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RECOMMENDATIONS FOR THE NUCLEAR SAFETY AND LAUNCH APPROVAL PROCESS FOR FISSION REACTORS

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NASA's Nuclear Power & Propulsion Technical Discipline Team has chartered a study of potential improvements to the nuclear safety and launch approval process. The study concurs with previous efforts that have identified excess duplication, complexity and uncertainty in the current approval process. With a focus on fission reactors, general design criteria and safety criteria are proposed that ensure public and environmental safety, while reducing the uncertainty and complexity in the review and approval process. These criteria take into account the long history of space reactor development and related government standards for nuclear safety. Also, recommendations are made for changes in organizational responsibilities to clarify roles and reduce duplication.

I. INTRODUCTION

NASA's Nuclear Power & Propulsion Technical Discipline Team chartered a study group to consider improvements to the nuclear launch approval process. The focus was on fission reactors used for power or propulsion and considered technical, process and organizational improvements to the launch approval processes. Numerous missions powered by radioisotope systems have been launched by the United States, and these have undergone rigorous analysis and review to achieve launch approval based upon Presidential Directive/National Security Council-25 (PD/NSC-25).[1] However, only one nuclear fission reactor, SNAP 10A, has been launched by the U.S., back in 1965, well before the current launch approval process was developed.[2]

The study team evaluated exclusively reactors that would not be started up prior to achieving at least a safe orbit. Potential criticality accidents were considered along with scenarios that might involve one or more Earth flybys or a return to Earth orbit of a radioactively hot reactor. The recommendations proposed for safety criteria are independent of the particular reactor design. A set of general design criteria are proposed along with a set of risk criteria. The study also considered the distinctive organizational roles and responsibilities within the current launch approval process and evaluated the differences among science, commercial and national security launches.

The Study Group was guided in our deliberations by a number of fundamental principles. These included the paramount importance of the maintenance of adequate and appropriate levels of public safety and environmental protection. They also included the importance of an independent review of any applications. All launches of nuclear reactors into space should have similar safety requirements; however, the safety review effort and the details of the analysis that are required should be commensurate with the potential hazards. Finally, we aimed to ensure that whatever processes and procedures are developed should be transparent.

II. LESSON LEARNED FROM PREVIOUS WORK

The US has developed a number of different space nuclear reactor technologies for power and propulsion. Past space reactor programs include SNAP, SP-100, Topaz, Prometheus and other smaller programs such as Fission Surface Power, and past nuclear reactor rocket programs include Rover, NERVA and Timberwind. In each program, safety played a key role in the design of the system and in establishing a test program. Safety analysis and testing has been a major cost in these programs.

Based on the previous 50+ years of space reactor design and development, there are a few key lessons learned for future missions. Specifically,

- All phases of a mission, including reentry, must be explicitly considered,
- Reactors should remain cold prior to reaching a safe altitude, and
- Designs should include a positive means to prevent inadvertent criticality.

Technical issues can arise when the safety strategy cannot be supported by the test results. This occurred in both the SNAP and Rover/NERVA programs that based their reentry on planned burnup of the fuel.[3] Over the thirteen years of the program, and extensive testing of the fuel and reactor vessel under reentry conditions, both programs concluded that the fuel would not burnup and an alternative strategy was required.

By incorporating both safety and safeguards into the established criteria it can be ensured that the design guidelines are in alignment. For example, it may be recommended from a safety perspective to disperse the core if there is an accidental cold reentry during the launch phase to ensure the reactor will not go critical, but it may be advantageous to keep the reactor intact so that the HEU fuel can be retrieved. The SP-100 program decided to include a reentry shield to ensure the reactor reentered intact, whereas the Topaz II program decided to disperse the reactor core. The Russians chose to use an active system, a core pusher, to ensure the fuel would adequately burnup upon reentry.

III. ISSUES WITH THE CURRENT PROCESS

The current launch approval process used for RPS has been described previously.[4] The process can take several years and tens of millions of dollars to complete without assurance of approval. However, multiple studies have identified problems with the process and this current study supports and extends those findings.[5,6]

First, there is significant duplication within the process. Typically, the process includes an EIS, multiple SARs, and a SER, each of which generates various risk estimates. Reference 5 showed previously that the various analyses generally produce risk estimates that are within the uncertainty range of the analyses. Therefore, consideration should be given to reducing the number of required analyses.

Second, the process is unduly complex, both in terms of the analyses required and the approval process. Small amounts of radioactive material can require the same extensive process as more hazardous payloads. The analyses also generate complex displays of risk and uncertainty that are generally not understood by the public.

Finally, the roles and responsibilities of the different agencies and review groups are not clear. The current process is ad hoc. There are no clear requirements for approval, no consistent set of reviewers, and no clear guidance for conducting independent reviews.

IV. GENERAL DESIGN CRITERIA

The use of General Design Criteria (GDC) has a long history in the nuclear safety community, e.g., the General Design Criteria for light water reactors codified in 10CFR50 Appendix A[7]. Generalized nuclear safety criteria were promulgated by the Department of Energy (DOE) in 1982[8] for space reactors as part of the SP-100 program. GDCs were used in all space reactor programs after SP-100, including Topaz II and the Jupiter Icy Moons Orbiter. After review of each of these programs, the following are the suggested GDC's for space reactors. These criteria are modified from those used for the Topaz program[9]. The recommended GDCs are then:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced
- Inadvertent criticality shall be avoided for both normal conditions and credible accident conditions
- The radiological risk and consequences on Earth's surface of a release from an accident in space shall be insignificant
- The reactor shall not be operated below a "sufficiently high orbit" per UN Resolution 47/68.
- In-space disposal shall be limited to sufficiently high orbits or extra-terrestrial planetary surfaces where not precluded by planetary protection requirements.

The use of GDCs will provide guidance to designers for achieving adequate nuclear safety. The criteria are purposely written in a non-proscriptive fashion to allow designers to choose their own individual path to achieving safety. These GDCs provide a high-level framework for safety, while numerical risk criteria help determine when the implemented safety strategy is adequate.

V. SAFETY CRITERIA

V.A. Approach to developing safety criteria

There are currently no explicit safety criteria for launch approval of nuclear systems. PD/NSC-25 merely requires the White House/OSTP to evaluate the risks versus the benefits of the mission.[1] Given the long lead time to design and build nuclear systems, mission managers are understandably reluctant to consider nuclear reactors whenever any other alternative is available. Specific acceptance criteria are needed so that designers and mission planners can have predictability of cost and schedule.

Previous work has identified different types of criteria that are possible.[10] In choosing a proposed set of safety criteria, three guidelines were used:

- The criteria should be simple to understand and implement
- The criteria should provide a similar level of safety to other federal nuclear safety criteria
- The criteria should be design independent

When considering similar levels of safety to other nuclear operations, it is very important to distinguish between *operational* limits and *accident* limits. The safety criteria defined herein for space reactors are for accident conditions, and thus should be compared to the criteria for accidents at other nuclear facilities.

Another issue in developing safety criteria is the choice between individual or collective risks. Individual risk criteria are chosen here, consistent with the International Commission on Radiological Protection which has stated:[11]

Collective effective dose . . . is inappropriate to use in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided.

In crafting the specific safety criteria, it is important to reflect all that we have learned in nuclear safety since the 1960's. Calculations have confirmed previous analyses that accidents involving dispersal of cold uranium fuel pose minimal risk. Therefore, accidents involving cold fuel should be treated as any other radioactive source, in most cases by an Environmental Assessment with a Finding of No Significant Impact. Thus, the safety approval process should be restricted to accidents involving criticality or previously operated reactors. The criteria below could be modified to take into account the magnitude of a criticality event, e.g., not counting criticality events below a threshold number of fissions. However, note that accidents involving criticality will lead to hazards to nearby personnel, costly cleanup activities and have political implications even if no members of the public are harmed. Therefore, consistent with the recommended GDCs, safety criteria are recommended that encourage designs that minimize the likelihood and consequences of criticality events.

V.B. Recommended Risk Criteria

The first part of the recommended risk criteria is a high-level criterion that is a statement of intent:

The likelihood of a space reactor accident shall be very small, and even if it occurs, will pose little threat to the public.

This high-level criterion contains two parts, one associated with likelihood or probability and one associated with consequences. In the discussions below, separate likelihood criteria are recommended for different accident types, while a single consequence criterion is recommended for the spectrum of accidents.

The approach to setting these criteria includes consideration of past work in space reactors and nuclear facilities. Most of the operating nuclear reactors in the US are regulated by the NRC or DOE. The safety criteria proposed here have philosophical similarities to criteria and levels of safety routinely used by those organizations. This facilitates communication with existing regulatory bodies and members of the public.

Inadvertent criticality can occur in any accident involving launch and ascent or reentry, including failure to reach orbit. First consider the portion of criticality accidents that occur during ground operations, launch and ascent. Accident probabilities in the range of 1E-4 are consistent with other existing safety criteria. Conservatively assuming a launch failure rate of 10%, then the conditional probability of inadvertent criticality should be less than 1E-3.

Now consider inadvertent criticality upon reentry. The probability of inadvertent reentry will be far less than 0.1, based on the experience of modern satellites and rockets. Therefore, a conditional probability of criticality during reentry and subsequent impact of 1E-3 is conservative. Thus, the single probability criterion for criticality for all mission phases is:

The conditional probability of an inadvertent criticality given an accident shall be no more than 1E-3.

Reentry involves a number of scenarios that are different from those that occur during ground operations, launch or ascent. Reentry can occur from failure to achieve orbit, from orbit, during a gravity-assist flyby, or during a return to Earth scenario. The latter would include, for example, a nuclear propulsion system that transports cargo back and forth to the moon or Mars. The actual reentry could involve a critical or subcritical reactor, and either hot or cold fuel. When the reentry occurs, the reactor might completely burn up, land intact, or something in between.

Risks to individuals are extremely low for reentry scenarios. If the reactor burns up and disperses the fission products globally, the doses to any particular person are vanishingly small. Further, if the reactor lands intact or in pieces, the likelihood of it landing near any particular person is also extremely low. However, if the reactor does not burn up, locally high doses may be present.

It is difficult to ensure complete burnup, because reactors include high temperature materials. As a result, some previously planned missions included measures to ensure intact reentry.[12**Error! Bookmark not defined.**] Even those designs are difficult and expensive to validate, due to the complexities of calculating high speed reentry behavior and the difficulty in performing validation tests. For these reasons, the proposed likelihood criterion focuses on minimizing the likelihood of an unintended reentry:

The probability of an unintended hot reentry shall be less than 1E-4 over the life of the mission.

In setting a public health criterion, it is useful to review radiation effects and existing dose limits. The average person in the U.S. is exposed to about 300 millirem/year due to naturally occurring background radiation.[13] According to the EPA, doses above about 75 rem can produce acute effects, while lower doses can potentially cause cancers or other latent health effects.[14] The NRC and the DOE have specified dose limits:

- NRC limit for person at the site boundary due to a design-basis accident – 25 rem[15]
- DOE guidance for consequence levels for DOE facilities – Low < 5 rem, Medium $\geq$ 5 rem, High $\geq$ 25 rem[16]

Before setting the actual criterion, it is important to consider the distance at which the dose is to be calculated. If a reactor criticality occurs at the launch site, the nearest members of the public will be several kilometers away. If a reactor lands adjacent to a person and becomes critical, the dose to the adjacent person will far exceed any reasonable dose limit. However, this risk is not dissimilar to the accepted risk of a rocket or rocket parts falling near an individual. The probability of such events is extremely low. However, a large rocket explosion can impact a significant area, and the approach taken here is to keep the impact of a critical or reentering hot reactor localized. This can be achieved by setting a reasonable distance from the reactor for the 25 rem limit. Setting the distance to 1 km is conservative with respect to accidents at the launch site and reasonable with respect to localizing the effects of accidents occurring in unexpected locations. Note that using 1 km for hot reentry implies that either full burnup or intact reentry is desired and not an accident that distributes hot pieces of fuel over a wide area. The recommended consequence criterion is then:

For any credible space reactor accident, doses to members of the public shall remain less than 25 rem at 1 km from the reactor.

For this criterion, *credible* is defined as having a probability that is greater than or equal to 1E-6. For launch and ascent, this means 1E-6 per launch, while for hot reentry this means 1E-6 over the mission life.

The criteria specified above are consistent with NRC Ref 17 and DOE Ref 16. They should be able to be met with conservative analyses in most cases. A graded approach is suggested that first considers using bounding analyses and more detail only if the bounding analyses do not meet the criteria.

VI. ORGANIZATIONAL AND PROCESS CHANGES

A number of potential organizational and process changes were considered during the course of this study. Various organizations have recently completed or are in the process of studying the complexities of the launch approval process for power and/or propulsion concepts which utilize nuclear materials. These include the NPAS[21] and OSTP/STPI RPS[28] studies which extensively discussed many of the organizational complexities related to the current nuclear launch approval processes.

These observations led this Study Group to consider the importance of a single review/decision process with a well-defined, clear, and documented pathway for both government and commercial agencies/organizations. Such a process does not need to include three separate safety analyses/reports, as currently is the practice, often containing similar or overlapping analyses. We make the following recommendations:

1. The Office of Science and Technology Policy (OSTP) should take a lead role in the reconsideration of the entire launch approval process for fission power and propulsion activities including the development of clear and specific safety standards and criteria. This reconsideration should be driven by a single operating principal: "What are you doing to improve safety?"
2. OSTP should utilize the regular technical and engineering standards development process, such as through ANS, for these "Standards".
3. OSTP should reduce the number of agencies and organizations involved in the process into three general categories of participants in the launch approval process. These three general categories would be known as the "Applicant", "Reviewer", and "Decision Maker/Regulator". It is possible that these last two could very well be embodied within the same agency or organization. These three separate roles would be independent of whether the launch is governmental, commercial or a hybrid of the two. Additionally, OSTP should develop a "Standard Review Plan," similar to the plans developed years ago by the U.S. Nuclear Regulatory Commission.

VII. CONCLUSIONS AND RECOMMENDATIONS

The Study Group produced a number of Conclusions and Recommendations. Some of these are extensions of those presented previously in other studies, but with more specificity. Without action to address the perceived and real problems in the launch approval process, designers and mission managers will be reluctant to commit the resources necessary to make space reactors a reality.

Conclusions

1. Progress has been made in the launch approval process for RPS; however, more work is needed especially for fission reactors.

2. Accidents involving cold reactors pose little risk without criticality.
3. Reactor designers need clear design guidance and acceptance criteria.
4. Roles and Responsibilities are unclear and have evolved over time, leading to redundancy of efforts and uncertainty in achieving approval.
5. Significant work will be required to implement a new launch approval process.

Recommendations

1. Continue to improve the launch approval process in a manner that complements activities in the RPS program.
2. Implement a graded approach that requires minimal effort for non-critical accidents.
3. Explicitly address criticality in design and safety criteria.
4. Adopt a set of General Design Criteria for space fission reactors, such as presented above.
5. Adopt a set of understandable Safety Criteria for space fission reactors, such as presented above. These criteria should provide levels of safety commensurate with other US government nuclear activities. Begin sample studies to develop the safety case for near-term designs.
6. Develop standards for acceptable methods and analyses to determine compliance with the adopted safety criteria.
7. Continue to support efforts at OSTP to clarify and improve the launch approval process.
8. Develop clear roles for applicants, reviewers and regulators.
9. Include independent technical review in the process, with clear guidance for the review process.
10. Develop a process that is consistent for government and commercial launches.
11. Utilize the regular technical and engineering standards development process for the development of safety and launch approval criteria.
12. Begin now to identify and update the procedures and processes inside and outside of NASA that may require modification.

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