Considerations for Nuclear Thermal Propulsion Reactor Technology Readiness Level Advancement

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Nuclear thermal propulsion (NTP) is a candidate in-space propulsion technology for crewed missions to Mars. An NTP engine relies on the use of a reactor as a heat exchanger to directly heat a hydrogen propellant which is expanded through a nozzle for high specific impulse (> 850s), high thrust (>15 klbf) propulsion. NTP reactor and engine technologies are currently being developed to enable a future NTP engine prototype demonstration. Technology readiness level (TRL) definitions are a useful tool to plan necessary technology advancement tasks as they provide guidance on expected development activities and necessary level of fidelity of test article or testing conditions for demonstration tasks. However, technology readiness definitions for an NTP reactor and related demonstration tasks have not yet been defined. This paper identifies relevant TRL definitions by the National Aeronautics and Space Administration (NASA) and Department of Energy (DOE). Based on these definitions, preliminary recommendations on testing conditions and important parameters to consider for NTP reactor technology development planning are provided for TRL 1 - 6. As a part of this effort, functional characteristics and important performance parameters for the reactor are identified, as well as a summary of relevant literature which was considered when assessing development tasks capable of meeting TRL definition criteria.

I. INTRODUCTION

Nuclear thermal propulsion (NTP) is a high-performance in-space propulsion technology which utilizes a reactor as a heat exchanger to directly heat a hydrogen propellant to enable high specific impulse ($I_{SP} > 850$ s) and thrust (> 15 klbf). This combination of high I_{SP} and thrust can reduce interplanetary trip times to destinations such as Mars to approximately half that of the best performing chemical propulsion methods, making NTP one of the leading propulsion technology candidates for future Mars missions. Current reference NASA missions under consideration for the late 2030s – early 2040s are opposition class missions requiring efficiencies in the range of 900+ s for up to 4 hours total burn time. To enable this performance, a robust and reliable reactor and fuel system design must be developed and demonstrated.

Historic NTP programs within the U.S. have significantly improved the knowledge base for the design, modeling, and performance of NTP fuel and reactor systems. While there are many lessons learned that can be carried forward from each of these programs, the reactor technologies developed under these programs often are not directly applicable to ongoing NTP efforts due to three primary factors: modern mission performance needs, loss of legacy feedstocks and fabrication technologies, and use of high assay low enriched uranium (HALEU). Modern NTP missions typically require higher performance (higher operating temperatures, longer lifetime) than demonstrated in historic test programs. This results in the need for NTP fuels and reactors capable of performing under more demanding operating conditions (for more information see ref. 1). Legacy fabrication technologies and feedstocks leveraged in historic programs may also be decommissioned or no longer exist. Therefore, direct recapture of historic components (considering exact alloy, impurity, and microstructure specifications) is often not possible. All historic NTP designs have proposed the use of high enriched uranium (HEU, ~93 wt% or greater U^{235} enrichment). Current presidential guidance for NASA space reactor development activities includes avoiding the use of HEU fuels in the reactor design unless HALEU (20.0 wt% or less U^{235} enrichment) or alternative energy sources are not feasible[2]. This typically results in designs with a more thermal neutron spectrum and / or higher fuel loadings to enable reactor criticality at low thrust levels ($\leq$ 25 klbf). These changes alter the nuclear environment of reactor components as well as underlying fuel materials compared to what was developed in historic programs.

NASA's Space Nuclear Propulsion (SNP) project is developing new reactor and fuel materials as a risk reduction activity under the SNP fuel and moderator development plan (F&MDP), as well as by industry led design teams. As a part of the overall SNP strategy, the project aims to mature NTP reactor technologies to an appropriate technology readiness level (TRL) to support a fuel / reactor down select prior to proceeding to an integrated reactor-engine demonstration (TRL 6). Improving TRL, through development and testing, reduces technical risk by providing test data for validating computational models or verifying that the proposed design is capable of meeting requirements. Furthermore, reduced technical risk associated with the manufacture, performance, and functionality of the reactor (and overall integrated system) improves programmatic confidence in projected cost and schedule estimates for system development.

Therefore, to support ongoing planning activities, it was desired to evaluate TRL guidance from both NASA and the DOE to identify specific considerations for maturing the NTP reactor components at each readiness level. It is envisioned that the recommendations included in this paper can be used as objective metrics for assessing the TRL of the NTP reactor subsystem following successful completion of NTP reactor component and subsystem level testing. This paper contains an overview of the NTP reactor subsystem technology considerations (including functional and performance parameters) relevant to technology maturation planning, NASA and DOE TRL definitions, and specific recommendations for NTP reactor testing and demonstration needs for each readiness level. This paper contains a review of TRL definitions applicable to NTP reactor development and preliminary recommendations on testing conditions and important parameters to consider for NTP reactor technology development planning for each TRL.

II. NTP REACTOR TECHNOLOGY OVERVIEW

When assessing the readiness level of a technology, the technology must be defined in context to the overall system and its functions identified. Typical NTP system key performance parameters (KPPs) and their relationship to the reactor design are listed below:

Thrust – the forward force generated by the rocket which is used to accelerate the spacecraft. Thrust is dependent upon fluid inlet and exit conditions leaving the nozzle (temperature, pressure, and gas velocity) and is directly proportional to mass flow rate. Engine thrust most directly impacts the reactor by controlling the amount of propellant that must be heated by the reactor, thereby impacting the total thermal power to be generated by the reactor.

Specific Impulse (I_{sp}) – a measure of the efficiency of the overall system, specific impulse corresponds to the amount of thrust generated per unit mass of propellant throughout the mission. Therefore, specific impulse is dependent upon the exit fluid conditions leaving the nozzle (temperature, pressure, gas velocity, and mass flow rate) and is maximized with increasing temperature and minimizing propellant molecular mass. To maximize specific impulse, reactor exit temperature is typically maximized and selection of a hydrogen propellant (reactor working propellant) is typically proposed.

Mass – to meet requirements related to launch and overall spacecraft design, mission optimization, the overall mass of each of the NTP subsystems is constrained with a goal to minimize each subsystem's mass to enable reduced propellant requirements or increase the amount of spacecraft payload. Since total reactor thermal power will be governed by specific impulse and thrust, the reactor design must enable criticality under proposed operating conditions (total thermal power, reactor exit conditions, and total mass flow rate) for a minimal mass and size which meets design requirements. This constraint, when paired with specific impulse and thrust, impacts overall reactor operating conditions by impacting maximum reactor power density which further impacts overall reactor power, temperature, and stress distributions for in-reactor components.

Total Lifetime and Number of Burns – Performance of the system must be maintained for all desired operational modes and overall system lifetime. The reactor must be able to satisfy heat transfer to the propellant intermittently and for multiple re-starts to satisfy the mission trajectory. Reactor components need to be able to survive total lifetime at full power, thermal cycling needed due to multiple engine burns, and required startup and shutdown transient conditions. Total lifetime encompasses total lifetime at full operational power as well as total lifetime at idle or standby conditions. Material performance and reactor criticality under designed operating conditions are critical to ensuring this KPP can be met.

Within a NTP system, the reactor's primary function is to act as a heat exchanger, directly transferring the heat generated from fission to a propellant (reactor working fluid) which is heated to sufficiently high outlet temperatures to be expanded out a nozzle to provide thrust at the target I_{sp}. In this manner, the NTP reactor is a critical technology element to ensure system performance is maintained over the entire mission (reactor lifetime). To ensure KPPs are met for the NTP system, the key functions of the reactor that must be considered in its design and operations include:

- Heat transfer to the propellant to meet desired engine-reactor interface conditions to close the power balance for all operating modes of the engine.
- Enable criticality and a controllable reactor response for all design conditions (including reactor transients, nominal full power, and design basis off nominal conditions). Reactor control is maintained by the engine-controller, the instrumentation, physical mechanisms, e.g. control drums, and reactor physics response must be reliable and predictable during operation.

- Maintain component performance (including acceptable thermodynamic / compositional stability and structural integrity) throughout lifetime for all design modes to ***ensure system safety and integrity throughout the mission***.

While the reactor subsystem is a key component within the NTP system, it must be able to interact with other subsystems in a way that does not diminish the ability of any subsystem from meeting its intended functional or performance requirements. In addition to TRL, system readiness level (SRL) should also be considered when assessing overall readiness. System readiness level maturation requires subsystems to consider the impact of related subsystems which is the subject of technology maturation planning. Key reactor subsystem interfaces to consider in the NTP system include the engine-reactor interface and reactor-spacecraft interface. Other interfaces may exist but have not been explicitly identified or considered in this study.

II.A. Engine-Reactor Interface

The engine-reactor interface is impacted by the exchange of the propellant across the engine-reactor power balance enables the performance of the system (specific impulse and thrust) and may enhance the engine subsystem functionality by providing heat to the propellant to power the engine-turbopump. This interface is represented as state points (fluid temperature, pressure, and mass flow rate) in the engine-reactor power balance. The engine controller will be responsible for interacting with the reactor control system and instrumentation to ensure the reactor physics response is appropriate for desired operating modes of the NTP system throughout the mission. The engine-reactor physical interface, which is impacted by external reactor volumes and overall reactor mass, may transmit stresses, radiation, or heat from the reactor subsystem to the engine subsystem.

II.B. Reactor-Spacecraft Interface

The primary reactor-spacecraft interface of concern to designers is the impact of reactor operation on the radiation fields (gamma and neutron) experienced by spacecraft components (including the cryogenic fluid management system and propellant tanks). The radiation environment that the spacecraft is exposed to will be highly dependent on shielding design both for the reactor internal shield and any external or component level shielding. Shielding effectiveness may be dictated by human or component level radiation protection as well as concept of operations (CONOPS) constraints throughout the mission. The spacecraft may indirectly impact the reactor due to its role in management and storage of the hydrogen propellant and payload. This may impact the state points at which the propellant initially enters the reactor or result in slight alterations to reactor operations including number of burns, total burn time, and rated power during each burn.

In order for the NTP reactor to perform its desired functions to enable NTP performance, technology maturation planning aims to adapt existing technologies as well as develop new and novel materials or components capable of enabling the performance goals governed by the reference NTP system. These development activities include the design, modelling, manufacture, and testing (demonstration) with increasing level of fidelity and complexity. Ultimately, these activities should culminate in the demonstration of each component and / or assembly, as well as the overall integrated subsystem up to the overall NTP system level to verify the design's ability to meet both functional and performance requirements. A key aspect of this verification will be to ensure acceptable function, performance, and reliability of the design under all prototypic operating environments. For the NTP reactor, the typical operating environment includes the following elements:

Hydrogen working fluid – consider temperature, pressure, mass flow rate (gas velocity), and possible fluid dynamic response from engine pump operation.

Temperature – consider fuel, moderator, and reactor component temperature profiles (radial and axial). Consider temperature profile and feedback due to reactor physics controlled parameters, match temperature and stress profiles.

Irradiation – consider power density (and neutron flux), total fluence (or burnup), transient irradiation response of materials.

Lifetime – consider thermal cycling, total lifetime at full power, total lifetime including low power or decay heating modes.

For all components that have not been previously matured for the specific NTP operating environments expected of the reference design, they must be developed and demonstrated under relevant conditions that are representative of underlying physical phenomena or technical risk areas. Specific areas of technical risk for the NTP reactor subsystem include:

Reactor Physics – controls power profiles, reactor criticality, and reactor transient response

Thermal-Structural – dependent on material properties, reactor power densities, and fluid flow conditions, controls maximum fuel and moderator temperature and interelement temperature and stress profiles

Fluid-Structural – dependent on reactor-engine interface, controls reactor heat transfer and efficiency, may result in different vibrational modes of the reactor components during operation

Material Performance – includes high temperature stability, corrosive interactions, and material irradiation response, contributes to reliability modelling of components

Manufacturability – readiness of fabrication processes and infrastructure

NTP reactor design requires modelling and analysis of many competing multi-physics phenomena. These models require validation if a pre-existing benchmark does not exist. Therefore, technology maturation tasks should be planned to allow for collection of appropriate test data needed for model validation.

III. APPLICABLE TECHNOLOGY READINESS LEVEL DEFINITIONS

The Department of Energy (DOE) has released updated guidance on performing technology readiness assessments and technology maturation planning for advanced reactor systems. The DOE technology readiness level definitions reported in this paper are transcribed from the Department of Energy's "Technological Assessment Guide", DOE G 413.3-4A (Ref. 3). Compared to alternative TRL definitions, DOE definitions give more specific guidance useful for reactor systems development, which considers both waste processes and commissioning readiness. The NASA TRL guidance is provided in Ref. 4. NASA TRL definitions include specific guidance for the development of hardware and software systems. For an NTP reactor, hardware definitions are most applicable, however modelling and simulation maturity and integration with the testing program is considered in the recommendations provided in this assessment.

To support this assessment, a wide range of documentation and published literature from NASA, DOE, the Department of Defense, and the U.S. Government Accountability Office was identified and surveyed. It is acknowledged that beyond TRL there are other aspects of readiness to consider when developing and assessing the maturity of the overall NTP system. Some additional readiness levels that were considered include:

Manufacture readiness level – "defines current level of manufacture maturity, identifies maturity shortfalls and associated costs / risks, provides basis for manufacture maturation and risk management" (Ref. 5).

Integration readiness level –"a metric to measure the integration maturity between two or more components. IRLs, in conjunction with TRLs, form the basis for the development of the system readiness level" (Ref. 6).

System readiness level – "[defines] a holistic picture of the readiness of complex system of systems by characterizing the effect of technology and integration maturity on a systems engineering effort". SRL definitions recommended by GAO are included in Ref. 6.

Advancement degree of difficulty (AD^2) – an alternative method for evaluating system maturity which focuses on development difficulty rather than readiness. From the NASA System Engineering Handbook, AD^2 assessment is defined as "the process to develop an understanding of what is required to advance the level of system maturity" (Ref. 7).

Fuel Readiness Level – defines readiness of a fuel form for use in a system. Fuel readiness assessment includes evaluation of fuel performance readiness and fuel manufacture readiness[8].

Additional supplemental references[9-12] considered included: "Technology Maturation Planning and Technology Roadmap Development Example Using the Technology and System Readiness Assessment Process" which contains recommendations on assessing TRL and system readiness level (SRL) using an "evidenced-based" response to specific questions included in Appendix A (section A-3 and A-4, Ref. 9). It is also noted that previous attempts to resolve NASA, DOE, and fuel TRL have been previously performed for the assessment of NTP reactor readiness[13]. When comparing NASA and DOE TRLs, DOE TRL will directly correspond to the TRL of the reactor subsystem only. NASA TRL will be limited to the overall limiting (lowest) TRL of all subsystems which may or may not be synonymous with the NTP reactor subsystem TRL. To capture this dependance, SRL considerations are also included for each TRL level in the following section.

III. TECHNOLOGY READINESS LEVEL TASKS FOR NTP REACTOR DEVELOPMENT

III.A. Technology Readiness Level 1

DOE guidance calls out TRL 1 as: *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.*

While NASA guidance calls out TRL 1 as:

Hardware: Scientific knowledge generated underpinning hardware technology concepts / applications.

Software: Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.

TRL 1 is the lowest level of readiness, at this stage a pre-conceptual idea of a reactor is formed, and initial attributes identified. For the NTP reactor subsystems, TRL 1 advancement tasks are expected to include:

- The overall system configuration is identified including propellant and mechanism for heating the propellant with the reactor.
- The trade space of technology and material candidates for the reactor subsystem are identified through literature review or equivalent survey.
- Research is limited to paper studies or observations.

III.B. Technology Readiness Level 2

DOE guidance calls out TRL 2 as: *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 still limited to analytic studies.*

While NASA guidance calls out TRL 2 as:

Hardware: Invention begins. Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture.

Software: Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.

Similar to TRL 1, TRL 2 is still primarily theoretical. Literature review and initial assessments may be performed. The concept is better defined including identifying critical subsystem components and functions. For the NTP reactor subsystems, corresponding TRL 2 advancement tasks would include:

- Confirmatory benchtop studies or supporting literature data is gathered to confirm the heat transfer mechanism from the reactor to the propellant.
- The functions of the reactor and related physical parameters are identified. Modeling and simulation tools are identified and / or adapted for analyzing the technology.
- A reference mission model is developed and a range of top-level performance needs and functions of the system identified for a candidate reference missions.
- The design space of the reactor subsystem is identified based on system level performance and functional requirements. Reactor subsystem technology options are identified at a conceptual design level. For each option, critical components are identified and design begins including identifying material compositions, fabrication readiness, component functional requirements, and range of operating environments.
- Candidate manufacture technologies are identified.

System readiness level considerations for TRL 2 include:

- Have the reactor subsystem interfaces been defined and how do they impact the reactor subsystem?
- Does integration of the reactor within the overall system impact any of the functions of the reactor or its components? The operating environment of the reactor or its components?
- Are there any breakpoints in the reactor technology design space with respect to performance or functional requirement ranges? Can all technology options enable reference missions?

III.C. Technology Readiness Level 3

DOE guidance calls out TRL 3 as: *Active research and development 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. Components may be tested with simulants.*

While NASA guidance calls out TRL 3 as:

Hardware: Analytical studies place the technology in an appropriate context; laboratory demonstrations, modeling, and simulation validate analytical prediction.

Software: Development of limited functionality to validate critical properties and predictions using non-integrated software components.

For the NTP reactor subsystems, TRL 3 marks a clear transition into research and development of reactor hardware. Laboratory scale fabrication and demonstration studies are initiated for fuels and other key components of the reactor. Laboratory environments testing is appropriate for screening concept feasibility. For NTP systems, laboratory environments may capture one (separate effects testing) or more of the reactor operating environment elements: hydrogen, temperature, irradiation, or lifetime. The environment does not necessarily match that necessary to enable the requirements of the operational system. Corresponding TRL 3 advancement tasks include:

- Fabrication technology development begins for critical reactor components. Subscale fabrication demonstration is completed with representative feedstocks (or surrogate materials) and fabrication technologies. Increased risk reduction is achieved if: fabrication process scalability is explored with representative feedstocks or surrogate materials.
- Material property measurements are initiated with representative, as-fabricated material coupons under relevant temperature ranges.
- Non-nuclear testing (separate effects testing) to assess chemical compatibility (hot hydrogen) and thermodynamic stability (high temperature) under

relevant conditions for subscale samples. Test data informs component level designs and reactor modelling activities to confirm target KPPs can be met or refine KPPs.

- Initial irradiation testing (transient and steady state) under representative transients, temperatures, power densities/fluxes, and fluences (subscale) is completed on critical reactor component materials (subscale samples).
- Nuclear data is generated through differential cross section measurements or integral critical experiments if data gaps or appropriate benchmark does not exist
- Component level quality control techniques proposed.
- Reactor component level finite element analysis (FEA) and multiphysics modeling commences. Applicable modelling and simulation (M&S) tools are adapted for the technology. Data gaps are identified for underlying property / performance databases.
- Mission models are refined and an integrated system model is developed. Pre-conceptual level trade studies are performed to down select specific reactor technologies and refine the NTP reactor-engine configuration (power balance). Target KPPs are established for the system and each of the subsystem technologies.

System readiness level considerations for TRL 3 include:

- Can the candidate reactor and component level designs satisfy proposed target system level KPPs?
- Do best available models and test data predict that reactor capable of satisfying the proposed engine-reactor power balance? How would changes to the engine side of the power balance impact the reactor and range of component operating conditions?

III.D. Technology Readiness Level 4

DOE guidance calls out TRL 4 as: *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.*

While NASA guidance calls out TRL 4 as:

Hardware: A low-fidelity system / component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.

Software: Key, functionally critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.

For the NTP reactor subsystems, TRL 4 initiates component level development and demonstration. Through *breadboard* testing, low fidelity fabrication and testing of component mock-ups is performed. Selected testing parameters may still be performed using separate effects testing, however, critical (or limiting) test environment conditions are matched. Limiting test conditions should be traceable to known failure modes or extreme operating conditions of the reactor (i.e. maximum and minimum temperature, maximum power density, etc.). Corresponding TRL 4 advancement tasks include:

- Fabrication technologies are down selected for critical reactor components. Component fabrication demonstration with representative feedstocks. Assembly and joining techniques required for assembly fabrication are assessed using surrogate materials or components (such as a fabrication demonstration of a mockup reactor core unit cell).
- Confirmatory material property measurement of representative as-fabricated material coupons is performed. Assessment of fabrication process repeatability is completed to understand impact to material properties or component reliability. Subcomponent level quality control techniques are validated. Component level quality control techniques are validated.
- Non-nuclear testing (separate effects testing) to assess chemical compatibility and thermodynamic stability under relevant conditions of representative fuel and moderator assemblies or other critical components (engineering scale). Testing informs component level designs and reactor modelling activities to confirm target KPPs can be met or refine KPPs.
- Irradiation testing (transient and steady state) under representative peak nominal transients, temperatures, power densities/fluxes, and fluences (subscale) is completed on critical reactor component materials. Post irradiation examination for materials characterization is completed following irradiation (including gamma spectroscopy, i.e., fission product inventory and activation measurement, as well as material property measurements).
- Non-nuclear “pre-prototypic” subscale mock-up (i.e. *breadboard*) structural and flow testing of proposed components using cold or hot flow testing.
- Zero power critical (mockup reactor or unit cell) testing to benchmark nuclear physics codes.
- Reactor component level and subsystem level finite element analysis (FEA), multiphysics models are

refined. Modeling activities establish component requirements and identify the range of operating parameters to explore through testing. *Note: M&S activities should be used to inform TRL 5 – 6 technology development task planning to gather the necessary test data to validate system, subsystem, or component models and reduce highest risk area / technology gaps.*

- Mission models and the integrated system model are further refined. Reactor modelling demonstrates system level KPPs can be met.

System readiness level considerations for TRL 4 include:

- Do validated models and preliminary testing activities indicate the reactor capable of satisfying the proposed engine-reactor power balance and mission KPPs? Do modelling activities require testing results to be extrapolated in order to meet KPPs? If so, is the extrapolation approach purely empirical or physics-based and does further testing need to be completed to confirm trends?
- How would changes to the engine side of the power balance impact the reactor and range of operating conditions for the components? Will any component level limits that have been identified be violated due to changes in the reactor-engine power balance?
- Is there any updated test data that indicates engine component technologies would impact the operating conditions of reactor components compared to what was demonstrated in the laboratory?

III.E. Technology Readiness Level 5

DOE guidance calls out TRL 5 as: *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 system in a simulated environment and/or with a range of real waste and simulants.*

While NASA guidance calls out TRL 5 as:

Hardware: A medium-fidelity system / component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.

Software: End-to-end software elements implemented and interfaced with existing systems / simulations conforming to target environment. End-to-end software system tested in relevant environment and meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.

For the NTP reactor, TRL 5 completes all reactor component level development and demonstration. Through *brassboard* testing, component fabrication and testing under medium fidelity conditions confirms desired performance is met in critical areas. For NTP systems, medium fidelity conditions would correspond to combined effects of near prototypic geometry components or component assemblies, for example: lifetime, combined effects reactor unit cell demonstration (roughly equivalent to fuel qualification) and cold or hot flow testing demonstration (representative reactor mockup, can be subscale, with prototypic working fluid). For the NTP reactor subsystems, TRL 5 advancement tasks are expected to include:

- Engineering scale fabrication demonstration with prototypic feedstocks and representative unit cell assembly. Laboratory equipment may be used in the fabrication of components to a scale nearing that of the prototypic use case. Full risk reduction may be achieved if reactor component fabrication is demonstrated on the production scale commensurate to that required for fabricating a test reactor (pilot line demonstration).
- Non-nuclear testing (separate effects testing) to assess chemical compatibility and thermodynamic stability under relevant conditions of integrated fuel and moderator assemblies or other critical components (prototypic scale components). Testing informs component level designs and reactor modelling activities to confirm target KPPs can be met or refine KPPs.
- Non-nuclear prototypic scale structural and flow testing of proposed integrated reactor design (may be non-prototypic pump and heat exchanger substitute for engine interface). This task may correspond to cold or hot flow testing of a mockup (unfueled *brassboard*) reactor.
- Component and assembly level vibrations and loads testing is completed with a mockup (unfueled *brassboard*) reactor.
- A statistical material property database is completed and baselined for demonstration reactor design activities.
- Combined effects prototypic irradiation testing of engineering scale components (representative unit cell) under the full range temperature, flux, working fluid interface, and spectrum expected for the reactor. Post irradiation examination confirms acceptable material performance. Quality assurance / control techniques for material manufacture are established based on test program data. A fuel specification for the demonstration reactor is finalized. Component level

quality control techniques are validated. Full risk reduction may be achieved if full scale reactor components are tested under prototypic, combined effects conditions with margin exceeding that expected for the operational use case.
- Reactor subsystem level finite element analysis (FEA) and multiphysics models are refined. Technology development tasks are used to validate system, subsystem, or component models and reduce highest risk area / technology gaps. Component performance and functional requirements are established for the demonstration system.
- Mission models and the integrated system model are further refined. Reactor testing activities confirm KPPs can be met.

System readiness level considerations for TRL 5 include:

- Is the reactor capable of satisfying the proposed engine-reactor power balance and mission KPPs? Was reactor performance observed to change due to combined effects testing and are these changes accurately captured in reactor models? Does further testing need to be completed to confirm or resolve underlying physical phenomena?
- Were reactor tests performed at the appropriate scale? How does scaling impact the reactor or reactor component performance, operating environments, or requirements? How is scaling predicted to impact interfaces of the reactor with different subsystems?
- Is there any updated test data that indicates engine component technologies would impact the operating conditions of reactor components compared to what was demonstrated?

III.F. Technology Readiness Level 6

DOE guidance calls out TRL 6 as: *Representative engineering scale model or prototype system, which is well beyond the lab scale tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype with real waste and a range of simulants.*

While NASA guidance calls out TRL 6 as:

Hardware: A high-fidelity system / component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.

Software: Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware / software systems. Limited documentation available. Engineering feasibility fully demonstrated.

TRL 6 is completed with a successful reactor-engine prototype demonstration. Engineering scaled testing (sub-scale prototype) is acceptable if the test data is shown to be extensible to the operational use case with validated models and analysis. Full power refers to full nominal power of the prototype reactor-engine system. This prototype may be subscale compared to the operational use case. Example: subscale reactor-engine system with all major scaling parameters matched. All of the critical relevant physics phenomena and operating conditions identified in the introductory portion of this presentation should be demonstrated within the same regime expected of the operational system. For the NTP reactor subsystems, TRL 6 testing would require the following tasks:

- Prototypic scale reactor hot or cold flow testing
- Prototypic scale reactor vibration and mechanisms (thermal vacuum) testing
- Prototypic scale reactor zero power critical testing
- Reactor subsystem level analysis to confirm traceability of prototype to operational system and confirmation that testing conditions are consistent with that expected for the operational reactor subsystem (if sub-scale prototype).

System readiness level considerations for TRL 6 include:

- How was reactor performance impacted by the engine interface?
- Was the demonstration test performed at the appropriate scale? How does scaling impact the reactor and integrated reactor-engine performance, operating environments, or requirements? How is scaling predicted to impact interfaces of the reactor or integrated reactor-engine with the other full scale NTP subsystems?

SRL 6 is completed with a successful reactor-engine demonstration. For the NTP reactor subsystems, SRL 6 testing would require the following tasks:

- Reactor-engine manufacture and assembly – Reactor component fabrication is demonstrated on the production scale commensurate to that required for fabricating a prototypical scale NTP reactor (pilot line demonstration).
- Reactor-engine zero power critical testing
- Reactor-engine electromagnetic (EM) field testing
- Reactor-engine prototypic full power and flux testing

Some complimentary activities to reduce risk related to reactor-engine scalability would include:

- Reactor-engine hot or cold flow testing
- Reactor-engine reactor vibration and mechanisms (thermal vacuum) testing

IV. CONCLUSIONS

TRL definitions provide useful guidance on the desired engineering activities and demonstration objectives to incrementally improve the readiness of new technologies. However, TRL definitions do not provide specific enough guidance to fully define the necessary testing or demonstration elements that should be included in the development plan for NTP reactor technologies. In this paper, relevant TRL definitions for NTP reactor subsystems are assessed. Technology advancement tasks and demonstration activities desired for the NTP reactor subsystem and component level technologies have been identified for TRL 1 – 6 activities to be performed ahead of a demonstration. Based on the specific design and performance requirements proposed for future NTP systems, the recommendations included in this paper may be used for future technology maturation planning.

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