Regulatory Approach for Nuclear Thermal Propulsion Reactor Systems

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Nuclear Thermal Propulsion (NTP) is being developed to support crewed or cargo transfer missions to Mars. Obtaining regulatory approval for NTP engine testing proves a challenge for not only the technology maturation required but also the fabrication, launch and operational nuclear regulatory environments. Existing regulations currently apply to either (1) high power, long duration commercial power plants, or (2) low power, short duration research reactors. NTP systems find themselves in a separate and unique area due to their higher power but short operating duration. This is supplemented by use of the reactor coolant as propellant. When planning the regulatory approach for NTP systems, operations in space and testing on Earth must be considered – each have their own challenges. This paper identifies a preliminary pathway for regulatory approval to operate a NTP demonstration engine as well as supporting test data that is recommended to be generated during the development program to support major regulatory milestones and deliverables.

I. INTRODUCTION

Nuclear technology use for space operation requires significant review and approval to comply with the regulations set in place to ensure the safe operation of that technology. The process to obtain regulatory approval has many steps and dependencies, which will require attention as each stage of the project is completed. This paper highlights the primary milestones, requirements, and challenges for achieving regulatory approval of an integrated NTP engine test.

To test an integrated NTP engine system, there are two primary options: testing on Earth (“ground test”) and in space (“flight test”). This study was performed in support of NASA’s Space Nuclear Propulsion (SNP) NTP Ground Test Study task – as a result, it focuses on ground testing as the primary route. This study also assumed a ground test at a Department of Energy (DOE) managed site. The NTP design concepts discussed here are based upon conceptual SNP engine designs.

II. REGULATORY MILESTONES

The key milestones throughout the regulatory process are submittals to the regulatory body, and the follow-on interaction with the regulatory body, resulting in a final approval to perform a set action. The ultimate outcome of successful completion of the regulatory process is the authorization to build and operate the integrated NTP engine as well as to operate the engine test facility. The regulations governing experimental nuclear approval are divided into several categories:

- Safety Analysis Reports
- Environmental Analysis Reports
- Facility Modification Approval
- Transportation Approval
- Flight Considerations

The related regulations are discussed in more detail in Sections II.A - E. The regulatory tasks included are shown also shown graphically in the Appendix, “Regulatory Roadmap Diagram”. This includes their interactions with broad design and testing tasks as well as separate lanes for ground and flight testing.

II.A Safety Reports

Safety reports demonstrate that the reactor design and proposed operational test pose no undue risk to either the public or the workers involved in the test. These submittals will identify the hazards and the risks associated with the planned test(s), define the design’s safety and control systems, and show that the reactor can be operated within the test boundaries safely and reliably. These reports will be submitted to the regulatory body for approval – for the SNP ground testing, the DOE is the most likely route based upon the test sites being considered. The order of the primary deliverables for the safety reports will be:

- Safety Design Strategy (SDS) - Outlines the planned approach to safety analysis for the reactor design.
- Preliminary Documented Safety Analysis (DSA) - Provides draft safety analysis ahead of final safety submittal to the DOE.

- Final DSA - Finalizes the safety analysis and forms the basis for authorized reactor operation.

Sections II.A.1 and II.A.2 discuss each of these deliverables.

II.A.1 Safety Design Strategy (SDS)

The SDS identifies the essential requirements for the DSA documentation as well as the planned approach for the safety analysis. The form and packaging of the SDS may vary based on the needs of the project. Contents may include:

- Identification and use of industry codes and standards
- Identification and use of DOE technical standards
- Summary of design criteria and design requirements
- Summary of process for hazard identification

These topics among others are included in the document. The SDS will be reviewed and approved by the local DOE office at the selected site to ensure that common expectations are established as the project moves forward. The document will then be submitted to the federal DOE Safety Basis Approval Authority for approval, with concurrence from the Chief of Nuclear Safety or Chief of Defense Nuclear Safety.

The SDS should be submitted during the design process to ensure that the design satisfies regulatory requirements. It also allows the DOE to raise questions that may have design implications before too much investment is made. For the SNP project, there are periodic design reviews of the reactor system occurring at 30%, 60%, 90%, and the final design. It is recommended that the SDS be developed prior to the 60% design review. This provides enough time for the design to mature but remains early enough in the design process to address DOE concerns and make any necessary changes without incurring significant cost. It should be noted that the facility design will have independent design reviews, and the SDS should be done at a similar point in the process to allow for DOE concerns to be identified and addressed.

II.A.2 Preliminary and Final DSA

The DSA forms the basis for authorization and operation of a planned project under DOE jurisdiction. The document will be developed according to the strategy laid out in the SDS, with analysis included supporting the planned range of operation.

A preliminary DSA is required for new DOE reactors and/or major modifications to existing reactors. The preliminary DSA serves as a draft to the DOE ahead of the final DSA submittal. It ensures that expectations are met and allows critical questions to be addressed ahead of the final DSA submittal. Completion of the preliminary DSA may prove vital to allowing the project to obtain regulatory approval in a timely fashion.

The final DSA provides an analysis of the full range of facility operations. The document objective is to demonstrate that the facility can be operated safely with respect to workers, the public, and the environment. It includes a description of the conditions, safe boundaries, and hazard controls that provide the basis for ensuring safety.

II.A.3 Flight Considerations

This paper primarily considers ground testing of an NTP system. However, flight testing should also be considered. When considering flight testing, the INSRB playbook and NASA NPR 8715.26, “Nuclear Flight Safety” should be used as guidance. These are not considered further in this paper.

II.B Environmental Reports

Environmental reports assess the impact of the construction and operation of the reactor during testing will have on the environment. and that any planned or accidental radiation release occurring during the planned action can be controlled. The program will also demonstrate to the governing body and the public that the benefit of operating the facility and the test merits the environmental risk incurred. These reports will be submitted to the federal register for public comment, before approval.

Environmental reports will be required for each new nuclear action, as defined in 10 CFR Part 50.20, for the project. These are mandated by the National Environmental Policy Act (NEPA) and serve an important function not only in meeting environmental impact requirements, but also in providing the public with an opportunity to review and approve of the proposed project actions. The required report has three variations based upon the project:

1. Categorical Exclusion determination (CATEX)

The CATEX determination allows an action to be categorically excluded from a detailed environmental analysis when the action does not have a significant effect on the human environment (defined in 10 CFR 40.1508).

2. Environmental Assessment (EA) / Finding of No Significant Impact (FONSI)

When a CATEX does not apply, an EA can be prepared. This document determines whether a federal action has the potential to cause significant environmental effects.

3. Environmental Impact Statement (EIS)

An EIS is prepared if a proposed action is determined to significantly affect the quality of the human environment. The regulatory requirements for an EIS are more detailed and rigorous than the requirements for an EA.

Environmental reports will be assembled and filed early in the project – per NEPA, this approval is required before "any irreversible and irretrievable commitments of resources" are made during the proposal. This is limited to those actions that would be covered by the environmental report but require that the project complete an environmental analysis prior to breaking ground on facility modifications or any new facility.

The environmental analyses are highly site dependent. They will require information on the site, the facility, and the extent of intended operation. It can then be determined what environmental impact is expected during the life of each facility considered by the project. For most actions during the SNP project, a CATEX or an EA will be appropriate. For the integrated engine test, an EIS may be required.

II.C Facility Modification Approval

Changes to existing facilities or the construction of new facilities will require regulatory approval. New or modified facilities will be used to accomplish the fabrication, assembly, and testing essential for an NTP engine demonstration to be successful.

These reports will be submitted to the DOE or NRC, based upon the existing facility framework. In general, facilities at DOE sites will be authorized through the DOE, while facilities at private sites will be authorized through the NRC.

Facilities for fabrication, assembly, and testing vary depending on the project scope and technology maturity. This paper considers nuclear component manufacturing and testing, zero and low power critical testing, fabrication and assembly of components, system integration, prototypic reactor testing, and integrated engine testing. A preliminary survey of existing facilities has been completed and a facilities plan drafted, with potential locations, designs, and construction or modification of facilities. The survey also showed gaps that must be filled by either new facilities or increased reliance on modeling and simulation.

The regulatory process is simpler for existing facilities compared to new facilities because a design basis and safety standards have already been developed and approved. After the test plan is established, and the facility determined to be viable, the existing facility license will be examined and compared to the capabilities and operation for the test plan. Any shortfall of the license compared to the test campaign can then be addressed by a proposed modification. The regulatory body or bodies involved in approval of the modifications should remain the same as the original license – as such this may involve NRC approval. An amendment to an existing environmental analysis or a new EA may also be required before proceeding with the modifications.

For a new facility, the process is more in-depth. As there is no existing license, the pertinent regulatory body must be determined and approached with a proposal for the new facility. The safety and environmental deliverables identified in Sections II.A and II.B must be provided, covering facility construction and operations. The currently identified new facilities candidates are:

1. Subscale Maturation of Advanced Reactor Technologies (SMART) reactor facility
2. Integrated engine test facility
3. Engine assembly and integration facility

The SMART facility is a proposed new facility capable of testing partial or full-scale fuel assemblies in their final configuration. Sustained operations would be enabled by a driver core. This would allow for "prototypic" operating conditions, with a combined nuclear and flowing hydrogen environment. Prototypic conditions are identified as operating temperature, chemical environment (e.g., hydrogen, pressure, mass flow rates), and nuclear environment expected in the final integrated engine system. SMART test data will provide detailed fuel information to support safety analyses and fuel modeling, thereby improving confidence for the integrated engine test campaign.

The integrated engine test facility is the most complex facility for the SNP project from a regulatory perspective, as engine operations have the potential to produce radioactive exhaust which must be processed or stored. The test data generated from the development program as well as predictive models will need to be leveraged to define the range of safe operations for which the test can proceed. These results and expected reactor performance will also inform the requirements for the test facility. Several concepts exist for this facility:

- The Rocket Exhaust Capture System (RECS), in which the exhaust is captured in its entirety with plans for post-test processing and decontamination, as required.
- The Real-Time (RT) processing system, in which the exhaust is filtered in real-time before flaring.
- The Post-Run Capture System (PRCS), in which a short duration test directly flares the exhaust without filtering, monitors for radioactivity, and halts testing if predetermined levels are exceeded.

The robustness of RECS or a RT processing system offer lower programmatic risk for full scale NTP engine certification testing. The maturation of these exhaust capture systems has been put on hold due to cost and schedule considerations and the refocus on an affordable subscale engine demonstration. The PRCS design reduces the cost and schedule time in exchange for a larger programmatic risk, given the planned exhaust release and relatively fewer physical barriers to fission product release.

An engine assembly and integration facility will be required for a ground or flight demonstration. This facility will allow for subsystems to be assembled and integrated into a single demonstration engine. This facility may be combined with the engine manufacturing facility if the entire integrated engine can be transported. Alternatively, this facility could be combined with the integrated engine test facility which would require separate shipment of subsystems / components to the test site and integration be performed at the test site. A disassembly facility may be required for a ground demonstration only if the components are to be inspected or transported off-site post-test. Otherwise, the test components and facility will be decommissioned, stored, and disposed of safely.

For a flight demonstration, an integration facility will be needed to support the integration of the engine and spacecraft. This may be the same facility as the engine assembly facility, or a different one, to be determined as the project's needs develop.

II.D Reactor Transportation Approval

The transportation of reactor fuel, or a fueled reactor in its entirety, requires regulatory approval through safety analysis and environmental analysis. For this project, transporting nuclear materials will be necessary at several stages of the project. Any transport of nuclear materials outside of a licensed DOE or NRC site requires approval of both the proposed route and the transportation cask. For fabricated assemblies or fueled reactors, this includes planning for anti-criticality measures, possible public radiation exposure, and transportation containment (i.e. design and licensure of transport casks specifically for the designed application). Regulatory approval for transportation entails interaction with the U.S. Department of Transportation (DOT) as well as the U.S. Nuclear Regulatory Commission (NRC).

The demonstration engine presents one of the largest challenges for reactor transport considerations due to the size and uranium content of a fully assembled engine. For this study, it was assumed that the reactor will be assembled at a fabrication facility and then transported to the test site, and therefore subject to these regulations. The reports required for transportation include a transportation plan and safety analysis during transport. These reports will be submitted to the DOT (for transportation routes) and the NRC (for nuclear safety related items, such as cask approval). The transportation plan will also require approval at the state level for each state passed through during transportation.

The transportation plan must include a planned route, transportation method, and consideration of potential hazards. The bulk of the responsibility for safe transport will be placed upon the cask. The cask must be capable of handling the hazards associated with transporting the reactor in whatever configuration is proposed. The most pertinent hazards include:

- Shock from expected transport loads and in the event of a drop,
- Engulfing fire, threatening to release nuclear material, and
- Immersion in water, leading to inadvertent criticality.

The cask selected must be analyzed for the full range of accident scenarios and ensure that transportation of components from one site to another can be carried out without risk of accidental criticality or radiation release.

The DOT will be responsible for approving the transportation route for nuclear material transport, in conjunction with local transportation authorities. Any planned route will have to consider hazards crossed (bodies of water, bridges). In addition, each state crossed through will require separate approval to confirm the planned route.

The DOT refers applicants to the NRC for approvals regarding nuclear safety in transit. This pertains primarily to the transportation method and storage while in transit. Safety analyses are required evaluating a variety of accident scenarios for damage and release of nuclear materials, as well as the potential for inadvertent criticality during those accidents. To satisfy this criteria, anti-criticality measures will be required during transport and a robust cask design must be demonstrated to successfully transport the reactor. This cask design may be a novel design specifically for the NTP reactor, or a modification of an existing design if a suitable candidate is found. The cask design and development will be dependent on cost and schedule considerations as well; current estimates show cask design could take up to three years for development and approval.

III. SUPPORTING DATA

The deliverables discussed in Section II will depend largely on the technical data made available by testing and modeling during the design process. Data required for regulatory deliverables and associated safety analysis is important to identify early in the project so that these requirements can inform planned test campaigns. This section highlights the recommended data to be generated in support of regulatory deliverables and identify options for acquiring this data.

A significant portion of the regulatory documents will be based upon modeling and simulation to perform safety analyses. The confidence in these models will therefore be a chief consideration, as predictive models are needed to plan for nuclear safety throughout the development program.

The NTP engine poses unique challenges for predictive modeling as it requires unique materials and operations. The high operating temperature, prolonged hydrogen exposure, and radiation environment ("prototypic conditions") planned for the NTP engine's operation is unique and often requires new material technologies. Test data for these materials under prototypic conditions is recommended to support regulatory submittals. Early-stage testing is expected to focus on "separate effects", performing tests without the full set of prototypic conditions. Late-stage testing is expected to consist of "combined effects" testing, with the test conditions as close as possible to the prototypic conditions, if not beyond to better assure performance. Sections III.A – C are provided as an overview to the data recommended to support regulatory milestones.

III.A Modeling and Simulation

Any new reactor design requires analysis throughout the intended operation of the reactor and beyond. For predicting both reactor performance and reliability, models can be used to predict reactor and integrated engine system behavior beyond test data that has been gathered.

For models to be relied upon to support regulatory analyses, the codes selected must be confirmed appropriate for the NTP application. This will require data in conditions similar or identical to the prototypic operating conditions for each major Structure, System, and Component (SSC) used in the reactor design. Validating predictive models with experimental data will confirm that the models are accurately predicting the reactor and engine behavior within the bounds of intended operation and assuring that accident scenarios are being treated accurately.

There are two broad categories of data needed for modeling and simulation: materials data (for predicting/verifying SSC thermal performance and structural integrity), and nuclear data (for predicting/verifying the reactor physics of the design). Until test data is generated, and models validated with this data, there may exist a large uncertainty in the results. This uncertainty needs to be considered in both the design and assumptions in the safety or environmental analysis. Section III.B and C further discuss this data.

III.B Separate Effects

III.B.1 Materials Data

Materials data, used here, refers to material properties and empirical performance database generated for the reactor material candidates. The material property database, which should be available for each SSC in the design, is recommended to include: melting point, thermal properties (such as thermal conductivity and expansion), temperature dependent stress and strain response, effects of hydrogen exposure, and strength at prototypic conditions. This data will support the reactor design and the DSA submittal (Section II.A.2). Empirical results from separate effects testing can also be used to confirm the predicted thermal models of the core.

Other data recommended to be collected includes temperature dependent diffusion behavior and release rates of fission products from the fuel. Data on this diffusion will support the EA or EIS (Section II.B), by providing information about what potential for release is expected during ground test operations.

This materials data can be gathered through the testing campaigns performed in support of the project's technology maturation plan (TMP) [9]. Basic material property data (melting points, hydrogen effects) will be obtained in the testing planned prior to the 30%+ design review. More detailed information (thermal expansion, thermal strain, effects of a nuclear environment) will be gathered during the critical and unit cell testing planned prior to the 60% design review on the TMP. These tests will use full scale test articles subjected to environments which match the bounding parameters expected during prototypic operations (i.e. peak temperature, thermal stresses, etc.).

III.B.2 Nuclear Data

In addition to the material data, data on the nuclear properties of the reactor should also be generated. The nuclear data gathered here will be used to provide confidence about the reactor performance and support safety analyses, both of which support the DSA (Section II.A.2). The reactor operation needs to be predicted within the intended operating range and beyond in the case of unexpected transients or design basis accidents. All components will need to have their nuclear properties defined. Of particular concern are the fuel elements (FEs) and moderator elements (MEs) for the core. These components form the basis for the reactor's reactivity balance and therefore the controls programs used to adjust the control drums and coolant flow. To affirm the reactor behavior, cross section data as well as material composition changes during operation are central to understanding reactor behavior and demonstrating that the reactor will be controllable for all planned operations.

The nuclear data will be gathered via testing in later phases of the TMP. Critical testing of unit cells, consisting of fully assembled FE/ME configurations, can be performed to assess the neutronic performance of the fuel and other core components without a fully assembled reactor. Zero Power Critical tests on a mockup reactor can be performed to further confirm the performance and configuration of the fuel. The mockup reactor can also include the control drums to confirm the performance of the absorber and control systems. These tests will gather specific nuclear data to confirm that the FE/ME and reactor design performs as expected.

III.C Combined Effects

Models capable of supporting the final integrated engine system ground testing can be validated using test data generated under prototypic conditions which include combined nuclear and non-nuclear environments. SSCs can be tested in some existing facilities and is planned using unit cells of the reactor core, taken to the prototypic reactor operating conditions. This will acquire valuable data confirming previous separate effects testing and confirming what impact the combined effects have on the fuel, enabling better coupling of the modeling and simulation work. However, combined effects testing at existing facilities is restricted to small fuel samples and could not test a full fuel assembly as will be used in the final reactor. This could limit the potential of the resulting data and incurs regulatory risk.

A SMART facility (Section II.C) could offer more robust testing of reactor core components ahead of the ground test itself. The facility can be designed to test candidate fuel assemblies (one or multiple assemblies) under prototypic conditions, thereby enabling more robust model evaluation. This testing capability would also allow for Post-Irradiation Examination of components, which allows for empirical material performance data (such as material degradation, fission product composition and release, moderator hydride migration data, and other material phenomena) to be generated. This materials data would be instrumental in modeling the fuel during startup/shutdown transients and providing information on restarting the core after the initial test operation. This testing can provide increased confidence in the models, supporting the final DSA as noted in Section II.A.2.

IV. CHALLENGES

The primary challenges for NTP system regulatory authorization of a ground test are novel system design and exhaust processing.

SNP project performance requirements result in reactor operating conditions beyond conventional terrestrial reactor applications. Therefore, there is a need for the generation of new fuel characterization data to inform the models and the safety analysis required to support regulatory approval at these conditions. The testing to generate this data poses an additional challenge as test facilities are limited for the range of environments, scale, and availability to match the reactor design conditions or desired statistical significance.

Regulations can also result in logistical and programmatic challenges for the engine test facility, such as in the case of exhaust processing. Facilities with the capability to capture the entirety of the exhaust are expensive and time consuming to build. However, they also offer the most surety for nuclear safety. A real-time processing or conditional capture system can reduce the cost and construction time of the engine test facility. However, facilities of these types necessitate higher confidence in the fuel integrity. This correlates with the first challenge of obtaining sufficient test data.

These challenges can be overcome through advanced project planning, early regulatory interaction, and thorough analysis of the systems involved. Identification of risks for meeting regulatory milestones and mitigation strategies in early planning is recommended.

V. CONCLUSIONS

The milestones identified this paper showcase the need for early communication with regulatory bodies as a key component to ensuring regulatory success and avoiding regulatory approval becoming the critical path for a ground demonstration. Feedback from the regulator during the design and development process will not only reduce the regulatory review time after final submittal, but also mitigate the risk of design changes late in the design process due to regulator comments.

Further, the link between the reactor design and the integrated engine test facility design is not to be understated. The reactor and engine are being designed for ultimate use in space, but a ground test will be further constrained by terrestrial regulations and safety requirements. The test facility must comply with terrestrial reactor requirements while accurately testing the integrated engine's performance for space applications. A prime example would be exhaust processing that protects the public (on Earth) but would be unnecessary in space. Additionally, safety or control system redundancies that are not commonly used for spacecraft given size and weight constraints would be safety features for reactors operating on Earth.

Finally, there is a need for materials and nuclear data to be generated to better inform the regulatory submittals and reactor design. The conclusions that must be drawn in the safety reports require models which must be backed by fuel data and experimental results to provide confidence in the reactor operations and safety. The required data should be identified as soon as possible, to ensure the essential facilities are constructed and available. This data is required for operational certainty as well as safety, but while operational confidence can be gleaned from testing, a test on Earth cannot proceed without an assurance of nuclear safety. Therefore, robust fuel testing is throughout the development program is recommended as a high priority to enable operation of an NTP system at the proposed prototypic conditions.

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APPENDIX: REGULATORY ROADMAP DIAGRAM