyzing each attribute of the flexibility sub-criteria in the context of the information available at each TRL level can also provide useful insights in determining the earliest (lowest) TRL at which each expanded flexibility criteria can be evaluated.

3.1 Background on TRLs

The TRA process was conceived by the National Aeronautics and Space Administration (NASA) and first used in the 1990s to measure the maturity of technologies for various space vehicles systems (Mankins, 1995). The General Accountability Office (GAO) has recommended that the TRA process be used by the Department of Defense (DoD) (GAO, 1999), the Department of Energy (DOE) environmental cleanup program (DOE-EM) (DOE, 2007), and the DOE nuclear energy (DOE-NE) RD&D program (GAO, 2011).

These organizations have committed to using the TRA process along with other government and private sector organizations (DOD, 2003a; DOE, 2010; DOE, 2003). As a result of this expanding adoption of the TRA process, it has been refined and codified in a variety of standards and guides (DOD, 2003b; DOE, 2011; DOE, 2013; EPRI, 2014b; EPRI, 2016c; ISO, 2013; Krahn et al., 2014; Miller, 2010; Sauser et al. 2006). Additional background on TRLs and the TRA process is provided in Appendix A.

One representation of the TRL scale employed by EPRI maps the nine TRLs to the broader stages of research, development, demonstration and deployment as illustrated in Figure 3-1 (EPRI, 2011).

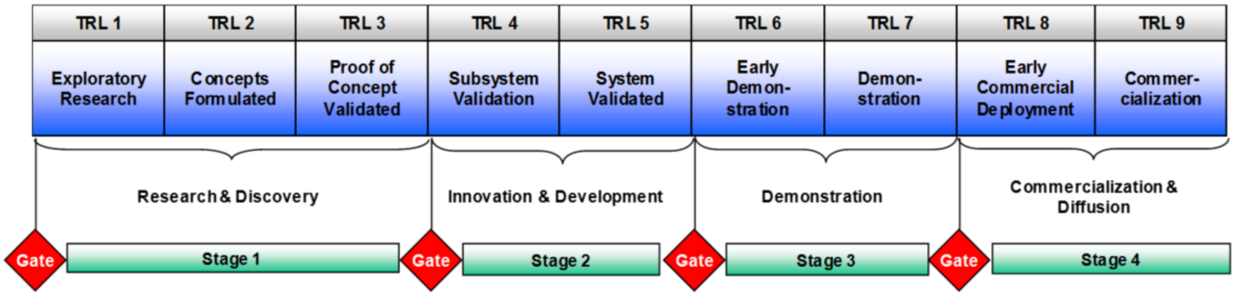

Figure 3-1
Technology Readiness Levels and Development Stages.

3.2 Development of TRLs for Advanced Nuclear Reactors

A review of relevant literature identified 16 scales for TRL determination about evenly split between nuclear applications and other complex technologies such as defense and aerospace. The results are summarized in terms of the label (a few words), definition (a phrase or sentence), and a description (several phrases sentences) where available. Key terms used in various TRL definitions and descriptions (e.g., high fidelity) are also included. The detailed results of the literature search are given in Section A.2 of Appendix A. These results were then used as the basis for synthesizing a proposed TRL scale for advanced nuclear reactors, including labels, identification of stages (commonly used groupings of TRLs) to reduce the level of detail and improve transparency in some applications, and characterization of each TRL with respect to specialized terms (e.g., fidelity) used to determine the TRL. The proposed scale and some of its key characteristics are summarized in Table 3-1.

One use of the TRL scale for advanced nuclear reactors, and the reason the scale was created in this report, is to provide a framework for determining the technical information that has to be available for a reactor design to achieve each TRL for use in determining the TRL at which flexibility attributes can be evaluated. However, the proposed advanced reactor TRL scale, when elaborated with lists of assessment questions at each TRL, could also constitute the basis for other important applications such as assessing the maturity of an advanced reactor concept and for establishing design goals and deployment specifications for an advanced reactor development program.

3.3 Analysis of Information Availability at Each TRL

The TRL scale defined in Table 3-1 is used as a framework for analyzing the technical information that would be available when each TRL is achieved. There are two types of technical information available at each TRL. The first type is a description of the technical information that is expected to be available to support a finding that a particular TRL has been achieved, including the TRL at which key design documents are completed. [4]

The second type of technical information is contained the key design documents. Key system design documents are also often used to consolidate and integrate the information available at various stages of reactor design and commercialization. As a consequence, a separate effort was undertaken to (a) survey the literature to determine the technical information that should be in each of the four key advance reactor design documents and (b) synthesize the literature survey results to yield a description of the information that should be in each design document that is consistent with the information available at the associated TRL. Nine sources of technical information availability in key design documents were identified although not all sources addressed all four design documents. Four of the sources were nuclear-oriented and the others addressed design maturation in general. The results of this effort are contained in Appendix B and the synthesis of information availability is contained in Tables B-1 through B-4.

The technical information that should be available as a function of TRL as described in this section, when combined with identification of the information that is required to evaluate each flexibility attribute (developed in Section 4) will provide the foundation for determining when each flexibility attribute can be provisionally and, separately, definitively evaluated.

[4] Pre-conceptual design, conceptual design, preliminary design, final design

Table 3-1
Proposed advanced nuclear reactor TRL definitions and key characteristics

TRL	1	2	3	4	5	6	7	8	9
Short Label	Basic Research	Concepts Formulated	Proof of Concept	Component Validation: Bench-Scale	Subsystem Validation: Bench-Scale	Subsystem Validation: Engineering-Scale	Test Reactor	Demonstration Reactor(s)	Commercialization
Stage	**(Basic and Applied) Research**			**Development**		**Demonstration**		**Deployment**	
Design Status at TRL Achievement			Pre-Conceptual		Conceptual		Preliminary Design (PD): Demo Reactor	Final Design (FD): Commercial Reactor	Licensed or Certified Designs (Including Evolutionary Improvements)
Technology Attributes at Each TRL									
Radiological or Nuclear Conditions[5]	N/A	N/A	Cold	Predominantly Cold Testing (transitioning from "cold" to "hot")	Predominantly Hot Testing (transitioning from "cold" to "hot")	Hot	Hot	Hot	Hot
Fidelity ("Exactness")[6]	On paper / incipient stage	On paper / lab bench	Partial: Matches component(s) of the system	Partial: Matches component(s) of the system	Similar: Matches final application in most respects	Similar: Matches final application in most respects	Similar: Matches final application in most respects	Identical / Prototypical: Matches final application in all respects	Identical: Matches final application in all respects

[5] This attribute is indicative of the radioactivity amounts involved in different phases of testing, development, demonstration and deployment. The "cold" designation indicates no significant amount of radioactivity involved (e.g., none at all, trace amounts, or bulk quantities of low specific activity materials. The term "hot" indicates use or generation of sufficiently radioactivity to present significant radiological hazards and/or operation of a critical system.

[6] This attribute is a measure of the extent to which a test, development, demonstration or deployment duplicates the actual conditions or task performed; the closer the match, the higher the fidelity

Table 3-1 (continued)
Proposed advanced nuclear reactor TRL definitions and key characteristics

TRL	1	2	3	4	5	6	7	8	9
Environment[7]	N/A	N/A	Functional – Created by any convenient and effective means	Functional – Created by any convenient and effective means	Relevant – Mostly functional but some operational	Relevant – Mostly functional but some operational	Operational – limited range	Operational – full range	Operational – full range
Materials[8]	On paper and computer models	Use of non-radioactive or low-radioactivity materials, possibly with tracers	Use of non-radioactive or low-radioactivity materials, possibly with tracers	Use of non-radioactive or low-radioactivity materials, possibly with tracers and limited highly radioactive materials	Use of non-radioactive or low-radioactivity materials, possibly with tracers, possibly with tracers and limited highly radioactive materials	Use of the actual materials	Use of the actual materials	Use of the actual materials	Use of the actual materials
Integration[9]	On paper / conceptual	Components	Components	Subsystems	Subsystems	Subsystems	System	System	System

[7] This attribute is indicative of the extent to which the test, development, deployment and demonstration conditions replicate the environmental conditions postulated events/ranges of operation for a specific system; it ranges from 'N/A" to "functional" which represent a general approximation of some environment conditions, to "relevant" and "operational"

[8] This attribute is a measure of the use of special nuclear materials (fertile or fissile isotopes) during various stages of testing, development and deployment

[9] This attribute is a measure of the completeness of a certain system, during various stages of testing, development and deployment. It ranges from "on paper/conceptual" to "components", "subsystems" and "system"

Table 3-2
Characterization of the technology maturity and information required to achieve each TRL

TRL	Characterization and Technical Information Availability
1	*Characterization* • Results of ongoing generic research or changes in the environment (regulatory, economic, etc.) enable a new reactor concept to be conceived. *Information Availability* • Expanding body of generic knowledge concerning materials, fluids, physics, chemistry, design; e.g., a new alloy, a cold-wall reactor design, a new manufacturing technique • Identification of environmental factors that have changed. • 'PowerPoint' idea for a new reactor concept and a qualitative rationale.
2	*Characterization* • Invention begins • Multiple alternatives are conceived for the new reactor concept. • Concept and alternatives are based on assumptions, judgment, and rudimentary analyses. • Owner-operator requirements are solicited • Technical information gaps are identified • Critical technology elements are identified • RDD&D planning commences *Information Availability* • Concept alternatives are identified. • Rudimentary steady-state neutronics, fluid flow, and heat transfer calculations performed for alternatives. • Candidate materials have been identified. • 'PowerPoint' representations are matured
3	*Characterization* • Substantial R&D is initiated • Analytical models of critical technology elements are developed • Bench-scale experimental studies are conducted to validate analytical models of critical technology elements or provide data needed to address integration, compatibility, or design issues • Preliminary owner-operator requirements are identified • Scaling approach is developed

Table 3-2 (continued)
Characterization of the technology maturity and information required to achieve each TRL

TRL	Characterization and Technical Information Availability
3	*Information Availability* • Preliminary Conceptual Design (PCD) contents • Multidimensional steady-state neutronics, fluid flow, and heat transfer calculations continue using newly acquired data. • Alternatives analyzed leading to selection of preferred alternative. • Reference materials are provisionally selected. • Initial Process Hazard Analyses (PHA and HAZOP)
4	*Characterization* • Experimental studies of realistic critical technology elements in a bench-scale configuration and environment that is functional but not necessarily realistic are completed • Analytical models are shown to accurately predict experimental results • Owner-operator requirements are solidified *Information Availability* • Performance data for critical technology elements • Results from validated analytical modeling of critical technology elements in a functional environment. • Experimental results are used to optimize the design of critical technology elements. • Multi-dimensional neutronic, fluid flow, and heat transfer under dynamic and off-normal conditions are performed. • Updated HAZOP, begin PRA development
5	*Characterization* • Experimental studies of realistic critical technology elements integrated into a complete bench-scale subsystem(s) in a realistic configuration and a relevant environment are completed • Models are shown to accurately predict experimental results *Information Availability* • Conceptual Design (CD) contents • Data from subsystem operation at a realistic bench-scale • Models have been validated based on bench-scale subsystem test results.

Table 3-2 (continued)
Characterization of the technology maturity and information required to achieve each TRL

TRL	Characterization and Technical Information Availability
5	• Test results and validated models are used to optimize the subsystems and plan for expansion to pilot scale. • Detailed reactor system modeling has been initiated. • Preliminary Test reactor design has been completed • Preliminary PRA results
6	*Characterization* • Experimental studies of realistic complete subsystems in a relevant environment are completed • Models are shown to accurately predict experimental results • A test reactor design has been prepared *Information* Availability • Data from subsystem operation at a realistic pilot-scale • Models have been validated based on engineering-scale subsystem test results. • Component and subsystem designs are optimized using engineering-scale data and models • Final test reactor design developed using optimized inputs • Detailed and integrated reactor system modeling (neutronic, fluid flow, heat transfer; static and dynamic) is completed for the test reactor and underway for the demo reactor. • Test Reactor, Final Design (FD), Licensing Application (LA) and Environmental Assessment (EA) or Environmental Impact Statement (EIS) • Alternative conceptual designs of the commercial reactor are prepared.
7	*Characterization* • A test reactor that includes all unique subsystems integrated into a system that provides a limited representation of the expected operational environment is built and operated. • Analytical models are shown to accurately predict data from test reactor operations. • A detailed demo reactor design has been prepared • A preliminary commercial reactor design is prepared.

Table 3-2 (continued)
Characterization of the technology maturity and information required to achieve each TRL

TRL	Characterization and Technical Information Availability
7	*Information Availability* • Preliminary Design (PD) contents • Measured data from operation of the test reactor under steady-state and transient conditions • Validated neutronic, fluid flow and heat transfer models under static and transient conditions based on test reactor operations • Detailed and integrated reactor system modeling (neutronic, fluid flow, heat transfer; static and dynamic) is completed for the demo reactor and underway for the commercial reactor based on operating experience. • Demonstration reactor Preliminary Design (PD) design with sufficient detail to allow for budgeting and procurement • Demo Reactor, Licensing Application (LA) and Environmental Impact Statement (EIS)
8	*Characterization* • A demo reactor, or reactors depending on scaling approach, including all ancillary and power utilization systems that is large enough to satisfy regulatory and scale-up requirements and essentially identical to anticipated commercial reactor designs is built and operated in an operational environment • Analytical models are shown to accurately predict data from test reactor operations. • Detailed commercial reactor designs have been prepared. *Information Availability* • Final Design (FD) contents • End of system development. • Technology proven to work in an operational environment at a scale fully relevant to a commercial reactor. • Validated models are available and have been used to optimize commercial reactor designs to meet utility requirements. • Detailed designs are available. • A commercial reactor design (FD) suitable for licensing and procurement is available. • Commercial reactor, Licensing Application (LA) and or Environmental Impact Statement (EIS)

Table 3-2 (continued)
Characterization of the technology maturity and information required to achieve each TRL

TRL	Characterization and Technical Information Availability
9	*Characterization* • First-of-a-Kind deployment of the reactor system followed by the commercialization of the technology leading to deployment of Nth–of–kind designs *Information* Availability • Evolutionary technology improvement based on operating experience

Section 4: How Early Can a Flexibility Attribute be Evaluated?

The confidence with which each flexibility attribute can be evaluated depends on the maturity of the technology because the information available to inform the evaluation is limited at early TRLs. As a consequence, it is both prudent and necessary to tailor the flexibility attributes considered in advanced reactor evaluation to a given level of maturity to the technological maturity (largely based on information availability) of the reactor being evaluated.

A first estimate of the TRL associated with each of the ten flexibility attributes can be evaluated by analyzing each attribute to identify the required technical information. Then, the information requirement is compared to the information available at each TRL (see Table B-1 and Appendix B) to determine the TRL at which the attribute can be evaluated. Each attribute is analyzed twice in this manner: once to determine the TRL at which the attribute might be initially (provisionally) evaluated to yield a threshold result and once to determine the TRL at which the attribute might be finally (definitively) evaluated. Between these levels, the quality of the available information increases as a function of the design maturity. The results of this analysis are given in Table 4-1 and shown graphically in Figure 4-1.

The color-coding in Figure 4-1 was determined in a two stage evaluation. In the first stage, the information necessary for a threshold (low-confidence) evaluation of an attribute given in Table 4-1 is compared to the information that is available for that attribute at each TRL, as given in Tables B-1 through B-4. Each attribute was assigned red until enough information became available for a threshold evaluation of the attribute at which point it was assigned yellow. In the second stage, the same comparison was performed respect to the information necessary for completing a definitive (high-confidence) evaluation of the attribute. Each attribute was assigned a green color for TRLs at which sufficient information was available for a high-confidence evaluation.

Table 4-1
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	**Threshold Evaluation** [10]		**Definitive Evaluation** [11]	
	Required Information	**TRL When Required Information is Available and Explanatory Notes**	**Required Information**	**TRL When Required Information is Available and Explanatory Notes**
Operational – Maneuverability	• Dynamic multi-dimensional reactor physics calculations that can simulate power transients to determine potential power ramp rates	**TRL 4** • Dynamic multi-dimensional calculation results are available here but not yet validated.	• Dynamic simulation of reactor and power conversion system using validated models to determine system responses to power ramps • Dynamic analysis of reactor and power conversion system components to determine impact of maneuvering on component degradation	**TRL 7** • Test results to validate dynamic simulations become available from test reactor operations • The dynamic analyses occur as part of the preliminary (demo reactor) design
Operational – Compatibility with Hybrid Systems	• Dynamic multi-dimensional reactor physics simulation	**TRL 4** • Dynamic multi-dimensional calculation results are available here but not yet validated.	• Dynamic simulation of reactor and power conversion and storage system(s) using validated models to determine compatibility and operating limits	**TRL 7** • Test results to validate dynamic simulations become available from test reactor operations

[10] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[11] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

Table 4-1 (continued)
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	**Threshold Evaluation** [12]		**Definitive Evaluation** [13]	
	Required Information	**TRL When Required Information is Available and Explanatory Notes**	**Required Information**	**TRL When Required Information is Available and Explanatory Notes**
Operational – Compatibility with Hybrid Systems	• Dynamic simulation of the response of a generic hybrid power conversions systems, e.g., Rankine cycle plus topping cycle or storage system	**TRL 4** • Dynamic simulation of alternative hybrid systems should be possible using generic sub-system models	• Analysis of reactor and power conversion system components to determine impact of maneuvering on component degradation	**TRL 7** • The dynamic analyses occur as part of the preliminary (demo reactor) design
Operational – Diversified Fuel Use	• Static reactor physics calculations to determine feasibility and performance of various fissile and fertile material combinations Qualitative analysis of the compatibility of various claddings, and fuel forms and geometries with the reactor concept based on available literature	**TRL 2** • Reactor physics calculations are being performed in support of developing design alternatives • Material compatibility analyses are being performed in support of developing design alternatives	• Dynamic multi-dimensional simulation of various combinations of fissile and fertile materials in various forms and geometries to establish the range of potential fuels that can reasonably be used • An analysis of the range of cladding materials that can be used	**TRL 4** • Simulations have been performed to reach this level • Sufficient information available on material performance and in-reactor conditions to establish range of potential cladding materials

[12] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[13] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

Table 4-1 (continued)
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	Threshold Evaluation [14]		Definitive Evaluation [15]	
	Required Information	TRL When Required Information is Available and Explanatory Notes	Required Information	TRL When Required Information is Available and Explanatory Notes
Operational – Island Mode Operation	• The extent to which a reactor concept is amenable to passive safety features	**TRL 4** • Unvalidated dynamic reactor physics and Thermo-Hydraulic calculations completed	• Dynamic simulation of the integrated reactor-power conversion system using validated models to determine system responses to the absence of off-site power • The minimum feasible reactor capacity which allows for more siting opportunities	**TRL 7** • Have detailed modeling results validated by component and test reactor results • Minimum feasible reactor capacity can be established earlier
Deployment – Scalability	• Static reactor physics calculations to establish the minimum reactor size that does not encounter a limit such as inability to achieve criticality or requiring uranium enrichments greater than 5%	**TRL 3** • Static multi-dimensional reactor physics calculations should suffice	• Static reactor physics calculations including fuel management schemes to establish the minimum reactor capacity that does not encounter a limit such as inability to achieve criticality and sustain it long enough to be practical	• Firm estimates of minimum reactor capacity should be available earlier

[14] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[15] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

Table 4-1 (continued)
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	Threshold Evaluation [16]		Definitive Evaluation [17]	
	Required Information	TRL When Required Information is Available and Explanatory Notes	Required Information	TRL When Required Information is Available and Explanatory Notes
Deployment – Scalability	• Comparison of rough estimates of key component sizes (e.g., pressure vessel, steam generators) to limits in manufacturing and transportation capabilities.	**TRL 3** • Reactor physics results for alternatives (power densities) and coolant energy balance calculations for alternatives should allow rough estimates of large component sizes to be made and compared to manufacturing capabilities.	• Comparison of firm estimates of key component sizes to limits in manufacturing and transportation capabilities	**TRL 7** • The need for firm designs for a real reactor are the limiting need and these would be part of the preliminary design.
Deployment – Siting	• The estimated thermal efficiency (i.e., reactor coolant outlet temperature): higher efficiency means less need for heat rejection to the environment and a greater range of feasible sites	**TRL 2** • Range of potential materials and energy balances for alternative designs should provide enough information for initial estimates of thermal efficiency	• Firm estimate of the thermal efficiency based on validated models and a real reactor design • The size of the Emergency Planning Zone for the reactor(s) on the site	**TRL 7** • Firm estimates for demonstration reactor would supply this • Licensing discussions and rulemaking for demo reactor or possibly earlier

[16] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[17] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

Table 4-1 (continued)
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	Threshold Evaluation [18]		Definitive Evaluation [19]	
	Required Information	TRL When Required Information is Available and Explanatory Notes	Required Information	TRL When Required Information is Available and Explanatory Notes
Deployment – Constructability	• Conceptual reactor design trade study results that provide some initial basis for the minimum economic reactor size as a basis for estimating the extent to which reactor components amenable to factory construction	**TRL 3** • This type of trade study will be needed to prepare the pre-conceptual design which identifies a preferred alternative	• Design of reactor components at a level of detail sufficient for procurement	**TRL 7** • The design of reactor components at this level of detail would be part of the preliminary design
Product – Electricity	• The estimated thermal efficiency (i.e., reactor coolant outlet temperature) based on basic energy balances for generic power conversion systems	**TRL 2** • Range of potential materials and energy balances for alternative designs should provide enough information for initial estimates of thermal efficiency	• Firm estimate of the thermal efficiency based on validated models and power conversion systems proposed for real reactors	**TRL 6** • Study of demo reactor alternative designs based on test reactor results should be reliable enough to support this evaluation.

[18] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[19] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

Table 4-1 (continued)
Required information and its availability for initial and final evaluation of flexibility attributes

Sub-Criterion and Attribute	Threshold Evaluation [20]		Definitive Evaluation [21]	
	Required Information	**TRL When Required Information is Available and Explanatory Notes**	**Required Information**	**TRL When Required Information is Available and Explanatory Notes**
Product – Process Heat	• The estimated reactor coolant outlet temperature	**TRL 2** • Range of potential materials and energy balances for alternative designs should provide enough information for initial estimates of reactor outlet temperatures	• Firm estimate of the reactor coolant outlet temperature using validated models	**TRL 6** • Study of demo reactor alternative designs based on test reactor results should be reliable enough to support this evaluation
Product – Radioisotopes	• Production rate (product of flux and cross section) of isotopes of interest based on static reactor physics calculations	**TRL 2** • Static reactor calculations for the alternatives being considered should provide enough information to support evaluation. Evaluation results will differ among candidate radioisotopes, e.g., some are favored by thermal neutrons, others by fast	• Firm estimate of radioisotope production rates based on static multi-dimensional reactor physics calculations and realistic fuel management schemes • For short-lived radioisotopes, the design of the system for inserting and removing targets and a safety analysis thereof.	**TRL 7** • Firm estimates of production rates should be available at TRL 4. This may be adequate for long-lived radioisotopes l • For short-lived radioisotopes, the design of the insertion-removal mechanism needs to be integrated into the design of the reactor vessel.

[20] The minimum amount of information that is needed to evaluate the attribute with some degree of reliability and the TRL when that information is available.

[21] The information needed to evaluate the attribute with a high degree of confidence and the TRL when that information is available.

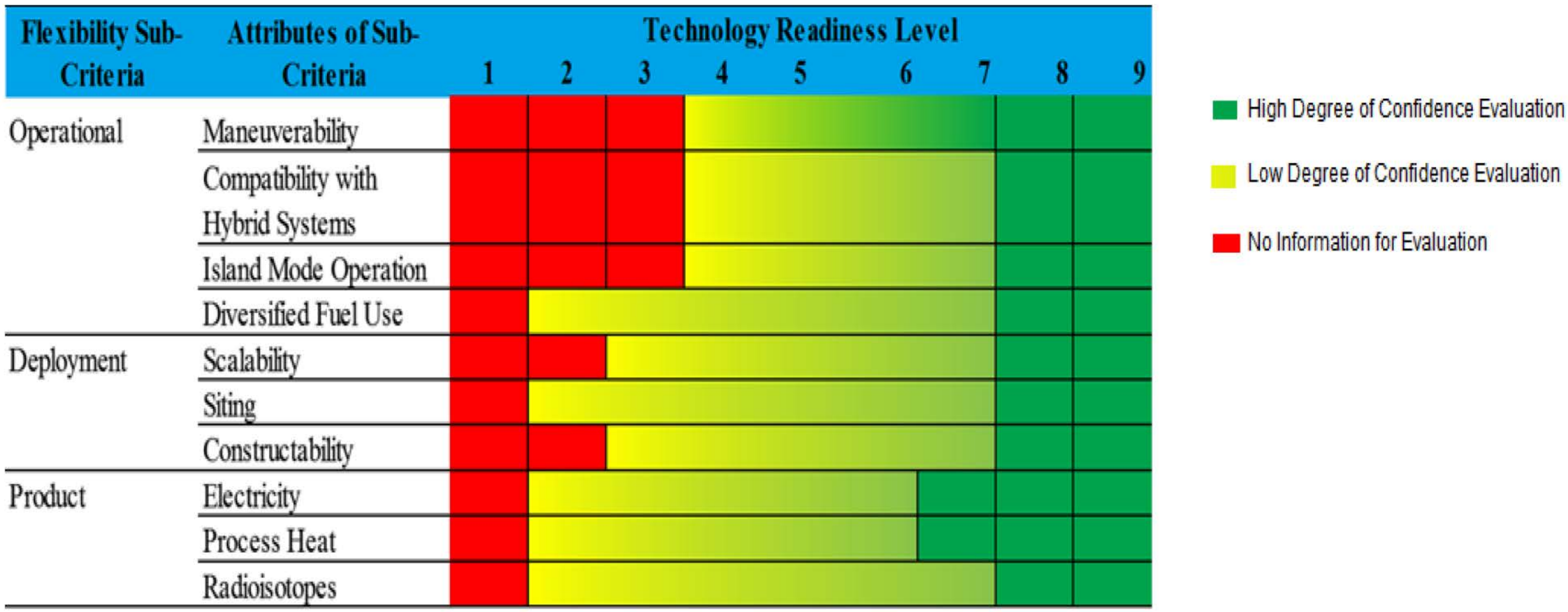

Figure 4-1
Technology Readiness Level Thresholds for Evaluating Flexibility of Advanced Reactor Technologies.

Section 5: Conclusions

The foregoing discussion and results lead to of the following conclusions:

1. **The flexibility attributes that are useful for comparing reactors at low TRLs are limited in number.** In general, the attributes that are most useful appear to be those that can be obtained via relatively simple calculations (e.g., reactor physics, heat balance) while those that are not useful in the early stages require data from complex experiments (e.g., test or demonstration reactor operation) or from sophisticated modeling of more detailed reactor designs.
2. **Examination of the attributes that can be evaluated in the early stages of maturation reveals that consideration of just a few underlying aspects of advanced reactor designs may provide a good indication of which design might be more preferred for additional R&D investment.** Foremost among these is the estimated reactor outlet temperature where a higher temperature is more favorable for electricity production, heat production, and potentially siting attributes (e.g., use of dry cooling). The outlet temperature is also important in evaluating the potential for diversified fuel use because a higher outlet temperature might also mean fewer materials for use as the fuel matrix or cladding materials would be suitable.
3. **The reactors built and operated corresponding to TRL 7 and TRL 8 (test and demonstration, respectively) play an important role in generating information needed to fully evaluate many flexibility attributes.** Operation of these reactors provides information of the dynamic behavior of operating reactors that is somewhat or fully representative of a large, complex, integrated system that includes some or all of the features required to be licensable. The resulting information is crucial to evaluating many attributes, especially for the operability or deployment sub-criteria.
4. **Comparison of advanced reactors with regard to flexibility at different TRLs is unlikely to be definitive.** Comparing a SCWR at TRL 2 or 3 to a more mature reactor design, like a certified advanced LWR design, will be problematic. For example, because evaluating many of the SCWR flexibility attributes would have to be based on expert judgment uninformed by tests and concept demonstration whereas the attributes for the ALWRs could be evaluated with a fairly high degree of confidence based on previous operational experience.

5. **Attributes that are not useful for comparing advanced reactor options at lower TRLs are still useful for establishing design goals throughout the RD&D process**. Even though an attribute may not be useful in comparing reactor options, it can still be useful at lower TRLs for reactor developers to drive the design and the work needed to complete the design, while informing the deployment specifications.
6. **The implications described in this report are likely to be generically applicable to other top-level criteria typically used to evaluate advanced reactor systems.** As with the attributes of the flexibility criterion, many attributes of other commonly used top-level criteria such as safety, economic competitiveness, and waste production cannot be fully evaluated at early TRLs.

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Appendix A: Results of a Literature Search for Historical and Current Technology Readiness Level Scales Relevant to Advanced Nuclear Reactors

A.1 Background on Technology Readiness Assessment and Levels

A Technology Readiness Assessment (TRA) is a systematic, metric-based process that assesses the maturity of technologies used in systems that are typically complex. It is the most widely accepted method for determining Technology Readiness Levels (TRLs). TRLs describe the progress of a technology through the sequential stages of RDD&D is measured on a scale of 1 to 9, with 1 representing basic research and 9 representing a technology that has been deployed at an industrial scale. [22] The TRA process to determine the TRL can be summarized as follows:

- Develop TRL Definitions: Typically, the first step is for the relevant 'industry' (e.g., aerospace, Department of Energy cleanup program, Department of Defense) to establish a TRL scale based on well-established precepts, but expressed in terms familiar to the industry. Then, a list of "yes" or "no" questions are developed for each TRL (TRL questions) with a "yes" answer verified by documents being required for all questions for the technology to be deemed to have achieved that TRL.
- Commit to Self-assessment: In this stage the developer identifies the need to assess the readiness of their technology. This is considered to be 'best practice' but not a requirement unless it is imposed by others, e.g., a funding organization.
- Establish a TRA team: A team composed of members having a range of expertise relevant to the technology being assessed is established. Ideally, the team members are independent of the technology development team.

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However, it may be necessary to involve team members that are not independent for immature systems (basic and applied research) where relevant expertise is limited.

- Identify Critical Technology Elements (CTEs): Most systems contain multiple sub-systems composed of multiple elements. To make TRA tractable and more efficient, the TRA process focuses on only unproven technologies – called CTEs – those that are essential to the successful operation of the system and are new or are being applied in novel ways or in a new environment.
- Determine the TRL of each CTE: The TRL indicates the maturity level of a given technology. The TRL is established by answering the "TRL questions for each CTE based on documentation related to the subject technology. The TRL for a technology is the highest value for which all questions were answered "yes".
- Prepare Technology Maturation Plan: If the TRL for a CTE is less than what is required for it to be used with confidence, then a maturity gap exists that requires further RD&D to bring the immature technology to the appropriate maturity level. The appropriate maturity level may be "deployed" or a lower level indicating a technology is ready for hand-off to another organization (e.g., from the R&D group to process engineering). A Technology Maturation Plan (TMP) identifies the activities required to bring immature CTEs up to the next desired TRL in a sequential RDD&D process.

Application of a TRA process to a program to develop advanced nuclear reactors raises some unique issues from the perspective of both history and context. These issues and their implications Using the U.S. as an example are as follows, Krahn et al. (2014) report:

- Many organizations deploy the technologies they are developing whereas advanced nuclear reactors are typically developed by DOE-NE up to a point and then transitioned to the private sector for deployment with shared responsibility in the demonstration phase. This raises the issue of the involvement of industry in TRAs performed before a technology is sufficiently mature to be transferred to industry. One consequence of the involvement of both a government developer and an industry owner/operator in decisions involving nuclear technology is that the customer/user/decision-maker for the TRA results is diffuse; potentially including: DOE-NE, senior DOE management, members of Congress, industry (utilities, equipment vendors), and review or oversight organizations[23].
- In some organizations (such as DoD and NASA) TRA is conducted in the context of a planned or approved "project," having a defined deployment goal, schedule, etc. to inform decisions on whether to proceed at critical

[23] Depending on the stage of nuclear technology development, interested oversight organizations could include the GAO, the National Academy of Sciences (NAS, if tasked), DOE-NE's own Nuclear Energy Research Advisory Committee (NERAC), the Nuclear Waste Technology Review Board (NWTRB), the Nuclear Regulatory Commission (NRC) and others.

junctures in a disciplined approach to achieving the goal, i.e., a 'decision gate' approach (Miller, 2010). Nuclear reactor RDD&D is not presently being conducted in such an atmosphere, i.e., there is not an approved "project" leading to deployment that requires a "Critical Decision" in accordance with DOE's project management requirements. Instead, RDD&D proceeds by convincing reviewers, stakeholders, and funding organizations, that a particular advanced reactor concept warrants their continuing support. This situation makes the TRA process even more important as a structured tool to provide evidence that the concept is ready for advancement.

- A TRA conducted by the RD&D project offers benefits. It can help to focus the project on what needs to be done to mature their technology and assemble the evidence required for an independent/peer review of their efforts. On the other hand, detailed TRAs can divert resources from the RD&D *per se* which can adversely impact low TRL RD&D projects that tend to be small. On balance, self-assessments are beneficial at any TRL and that DOE's 'best practices' provision – but not a requirement – is appropriate. In particular, at lower TRLs (e.g., 1-3) self-assessments that are reviewed by independent experts may be appropriate.

The definition of each TRL (a few sentences or phrases) is standard across many organizations (e.g., NASA, DoD) but other organizations have adopted definitions specific to their applications (e.g., DOE-EM), and organizations involved in advanced nuclear reactors (e.g., DOE-NE, GIF) have used both standard and application-specific TRL definitions. The approach to TRL questions differs among organizations. For example, DOE-EM has created standard TRL questions that are related to site-specific decisions on whether and how to proceed with various cleanup projects (DOE, 2013) whereas there is no evidence that organizations developing advanced nuclear reactors are using TRL questions to assess technology maturity. On balance, the following observations seem appropriate:

- Ideally, accepted international standard definitions for TRLs should be used but such can pose difficulties because the need to translate technical jargon between (e.g., what is a "breadboard" in a nuclear reactor system) can lead to differing interpretations of the TRL definitions across various industries. Thus, standard industry-specific[24] definitions reflecting the intent of accepted foundational definitions standard definitions should be developed.
- Industry-specific TRL questions need to be developed and used to ensure transparency and consistency in how TRLs are determined, and unambiguity in interpretation of the basis for the assessment. Currently, expert-based approaches to determining advanced reactor TRLs seem to be used and there was no evidence that questionnaires necessary to determine whether there was evidence that a particular TRL had been achieved were being used.

[24] "Industry-specific" means specific to a broad class of generic applications such as space, chemical processing, advanced reactors, pharmaceutical drug production, industrial chemical production, etc.

However, a technology having a TRL 7 may not be capable of being demonstrated or deployed because it cannot be licensed or because critical development or industrial infrastructure does not exist. Regulatory and infrastructure issues can clearly impact the ability to deploy technology. Thus, regulatory and infrastructure readiness should be considered in process of determining technology maturity. Regulatory and infrastructure evaluation can also define additional RD&D work that is needed to address the issues so identified. Regulatory and infrastructure readiness are frequently considered in TRA at TRLs 4 and 6, although regulatory and infrastructure issues that could impede RD&D may need earlier consideration.

An issue arising in TRA of very complex systems (i.e., systems composed of already-complex sub-systems) such as nuclear reactors is how to properly assess the TRL of the entire system given the existence of TRLs for the complex sub-systems. The difficulty is assessing whether the sub-systems will be fully compatible until they have been tested in an integrated system under operational conditions: possibly in a test reactor, but often, for power production and auxiliary systems, in a demonstration reactor (EPRI, 2016c).

A.2 Results of Literature Search for Technology Readiness Scales that are Potentially Relevant to Advanced Nuclear Reactors

This section contains the results of a literature search for scales that characterize TRLs that are stated to be applicable to advanced nuclear reactors or that involve complex, high-technology systems that have the potential to be adapted for application to advanced nuclear reactors. Each potential source of a scale is described using all available information in the source document (indicated in footnotes) at each TRL. Due to the large amount of information, summary results are divided into three groups: TRL 1-3 (Table A-1), TRL 4-6 (Table A-2), and TRL 7-9 (Table A-3).

Table A-1
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
DOE TRA Guide for EM construction[25]			
Label	Basic Technology Research	Research to Prove Feasibility	Research to Prove Feasibility
Definition	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof of concept
Description	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments

[25] Technology Readiness Assessment Guide, Table 1, DOE G 413.3-4A (September 15, 2011)

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
DOE TRA Guide for EM Waste Processing[26]			
Label	Technology Development	Technology Development	Technology Development
Scale	Concepts	Lab Scale (<10%)	Lab Scale (<10%)
Materials	None	Simulants	Simulants
Integration	Paper	Pieces	Pieces
Facility Design Status	Not Applicable	Not Applicable	Not Applicable
DOE TRA Guide for Generic Applications[27]			
Label	Basic Technology Research	Research to Prove Feasibility	Research to Prove Feasibility
Definition	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof of concept
Scale	Not Applicable	Not Applicable	Lab (<10%)
Fidelity	Paper – no hardware	Paper – no hardware	Pieces – matches a piece or pieces of final application
Environment	Not Applicable	Not Applicable	Simulated – range of simulants
Department of Defense[28]			
Labels	Not Assigned	Not Assigned	Not Assigned
Definition	Basic principles observed and reported	Technology concept and/or application formulated.	Analytical and experimental critical function and/or characteristic proof of concept.

[26] Technology Readiness Assessment Guide, Figures 2 and 3, Tables 2 and 3 from DOE G 413.3-4A (September 15, 2011)

[27] Technology Readiness Assessment Guide, Table 4, DOE G 413.3-4A (September 15, 2011)

[28] Technology Readiness Assessment Guidance, Department of Defense Assistant Secretary for Defense Research and Engineering (April 2011)

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
Description	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
Definition of Terms	Breadboard: Integrated components that provide a representation of a system/subsystem and that can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only		
	High Fidelity: Addresses form, fit, and function. High-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.		
	Low Fidelity: A representative of the component or system that has limited ability to provide anything but first-order information about the end product. Low-fidelity assessments are used to provide trend analysis		
	Model: A functional form of a system, generally reduced in scale, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system		
	Operational Environment: Environment that addresses all the operational requirements and specifications required of the final system to include platform/packaging		
	Prototype: A physical or virtual model used to evaluate the technical or manufacturing feasibility or military utility of a particular technology or process, concept, end item, or system.		
	Relevant Environment: Testing environment that simulates the key aspects of the operational environment		
	Simulated Operational Environment: Either (1) a real environment that can simulate all of the operational requirements and specifications required of the final system or (2) a simulated environment that allows for testing of a virtual prototype; used in either case to determine whether a developmental system meets the operational requirements and specifications of the final system.		

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
NASA[29]			
Label	None	None	None
Definition	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof-of-concept
Description	This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).	Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. For example, following the observation of high critical temperature (HCT) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture	At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory
Cost	Very low unique cost (uses generic R&D results)	Very low unique cost	Low unique cost

[29] Mankins, John C. (6 April 1995). "Technology Readiness Levels: A White Paper" (PDF). NASA, Office of Space Access and Technology, Advanced Concepts Office.

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
International Organization for Standards[30]			
Label	None	None	None
Definition	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof-of-concept
Description	Potential applications are identified following basic observations but element concept not yet formulated	Element concept is elaborated and expected performance is demonstrated through analytical models supported by experimental data/characteristics.	Element functional performance is demonstrated by breadboard testing in laboratory environment.
Canadian Public Works[31]			
Label	None	None	None
Definition	Basic principles of concept are observed and reported.	Technology concept and/or application formulated.	Analytical and experimental critical function and/or proof of concept.
Description	At this level, scientific research begins to translate into applied research and development. Activities might include paper studies of a technology's basic properties.	At this level invention begins. Once the basic principles are observed, practical applications can be invented. Activities are limited to analytical studies.	At this level, active research and development is initiated. Activities might include components that are not yet integrated or representative.

[30] Space systems — Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment, ISO/FDIS-16290 (2013)

[31] *"Technology Readiness Level". Public Works and Government Services Canada, Office of Small and Medium Enterprises. 2011-08-12.*

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
NGNP[32]			
Label	None	None	None
Definition	Basic principles observed	Application formulated	Proof of concept
Advanced Nuclear Fuels[33]			
Label	Proof-of-Concept	Proof-of-Concept	Proof-of-Concept
Definition	None	None	None
Description	A new concept is proposed. Technical options for the concept are identified and relevant literature data reviewed. Criteria development.	Technical options are ranked. Performance range and fabrication process parametric ranges defined based on analysis.	Concepts are verified through laboratory-scale experiments and characterization. Fabrication process verified using surrogates.
Gen IV Concepts[34]	Identical with DOE-G-413.3-R4a above		
INPRO[35]	Uses NASA definitions given above including references to space		

[32] Next-Generation Nuclear Plant: A Report to Congress, U.S. DOE (April 2010).

[33] J. Carmack, Technology Readiness Levels For Advanced Nuclear Fuels and Materials Development, INL/EXT-14-31243 (January 2014).

[34] H. D. Gougar et al., Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications, INL/EXT-15-36427 Rev 2 (October 2015)

[35] R. Beatty, Technology Readiness Levels, INPRO Dialog Forum Workshop February 1-4, 2010.

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
AHTR Thermochemical Cycle[36]			
Label	Concept Development	Concept Development	Concept Development
Definition	Scientific research begins to be translated into applied research and development (R&D).	Application begins once basic principles are observed; practical applications can be invented. Applications are speculative, and no proof or detailed analysis to support the assumptions may yet exist	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology
Description	New discoveries that may lead to performance improvements or cost reductions. At this TRL, the basic properties of advanced materials might be studied (e.g., tensile strength as a function of temperature and compatibility with fluoride salt) and once shown that the program understands these fundamental properties, the advanced materials would mature to the next TRL	New discoveries may result in performance improvements or cost reductions in future plants. For example, following the observation of advanced materials properties at TRL 1, the potential applications of the new material for structural materials applications can be defined. At this level, the application is still speculative; there is no experimental proof or detailed analysis to support the conjecture	Analysis of the performance of systems, structures, and components (SSC) produces favorable results, but testing is needed to validate the prediction and provide data supporting key features. Examples would include testing of carbon sacrificial electrode based oxygen removal and redox control for corrosion minimization in FLiBe and confirming performance of new optical access concepts for in-service inspection of components and structures. In addition, continuous fiber composites (CFCs) are key new materials for FHRs.

[36] D. E. Holcomb, Small, Modular Advanced High-Temperature Reactor—Carbonate Thermochemical Cycle Technology Readiness Level Assessment, ORNL/TM-2014/69 (March 2014).

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
Description			SmAHTR depends on the irradiation and thermo-physical properties of both SiC-SiC and C-C CFCs–TRL 3 would be attained when these materials have undergone irradiation with subsequent post-irradiation examination and their post-irradiation thermo-physical properties are defined and known.
GNEP Tech Dev Plan for SFR Fuel Reprocessing[37]			
Label	Concept Development	Concept Development	Concept Development
Definition	Concept for separations process developed; process options (e.g., electrolyte composition, process equipment) identified; separations criteria established	Calculated mass-balance flowsheet developed; scoping experiments on process options completed successfully with simulated advanced recycling reactor spent fuel; preliminary selection of process equipment.	Bench-scale batch testing with simulated advanced recycling reactor spent fuel completed successfully; process chemistry confirmed; reagents selected; preliminary testing of equipment design concepts done to identify development needs; complete system flowsheet established.
GNEP Tech Dev Plan for Advanced Recycling Reactor[38]			
Label	Concept Development	Concept Development	Concept Development
Definition	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology.

[37] U.S. Department of Energy, "Global Nuclear Energy Partnership Technology Development Plan", GNEP-TECH-TR-PP-2007-00020, Rev 0, Table E-4 (July 25, 2007)

[38] U.S. Department of Energy, "Global Nuclear Energy Partnership Technology Development Plan", GNEP-TECH-TR-PP-2007-00020, Rev 0, Table A-1 (July 25, 2007)

Table A-1 (continued)
Results of a literature review for technology readiness scales: TRL 1-3

Parameter	TRL 1	TRL 2	TRL 3
Description	New discoveries (i.e., in materials for cladding and ducts) may lead to performance improvement or cost reductions. At this technology readiness level, the basic properties of advanced materials might be studied (e.g., tensile strength as a function of temperature, irradiation effects, and compatibility with fast reactor coolants or fuels) and once shown that the program understands these fundamental properties, the advanced material would mature to the next TRL level.	Although sodium-cooled fast reactor technology is mature, new discoveries may result in performance improvements or cost reductions in future plants. For example, following the observation of advanced materials properties at TRL 1, the potential applications of the new material for structural materials applications, fast reactor fuel cladding, etc. can be defined. At this level, the application is still speculative; there is no experimental proof or detailed analysis to support the conjecture.	Analysis of the performance of SSCs (System, Structure or Component) produces favorable results, but testing is needed to validate the prediction and provide data supporting key features. Examples would include testing of printed circuit heat exchangers to confirm performance with sodium and testing of new concepts for under-sodium in-service inspection of components and structures. In addition, a compact fast reactor loop concept might depend on the irradiation and thermo-physical properties of an advanced material: TRL 3 might be attained when these materials have undergone irradiation with subsequent post-irradiation examination and their post-irradiation thermo-physical properties are defined and known.

Table A-2
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
DOE TRA Guide for EM construction[39]			
Label	Technology Development	Technology Development	Technology Demonstration
Definition	Component and/or system validation in laboratory environment.	Laboratory scale, similar system validation in relevant environment.	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment.
Description	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system.	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants1 and actual waste2. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.1 Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system.

[39] Technology Readiness Assessment Guide, Table 1, DOE G 413.3-4A (September 15, 2011)

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Description	The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.		The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
DOE TRA Guide for EM waste processing[40]			
Label	Technology Development	Technology Development	Technology Development
Scale	Bench scale (<10%)	Engineering scale (10%-100%)	Engineering scale (10%-100%)
Materials	Simulants or actual waste	Simulants or actual waste	Simulants
Integration	Prototypes	Prototypes	Prototypes
Facility Design Status	Conceptual Design		Preliminary and final designs
DOE TRA Guide[41]**: DOE generic**			
Label	Technology Development	Technology Development	Technology Demonstration
Definition	Component and/or system validation in laboratory environment	Laboratory scale, similar system validation in relevant environment	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
Scale	Lab (<10%)	Lab (<10%)	Engineering-Pilot (<10% to 100%_
Fidelity	Pieces – matches a piece or pieces of final application	Similar – matches final application in almost all respects	Similar – matches final application in almost all respects
Environment	Simulated – range of simulants	Relevant – range of simulants plus limited range of actual waste	Relevant – range of simulants plus limited range of actual waste

[40] Technology Readiness Assessment Guide, Figures 2 and 3, Tables 2 and 3 from DOE G 413.3-4A (September 15, 2011)

[41] Technology Readiness Assessment Guide, Table 4, DOE G 413.3-4A (September 15, 2011)

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Department of Defense[42]			
Labels	Not Assigned	Not Assigned	Not Assigned
Definition	Component and/or breadboard validation in a laboratory environment	Component and/or breadboard validation in a relevant environment.	System/subsystem model or prototype demonstration in a relevant environment
Description	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
Definition of Terms	Defined in Table A-1.		
NASA[43]			
Label	None	None	None
Definition	System prototype demonstration in a space environment	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Actual system "flight proven" through successful mission operations

[42] Technology Readiness Assessment Guidance, Department of Defense Assistant Secretary for Defense Research and Engineering (April 2011)

[43] Mankins, John C. (6 April 1995). "Technology Readiness Levels: A White Paper" (PDF). NASA, Office of Space Access and Technology, Advanced Concepts Office.

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Description	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new 'fuzzy logic' approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.	At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. From one-to-several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array 'blanket' that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system — which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding — would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
			.At this level, several-to-many new technologies might be integrated into the demonstration. For example, an innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scalable) model of the system on a Space Shuttle or International Space Station 'pallet'. In this example, the reason space is the 'relevant' environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system
Description			
Cost	Low unique cost	Low-to-moderate unique cost	Moderate unique cost
International Organization for Standards[44]			
Label	None	None	None
Definition	Component and/or breadboard functional verification in laboratory environment	Component and/or breadboard critical function verification in relevant environment	Model demonstrating the critical functions of the element in a relevant environment

[44] Space systems — Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment, ISO/FDIS-16290 (2013)

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Description	Element functional performance is demonstrated by breadboard testing in laboratory environment	Critical functions of the element are identified and the associated relevant environment is defined. Breadboards not full-scale are built for verifying the performance through testing in the relevant environment, subject to scaling effects	Critical functions of the element are verified, performance is demonstrated in the relevant environment and representative model(s) in form, fit and function
Canadian Public Works[45]			
Label	None	None	None
Definition	Component and/or validation in a laboratory environment.	Component and/or validation in a simulated environment.	System/subsystem model or prototype demonstration in a simulated environment.
Description	At this level, the basic technological components are integrated to establish that they will work together. Activities include integration of "ad hoc" hardware in the laboratory.	At this level, the basic technological components are integrated for testing in a simulated environment. Activities include laboratory integration of components.	At this level, a model or prototype is developed that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory.
NGNP[46]			
Label	None	None	None
Definition	Bench-scale testing	Component demonstration at experimental scale	Subsystem demonstrated at pilot scale

[45] *"Technology Readiness Level". Public Works and Government Services Canada, Office of Small and Medium Enterprises. 2011-08-12.*

[46] Next-Generation Nuclear Plant: A Report to Congress, U.S. DOE (April 2010).

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Advanced Nuclear Fuels[47]			
Label	Proof-of-Principle	Proof-of-Principle	Proof-of-Principle
Definition	None	None	None
Description	Fabrication of samples using stockpile materials at bench-scale. Irradiation testing of small samples (rodlets) in relevant environment. Design parameters and features established. Basic properties compiled.	Fabrication of pins using prototypic feedstock materials at laboratory scale. Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified. Fuel behavior models developed for use in fuel performance codes.	Fabrication of pins using prototypic feedstock materials at laboratory scale and using prototypic fabrication processes. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Predictive fuel performance codes and safety basis established.
Gen IV Concepts[48]	Identical with DOE-G-413.3-R4a above		
INPRO[49]	Uses NASA definitions given above including references to space		

[47] J. Carmack, Technology Readiness Levels For Advanced Nuclear Fuels and Materials Development, INL/EXT-14-31243 (January 2014).

[48] H. D. Gougar et al., Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications, INL/EXT-15-36427 Rev 2 (October 2015)

[49] R. Beatty, Technology Readiness Levels, INPRO Dialog Forum Workshop February 1-4, 2010.

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
AHTR Thermochemical Cycle[50]			
Label	Proof-of-Principle	Proof-of-Principle	Proof-of-Principle
Definition	Integration of basic technological components for testing in laboratory environment. Includes integration of ad hoc hardware in the laboratory.	Integration of basic technological components with realistic supporting elements for testing in relevant environment	Model or prototype system testing in a relevant environment.
Description	Laboratory testing of individual components or portions of systems have been completed successfully. Examples would include separate effects testing of component performance, such as mounting an ultrasonic flowmeter onto nickel alloy piping or testing of fluidic diode performance with water.	Individual components or portions of systems have been successfully tested at less than full scale in a test reactor, out-of-pile test facility, or in another application. Examples would include successful testing of a section of a fuel element in a test reactor or successful testing of individual hydraulic components of a molten salt system in a molten salt loop. For example, a reduced-size, canned rotor, magnetic bearing pump will be built and tested with its power supply and control system.	The SSC has been demonstrated at less than full scale in a test reactor, in an out-of-pile test facility, or in another application. Examples would include successful demonstration of individual fuel elements in a test reactor or successful operation of a section of a steam generator connected to a salt loop.

[50] D. E. Holcomb, Small, Modular Advanced High-Temperature Reactor—Carbonate Thermochemical Cycle Technology Readiness Level Assessment, ORNL/TM-2014/69 (March 2014).

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
GNEP Tech Dev Plan for SFR Fuel Reprocessing[51]			
Label	Proof-of-Principle	Proof-of-Principle	Proof-of-Principle
Definition	Unit operations testing at engineering scale for process validation with simulated advanced recycling reactor spent fuel consisting of unirradiated materials; materials balance flowsheet confirmed; separations chemistry models developed. NOTE: engineering scale is defined as a process equipment scale and throughput rate that can be scaled to industrial operations levels.	Unit operations testing completed at engineering scale with actual fast reactor spent fuel for process chemistry confirmation; reproducibility of process confirmed by repeated batch tests; simulation models validated.	Unit operations testing in existing hot cells with full-scale equipment completed successfully, using actual fast reactor spent fuel; process monitoring and control system proven; process equipment design validated.
GNEP Tech Dev Plan for Advanced Recycling Reactor[52]			
Label	Proof-of-Principle	Proof-of-Principle	Proof-of-Principle
Definition	Integration of basic technological components for testing in laboratory environment. Includes integration of "ad hoc" hardware in the laboratory.	Integration of basic technological components with realistic supporting elements for testing in relevant environment.	Model or prototype system testing in relevant environment.

[51] U.S. Department of Energy, "Global Nuclear Energy Partnership Technology Development Plan", GNEP-TECH-TR-PP-2007-00020, Rev 0, Table E-4 (July 25, 2007)

[52] U.S. Department of Energy, "Global Nuclear Energy Partnership Technology Development Plan", GNEP-TECH-TR-PP-2007-00020, Rev 0, Table A-1 (July 25, 2007)

Table A-2 (continued)
Results of a literature review for technology readiness scales: TRL 4-6

Parameter	TRL 4	TRL 5	TRL 6
Description	Laboratory testing of individual components or portions of systems has been completed successfully. Examples would include separate effects testing of component performance, such as heat exchanger plugging tests or metallurgical compatibility testing or successful operation of gas turbine components that might be used in a supercritical CO2 system.	Individual components or portions of systems have been successfully tested at less-than-full scale in a test reactor, out-of-pile test facility or in another application. Examples would include successful testing of a section of a fuel element in a test reactor or successful testing of individual components of a sodium system (e.g. full-size electromagnetic pump, tested with its power supply and control system) in a sodium loop.	Systems, subsystems or components have been demonstrated at less-than-full scale in a test reactor, in an out-of-pile test facility or in another application. Examples would include successful demonstration of individual fuel elements in a test reactor, successful operation of a section of a steam generator in a sodium loop or successful operation of a supercritical CO2 energy conversion system under prototypic but non-nuclear conditions

Table A-3
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
DOE TRA Guide[53] for EM construction			
Label	System Commissioning	System Commissioning	System Operation
Definition	Full-scale, similar (prototypical) system demonstrated in relevant environment	Actual system completed and qualified through test and demonstration	Actual system operated over the full range of expected mission conditions.
Description	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning1. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.

[53] Technology Readiness Assessment Guide, Table 1, DOE G 413.3-4A (September 15, 2011)

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
DOE TRA Guide[54] for EM waste processing			
Label	Cold Commissioning	Hot Commissioning	Operations
Scale	Full scale	Full Scale	Full Scale
Materials	Simulated Waste	Actual Waste	Actual Waste
Integration	Plant	Plant	Plant
Facility Design Status	Not Applicable	Not Applicable	Not Applicable
DOE TRA Guide[55]: DOE generic			
Label	System Operations	System Operations	System Operations
Definition	Full-scale, similar (prototypical) system demonstrated in relevant environment	Actual system completed and qualified through test and demonstration.	Actual system operated over the full range of expected conditions.
Scale	Full	Full	Full
Fidelity	Similar – matches final application in almost all respects	Identical – matches final application in all respects	Identical – matches final application in all respects
Environment	Relevant – range of simulants plus limited range of actual waste	Operational – limited range	Operational – full range

[54] Technology Readiness Assessment Guide, Figures 2 and 3, Tables 2 and 3 from DOE G 413.3-4A (September 15, 2011)

[55] Technology Readiness Assessment Guide, Table 4, DOE G 413.3-4A (September 15, 2011)

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
Department of Defense[56]			
Labels	Not Assigned	Not Assigned	Not Assigned
Definition	System prototype demonstration in an operational environment.	Actual system completed and qualified through test and demonstration.	Actual system proven through successful mission operations
Description	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.
Definition of Terms	Defined in Table A-1.		
NASA[57]			
Label	None	None	None
Definition	System prototype demonstration in a space environment	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Actual system "flight proven" through successful mission operations
Description	System prototype demonstration in a space environment	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Actual system "flight proven" through successful mission operations

[56] Technology Readiness Assessment Guidance, Department of Defense Assistant Secretary for Defense Research and Engineering (April 2011)

[57] Mankins, John C. (6 April 1995). "Technology Readiness Levels: A White Paper". NASA, Office of Space Access and Technology, Advanced Concepts Office.

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration <u>must be</u> of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program	By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true 'system development' for most technology elements. Example: this would include DDT&E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.	By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. For example, small fixes/changes to address problems found following launch (through '30 days' or some related date). This might include integration of new technology into an existing system (such operating a new artificial intelligence tool into operational mission control at JSC). This TRL does <u>not</u> include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9: such 'technology' upgrades would start over at the appropriate level in the TRL system.
Cost	Variable depending on whether on ground or in space	High	Somewhat less than TRL 8

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
International Organization for Standards[58]			
Label	None	None	None
Definition	Model demonstrating the element performance for the operational environment	Actual system completed and accepted for flight ("flight qualified")	Actual system "flight proven" through successful mission operations
Description	Performance is demonstrated for the operational environment, on the ground or if necessary in space. A representative model, fully reflecting all aspects of the flight model design, is built and tested with adequate margins for demonstrating the performance in the operational environment.	Flight model is qualified and integrated in the final system ready for flight	Technology is mature. The element is successfully in service for the assigned mission in the actual operational environment
Canadian Public Works[59]			
Label	None	None	None
Definition	Prototype ready for demonstration in an appropriate operational environment.	Actual technology completed and qualified through tests and demonstrations.	Actual technology proven through successful deployment in an operational setting.
Description	At this level, the prototype should be at planned operational level and is ready for demonstration of an actual prototype in an operational environment. Activities include prototype field testing.	At this level, the technology has been proven to work in its final form and under expected conditions. Activities include developmental testing and evaluation of whether it will meet operational requirements.	At this level, there is actual application of the technology in its final form and under real-life conditions, such as those encountered in operational test and evaluations. Activities include using the innovation under operational conditions.

[58] Space systems — Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment, ISO/FDIS-16290 (2013)

[59] *"Technology Readiness Level". Public Works and Government Services Canada, Office of Small and Medium Enterprises. 2011-08-12.*

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
NGNP[60]			
Label	None	None	None
Definition	System demonstrated at engineering scale	Integrated prototype tested and qualified	Plant operational
Advanced Nuclear Fuels[61]			
Label	Proof-of-Performance	Proof-of-Performance	Proof-of-Performance
Definition	None	None	None
Description	Fabrication of test assemblies using prototypic feedstock materials at engineering scale and using prototypic fabrication processes. Assembly-scale irradiation testing in prototypic environment. Predictive fuel performance codes validated. Safety basis established for full-core operation.	Fabrication of a few core loads of fuel and operation of a prototype reactor with such fuel.	Routine commercial scale operations. Multiple reactors operating.
Gen IV Concepts[62]	Identical with DOE-G-413.3-R4a above		
INPRO[63]	Uses NASA definitions given above including references to space		

[60] Next-Generation Nuclear Plant: A Report to Congress, U.S. DOE (April 2010).

[61] J. Carmack, Technology Readiness Levels For Advanced Nuclear Fuels and Materials Development, INL/EXT-14-31243 (January 2014).

[62] H. D. Gougar et al., Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications, INL/EXT-15-36427 Rev 2 (October 2015)

[63] R. Beatty, Technology Readiness Levels, INPRO Dialog Forum Workshop February 1-4, 2010.

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
AHTR Thermochemical Cycle[64]			
Label	Proof-of-Principle	Proof-of-Performance	Proof-of-Performance
Definition	Demonstration of prototype system in an operational environment at the engineering scale.	End of system development. Technology proven to work in operational environment at the engineering to full scale.	Full-scale application of technology in its final form at mission conditions.
Description	The SSC or system behavior has been successfully demonstrated under prototypic conditions in a test reactor or in an out-of-pile test facility if the SSC or system will never see a radiation environment during anticipated deployment operations. Examples would include successful testing of a tritium trapping heat exchanger at a test reactor or demonstration of redox control of the coolant salt in a large test loop.	The SSC has been successfully deployed in operation of a test reactor, or a prototype of the SSC has been successfully deployed in power reactor operations, or a system characteristic has been demonstrated in an experiment (i.e., loss of forced flow passive safety demonstration).	The SSC has been successfully deployed in operations of a commercial FHR (or another commercial power reactor if the SSC is not liquid salt related, such as containment structures), or a relevant system behavior has been demonstrated in such a reactor

[64] D. E. Holcomb, Small, Modular Advanced High-Temperature Reactor—Carbonate Thermochemical Cycle Technology Readiness Level Assessment, ORNL/TM-2014/69 (March 2014).

Table A-3 (continued)
Results of a literature review for technology readiness scales: TRL 7-9

Parameter	TRL 7	TRL 8	TRL 9
GNEP Tech Dev Plan for Advanced Recycling Reactor[65]			
Label	Proof-of-Performance	Proof-of-Performance	Proof-of-Performance
Definition	Demonstration of prototype system in an operational environment at the engineering scale.	End of system development. Technology proven to work in operational environment at the engineering to full scale.	Full scale application of technology in its final form at mission conditions
Description	The SSC or system behavior has been successfully demonstrated under prototypic conditions in a test reactor or in an out-of-pile test facility if the SSC or system will never see a radiation environment during anticipated deployment operations. Examples would include successful testing of a fuel assembly or multiple fuel elements in a test reactor or successful operation of a sodium-water steam generator in a large test loop.	The system, structure, or component (SSC) has been successfully deployed in operations of a sodium-cooled test reactor or a prototype of the SSC has been successfully deployed in power reactor operations, or a system characteristic has been demonstrated in an experiment (i.e., the EBR-II passive safety demonstration).	The system, structure or component has been successfully deployed in operations of a commercial sodium-cooled power reactor (or another commercial power reactor if the SSC is not sodium-related, such as containment structures), or a relevant system behavior has been demonstrated in such a reactor. This TRL does not include technologies for planned product improvement of ongoing or reusable systems. For example, an advanced fuel handling system concept for the commercial ABR plant would not start at TRL 9: such 'technology' upgrades would start over at the appropriate level in the TRL system.

[65] U.S. Department of Energy, "Global Nuclear Energy Partnership Technology Development Plan", GNEP-TECH-TR-PP-2007-00020, Rev 0, Table A-1 (July 25, 2007)

Appendix B: Technical Information Available in Key Design Documents

Appendix B summarizes the results of a literature search evaluating the expected technical information in key design documents corresponding to the four major design phases: pre-conceptual design, conceptual design, preliminary design and final design. The results are divided into four tables for ease of review. Tables B-1 and B-2 for the pre-conceptual and conceptual design, and Tables B-3 and B-4 for the preliminary and final designs respectively. The last row in each table provides a synthesis of the results for that design stage.

Table B-1
Literature search for technical information expected to be available in pre-conceptual designs

Source	Pre-Conceptual Design
Yezioro[66]	In the pre-conceptual design stage first adaptations between project demands as is dictated by the program, specific constraints, specific conditions of the place and the available design strategies are taken place. In this stage, local climatic conditions are verified and checked against goals to establish design principles that best suit both place and project.
INCOSE Handbook[67] Stages don't align well. Definition of what happens in a stage is associated with the design document at the end of a stage to the extent possible.	The Pre-Concept Exploratory Research Stage is sometimes referred to as the User Requirements Definition Phase. In many industries, it is common for research studies to lead to new ideas or enabling capabilities which then mature into the initiation of a new project (system-of-interest). A great deal of creative systems engineering is done in this exploratory stage, and the systems engineer leading these studies is likely to follow a new idea into the Concept Stage, perhaps as project champion. Often the Pre-Concept activities identify the enabling technologies. [Stage ends at ~TRL 3]
DOE-STD-1189-2016[68] Focused on the integration of safety into design, not the contents of a design per se.	During the pre-conceptual phase, an analysis of alternatives is performed to explore whether a new facility or a modification to an existing facility would best satisfy the mission need. Potential costs, benefits, and significant hazards are addressed to the extent required to determine the program gap and therefore the mission need. Figure A.4.1-1 below illustrates how project management and safety basis activities interact during the pre-conceptual design phase. Includes development of mission requirements, program requirements, and technology requirements.

[66] Abraham Yezioro, "A knowledge based CAAD system for passive solar architecture", Renewable Energy 34, 769-779 (2009). Subject is building construction

[67] International Council on Systems Engineering, Systems Engineering Handbook A Guide for System Life Cycle Processes and Activities, INCOSE-TP-2003-002-03 (June 2006)

[68] U.S. Department of Energy, Integration of Safety Into the Design Process, DOE-STD-1189-2016 (December 2016) Appendices A and H.

Table B-1 (continued)
Literature search for technical information expected to be available in pre-conceptual designs

Source	Pre-Conceptual Design
Miller Presentation[69] Large facility construction	- Formulation of science questions - Requirements definition, prioritization, and review - Identify critical enabling technologies and high-risk items[70]
Van Goethem[71] Focused on advanced reactors but not well focused.	Focus is basic concepts for reactor technologies, fuel cycle, and energy conversion processes, established through testing at appropriate scale under relevant conditions, with all potential obstacles identified and resolved, at least in theory; very preliminary cost analysis. 5–15 years of R&D needed. Mainly in the hands of research organizations focused on viability. Options and ideas.
INL/EXT-08-14777[72]	Definition stage of a project where mission need is formulated and iteratively reviewed, project planning is performed, early budget estimates made and initial assessment of requirements made
Gigon[73]	No information in this source for this design stage.
LaPorte[74]	No information in this source for this design stage.
DOE Cost Estimating Guide[75]	No information in this source for this design stage.

[69] W. L. Miller, Preconstruction Planning for Large Science Infrastructure Projects – A Comparative Analysis of Practices and Challenges at DOE, NASA and NSF, presentation to the NAS Board on Physics and Astronomy (April 24, 2010).

[70] These items were assigned to the PCD by the authors because the source document did not address the PCD.

[71] G. Van Goethem, Nuclear Fission, Today and Tomorrow: From Renaissance to Technological Breakthrough (Generation IV), Journal of Presssure Vessel Technology, 133 (August 2011).

[72] T. Bjornad et al, Institutionalizing Safeguards by Design: High-Level Framework, INL/EXT-08-14777 (February 2009) glossary.

[73] M. Gigon, "Critical Steps in Process Design", LaPorte Consultants, presentation to unknown audience (September 28, 2006)

[74] LaPorte Consultants web site URL http://laporteconsultants.com/know-how/process/

[75] U.S. Department of Energy, Cost Estimating Guide, DOE G430.1-1 (March 28, 1997).

Table B-1 (continued)
Literature search for technical information expected to be available in pre-conceptual designs

Source	Pre-Conceptual Design
GIF-002-00[76]	Viability phase. Basic concepts, technologies and processes are proven out under relevant conditions, with all potential technical show-stoppers identified and resolved. PHASE ENDPOINTS - Pre-conceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams - Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale - Cost analysis based on pre-conceptual design - Simplified PRA for the system - Definition of analytical tools - Pre-conceptual design and analysis of safety features - Simplified preliminary environmental impact statement for the system - Preliminary safeguards and physical protection strategy - Consultation(s) with regulatory agency on safety approach and framework issues
Synthesis of information available in each design stage	This is the definition stage of RDD&D. Something new in the continuously growing body of basic science or the external environment of nuclear power leads to a new advanced reactor concept that is believed to have the potential to meet utility requirements better than other current and presently-proposed advanced reactors. Simple process flow and general arrangement diagrams are prepared to allow a reactor development project to be planned.

[76] U.S. Nuclear Energy Research Advisory Committee and the Generation IV International Forum, Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00 (December 2002) p. 79ff.

Table B-1 (continued)
Literature search for technical information expected to be available in pre-conceptual designs

Source	Pre-Conceptual Design
Synthesis of information available in each design stage	Preliminary critical technology elements (CTEs) are identified and sufficient research is performed to demonstrate that there are no "show-stoppers." At the end of this stage (TRL 3) the following information should be available: - Identification of preliminary user requirements and constraints for the system - Initial multi-dimensional steady-state neutronic, fluid flow, and heat transfer results available for the primary system and generic power conversion systems - Identification of candidate materials for reactor, primary and power system construction - Some results of bench-scale experimental work in a functional environment and low-fidelity configuration using mostly non-radioactive materials - Identification of candidate geometries and chemical form for the fuel - Identification of candidate system layouts and arrangement, e.g., pool vs loop - Estimates of coolant, fuel and other material inventories for primary and secondary systems - A development plan for the conceptual design stage - Place-holder technologies for secondary and ancillary sub systems - Appropriate Preliminary Hazard Assessment (PHA) completed - Familiarization discussions with regulators

Table B-2
Literature search for technical information expected to be available in conceptual designs

Source	Conceptual Design
Yezioro	In the conceptual design stage schematic alternatives are checked according to the program demands and the specific place. This stage relates mainly to the definition of building geometry and orientation without referring in detail to materials.
INCOSE Handbook Stages don't align well. Definition of what happens in a stage is associated with the design document at the end of a stage to the extent possible.	This stage is a refinement and broadening of the studies, experiments, and engineering models pursued during the Pre-Concept Stage. The processes described in this handbook are requirements-driven, as opposed to product driven. Thus, the first step is to identify, clarify, and document stakeholders' requirements. If there was no Pre-Concept stage, that effort is done here. During the Concept Stage, the team begins in-depth studies that evaluate multiple candidate concepts and eventually provide a substantiated justification for the system concept that is selected. As part of this evaluation mockups may be built (for hardware) or coded (for software), engineering models and simulations may be executed, and prototypes of critical components may be built and tested. Prototypes are helpful to verify the feasibility of concepts and to explore risks and opportunities. [This stage ends at about TRL 5]
DOE-STD-1189-2016 Focused on the integration of safety into design, not the contents of a design per se.	The conceptual design phase is devoted to evaluating alternative design concepts, preparing a Safety Design Strategy (SDS), and providing a conservative safety design basis for the preferred design concept. Once a preferred alternative has been selected, the identification of necessary structures, systems, and components SSCs begins. The focus of safety work at this stage is to: (1) establish and document a preliminary inventory of hazardous materials; (2) establish and document the preliminary hazard categorization of the facility; (3) identify and analyze (as needed) primary facility hazards and facility-level accidents, and (4) provide an initial determination, based on the Hazards Analysis, of safety class and safety significant SSCs. Includes project cost/schedule range estimates, identification of required technical studies, and design for recommended alternatives. Technology Maturation Plan developed in TRL 4.

Table B-2 (continued)
Literature search for technical information expected to be available in conceptual designs

Source	Conceptual Design
Miller Presentation Large facility construction	- Development of conceptual design - Top down parametric cost and contingency estimates - Formulate initial risk assessment
Van Goethem Focused on advanced reactors but not well focused.	Assessment of the entire system, sufficient for procurement specifications for construction of a demonstration plant; validation of waste management strategy; optimization of materials capabilities under prototypical conditions; detailed cost evaluation. 5–10 years of R&D needed. System integration and performance phase. Viability report, design and fuels requirements.
INL/EXT-08-14777	The concept for meeting a mission need. The conceptual design process requires a mission need as an input. Concepts for meeting the need are explored and alternatives considered arriving at the set of alternatives that are technically viable, affordable, and sustainable
Gigon	Definition of the user requirements: Process (what size and type follow-on facilities, e.g., pilot, demo), Production capacity for the various facilities), Product specification (purity, reliability). Development phase of the product (project).
LaPorte	- Process, block, engineering flow diagrams - Process simulation - Material and energy balance - Design development
DOE Cost Estimating Guide	Consists of a development phase and a conceptual design report (CDR). Investigations and studies are conducted to compile the information that is essential for the design stage. Through these investigating processes, planning feasibility study estimates are derived for preliminary budget estimates of total project cost on the basis of any known research and development requirements.

Table B-2 (continued)
Literature search for technical information expected to be available in conceptual designs

Source	Conceptual Design
DOE Cost Estimating Guide	This preliminary phase establishes the scope, feasibility, need, and activities included in the CDRs, which results in a budget/conceptual design estimate, which is used to request Congressional authorization for funding. The CDR is a document that describes the project in sufficient detail to produce a budget cost estimate and to evaluate the merits of the project. A conceptual design report shall be prepared for line item construction projects prior to inclusion of the project in the DOE budget process
GIF-002-00	<u>Performance Phase</u>. Engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions PHASE ENDPOINTS - Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams - Processes validated at scale sufficient for demonstration plant - Detailed cost evaluation for the system - PRA for the system - Validation of analytical tools - Demonstration of safety features through testing, analysis, or relevant experience - Environmental impact statement for the system - Safeguards and physical protection strategy for system, including cost estimate for extrinsic features - Pre-application meeting(s) with regulatory agency

Table B-2 (continued)
Literature search for technical information expected to be available in conceptual designs

Source	Conceptual Design
Synthesis of information available in each design stage	This is the performance stage of RDD&D. It involves refinement and broadening of the studies, bench-scale experiments, and engineering models developed during the definition stage. In-depth studies are performed to evaluate candidate concepts and eventually provide a substantiated justification for the system concept that is selected. As part of this evaluation mockups may be built (for hardware) or coded (for software), engineering models and simulations are developed and executed; prototypes of critical components may be built and tested (prototypes can be helpful to verify the feasibility of concepts and to explore risks and opportunities). At the end of this stage (TRL 5) the following information should be available: - Critical technology elements and models are shown to work in a realistic subsystem and environment. - Preferred technologies have been selected for CTEs and subsystems - Bench-scale test results in a realistic environment, and high-fidelity configuration, using radioactive materials are used to optimize the CTEs, subsystems containing them, and to plan for engineering-scale testing - Multi-dimensional dynamic neutronic, fluid flow, and heat transfer results for the preferred reactor-power conversion system - Identification of the preferred geometry and chemical form of the fuel, and fuel management schemes - Analytical models have been validated based on experimental results to represent subsystem performance.

Table B-2 (continued)
Literature search for technical information expected to be available in conceptual designs

Source	Conceptual Design
Synthesis of information available in each design stage	- Detailed reactor system modeling has been initiated. - Top-down, parametric cost estimates - SSCs important to safety identified - Detaled PHA and Preliminary PRA results and safety strategy - Demonstration of key safety features of the system through testing, analysis, or relevant experience - Conceptual design document for the entire system sufficient to support development of procurement specifications for construction of a test/demonstration reactor. Includes process, block, engineering flow diagrams; results of process simulations; and material and energy balances - Validated acceptability of disposal of all waste streams. - Preliminary environmental assessment for the system - Safeguards and physical protection strategy for system - Pre-application meeting(s) with regulators

Table B-3
Literature search for technical information expected to be available in preliminary designs

Source	Preliminary Design
Yezioro[77]	No information in this source for this design stage.
INCOSE Handbook[78] Stages don't align well. Definition of what happens in a stage is associated with the design document at the end of a stage to the extent possible.	No information in this source for this design stage.
DOE-STD-1189-2016[79] Focused on the integration of safety into design, not the contents of a design per se.	The preliminary design phase is devoted to a more rigorous evaluation of the conceptual design. The hazards analysis evolves from a facility-level analysis to a system-level analysis as more design detail becomes available. As it is refined, the selection of controls, safety functions, and SSC classifications made during the conceptual design phase will be revisited. A more complete assessment of hazard controls, based on hazards analyses at the process level, is developed, including those intended for in-facility worker protection. All relevant contractor and DOE safety personnel will participate in design reviews. Includes identifying project functional and operational requirements, project alternative analysis, and recommending alternatives, an update of the preliminary technical, cost, and schedule estimates. Update TMP at TRL 7.

[77] Abraham Yezioro, "A knowledge based CAAD system for passive solar architecture", Renewable Energy 34, 769-779 (2009). Subject is building construction

[78] International Council on Systems Engineering, Systems Engineering Handbook A Guide for System Life Cycle Processes and Activities, INCOSE-TP-2003-002-03 (June 2006)

[79] U.S. Department of Energy, Integration of Safety into the Design Process, DOE-STD-1189-2016 (December 2016) Appendices A and H.

Table B-3 (continued)
Literature search for technical information expected to be available in preliminary designs

Source	Preliminary Design
Miller Presentation[80] Focused on generic large facility construction	- Develop site-specific preliminary design, environmental impacts - Develop enabling technology Bottoms-up cost and contingency estimates, updated risk analysis - Develop preliminary operations cost estimate - Develop Project Management Control System - Update of Project Execution Plan
Van Goethem[81] Focused on advanced reactors but not well focused.	- Demonstration of safety features through large scale testing - Environmental impact assessment - Safeguards and physical protection strategy for the system - Application meetings with regulatory agencies. - 3-6 years needed - System assessment and demonstration phase. - Performance report. - Done by vendor.
INL/EXT-08-14777[82]	No information in this source for this design stage.
Gigon[83]	Facility definition and sizing: Preliminary specifications of the process equipment (size, functionality, process parameters, temp-pressure operating range), Sizing of utilities (process support like feed prep, process utilities, building utilities, spaces), Preliminary specifications of the automation system (degree and level)

[80] W. L. Miller, Preconstruction Planning for Large Science Infrastructure Projects – A Comparative Analysis of Practices and Challenges at DOE, NASA and NSF, presentation to the NAS Board on Physics and Astronomy (April 24, 2010).

[81] G. Van Goethem, Nuclear Fission, Today and Tomorrow: From Renaissance to Technological Breakthrough (Generation IV), Journal of Presssure Vessel Technology, 133 (August 2011).

[82] T. Bjornad et al, Institutionalizing Safeguards by Design: High-Level Framework, INL/EXT-08-14777 (February 2009) glossary.

[83] M. Gigon, "Critical Steps in Process Design", LaPorte Consultants, presentation (September 28, 2006)

Table B-3 (continued)
Literature search for technical information expected to be available in preliminary designs

Source	Preliminary Design
LaPorte[84]	- Preliminary P&ID's - Development drawings - Purchasing specifications - Performance specifications
DOE Cost Estimating Guide[85]	The Title I (preliminary) design phase defines the project criteria in greater detail, permitting the design process to proceed with the development of alternate concepts and a Title I design summary. The approved Title I concept and the supporting documentation I form the basis of all activity in the definitive phase. The preliminary stage of project design. In this phase, the design criteria are defined in greater detail to permit the design process to proceed with the development of alternate concepts and a Title I design summary, if required.
GIF-002-00[86]	Demonstration Phase. This phase involves the licensing construction and operation of a prototype or demonstration system in partnership with industry and perhaps other countries. The detailed design and licensing of the system will be performed during this phase.
Synthesis of information available in each design stage	This is the demonstration phase of RDD&D. It first involves design, siting, licensing, construction, and operation of a (pilot-scale) test reactor or possibly pilot-scale testing of unique subsystems in existing test reactors or out-of-pile experiments, depending on how different the reactor concept is from existing reactors. This stage culminates in the (preliminary) design of a demonstration reactor in partnership with industry (and perhaps other countries).

[84] LaPorte Consultants web site URL http://laporteconsultants.com/know-how/process/

[85] U.S. Department of Energy, Cost Estimating Guide, DOE G430.1-1 (March 28, 1997).

[86] U.S. Nuclear Energy Research Advisory Committee and the Generation IV International Forum, Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00 (December 2002) p. 79ff.

Table B-3 (continued)
Literature search for technical information expected to be available in preliminary designs

Source	Preliminary Design
Synthesis of information available in each design stage	In some cases, this may be the same reactor depending on scaling approach and regulatory requirements. The test reactor may not include all subsystems necessary for the demonstration reactor. At the end of this stage (TRL 7) the following information should be available: - Reactor subsystem and system definition and sizing: specifications of the process equipment (size, functionality, process parameters, temp-pressure operating range), sizing of process support like feed prep, process utilities, building utilities, spaces, specifications of the automation system (degree and level) - Documentation necessary to permit procurement, construction, testing, checkout, and turnover to proceed. - Detailed piping and instrumentation diagrams - Installation drawings: isometric and 3D - Installation specifications - Site Specifications - Safety Analysis Report (licensee) and SER (NRC) for test reactor - EA and EIS for test reactor - Preliminary (SAR) and SER for demonstration reactor - Considerable data from test reactor operations, including behavior under steady-state and transient conditions, and reactor operational responses and limits, will be available at the end of TRL 6 and extensive data by the time TRL 7 is reached.

Table B-4
Literature search for technical information expected to be available in final designs

Source	Final Design
Yezioro	No information in this source for this design stage.
INCOSE Handbook Stages don't align well. Definition of what happens in a stage is associated with the design document at the end of a stage to the extent possible.	No information in this source for this design stage.
DOE-STD-1189-2016 Focused on the integration of safety into design, not the contents of a design per se.	Decisions made during the preliminary design phase provide the basis for detailed design and construction. Major course changes after this phase can have significant impacts on overall project cost and schedule.
Miller Presentation Focused on generic large facility construction	- Development of final construction-ready design and Project Execution Plan - Industrialize key technologies - Refine bottoms-up cost and contingency estimates - Finalize Risk Assessment and Mitigation, and Management Plan - Complete recruitment of key staff
Van Goethem Focused on advanced reactors but not well focused.	Done by vendor and utilities.
INL/EXT-08-14777	Completion of the design effort and production of all design documentation necessary to permit procurement, construction, testing, checkout, and turnover to proceed.
Gigon	Detailed specification of all components of the installation: Mechanical components, Fabrication specification, Installation specification, Automation, Hardware, Software

Table B-4 (continued)
Literature search for technical information expected to be available in final designs

Source	Final Design
LaPorte	- Detailed P&ID's - Installation drawings - Isometric - 3D drawings - Installation specifications
DOE Cost Estimating Guide	Title II incorporates all the restudy and redesign work, the final specifications and drawings for bids from contractors, and the construction cost estimator along with analyses of health and safety factors. Moreover, the coordination of all design elements and local and government agencies is also included. The definitive stage of project design. The approved Title I concept and the supporting documentation prepared for Title I forms the basis of all activity in Title II. Definitive design includes any drawings, specifications, bidding documents, cost estimates, and coordination with all parties that might affect the project; development of firm construction and procurement schedules; and assistance in analyzing proposals or bids.
GIF-002-00	No information in this source for this design stage.
Synthesis of information available in each design stage	This is the deployment phase of RDD&D. It first involves siting, licensing, construction, and operation of a demonstration reactor. It culminates in the (final) design, siting, licensing, construction, and operation of a commercial reactor. The demonstration reactor would include all subsystems necessary for a commercial reactor.

Table B-4 (continued)
Literature search for technical information expected to be available in final designs

Source	Final Design
Synthesis of information available in each design stage	The final reactor design will include all of the information present in the demonstration reactor design. Details of the commercial design will be optimized because of (a) the larger size of the reactor and (b) lessons learned from operating the demonstration reactor that are expected to become available at TRL 8 and beyond. Commercial reactor design details will evolve as experience is gained and possibly in response to the need for differing product portfolios or operational capabilities.

Program:

Technology Innovation

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