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Safety Program Considerations for Space Nuclear Reactor Systems

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Prepared by
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**SAFETY PROGRAM CONSIDERATIONS
FOR SPACE NUCLEAR REACTOR SYSTEMS**

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ABSTRACT

This report discusses the necessity for in-depth safety program planning for space nuclear reactor systems. The objectives of the safety program and a proposed task structure is presented for meeting those objectives. A proposed working relationship between the design and independent safety groups is suggested. Examples of safety-related design philosophies are given.

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SAFETY PROGRAM CONSIDERATIONS FOR SPACE NUCLEAR REACTOR SYSTEMS

I. INTRODUCTION

In today's political and environmental activist climate, an impeccable safety program is absolutely necessary to successfully deploy space nuclear power systems. The safety program must be initiated with the concept design phase and continued throughout system development.

This paper outlines the benefits of such a program for space reactor systems. A general list of tasks that must be accomplished will be outlined, and a method will be described which would enable the design safety and independent safety groups to assist each other in this effort. In addition, safety design philosophies used to guide the design and development of terrestrial reactors and space power sources will be described to highlight general guidance that can sometimes be developed to aid the designers.

Program task assignments are discussed as they relate to a typical organization structure shown in Figure 1.

ILLUSTRATIVE ORGANIZATION STRUCTURE

FIGURE 1

The independent safety group must report to and receive funding from the program manager for reasons that are described later. As a result, it may not appear to be completely independent to someone outside the program. This group and the program manager are motivated by the fact that the power system will eventually have to be approved for flight by organizations outside of the program, such as the Interagency Nuclear Safety Review Panel. The independent safety group's authority and potential impact are absolutely dependent on the program manager's support. Conversely, the program manager must ensure that this group does not inordinately dominate the design process. He must realize that full-time involvement of an independent safety group is not a natural process. It is, therefore, his responsibility to ensure that safety is given proper consideration early in the concept development phase.

II. NECESSITY FOR IN-DEPTH SAFETY PLANNING

The benefits of a properly implemented safety program for space reactor systems are apparent if viewed in the context of overall program requirements. First, public health and safety are of paramount importance when operating nuclear reactors. These are real, non-abating, requirements which must be understood by users and designers alike. Second, it is not surprising that safety considerations may necessitate design changes and that the cost to implement these changes may increase exponentially with time over the duration of the project. An obvious conclusion, therefore, is that an in-depth safety program must be considered at the outset because every dollar spent early-on could save hundreds to thousands of dollars later. An alternative approach delays consideration of safety until later in the project and attempts to address safety issues "after the fact." The latter approach produces disastrous results! It often incurs the extreme expense of incorporating design changes late in the product development cycle and is the genesis of the "bandaid" and "bring me another rock" approaches to system safety. The problems inherent in dealing with safety "after the fact" can be eliminated if safety concerns are articulated and communicated to system designers at the outset. The key to achieving a cost effective safety program is a high degree of cooperation between the safety and design groups. Safety groups cannot function only to uncover safety problems to dump into the designers' laps. Instead, the safety analysts must assist in achieving project objectives by offering clear explanations of safety problems as they relate to the design, critiquing test plans, and offering insights gained from safety analyses and tests, etc. A safety program which is implemented at project inception and fosters cooperative efforts will maximize system safety as well as minimize total system development time and costs.

III. SAFETY PROGRAM OBJECTIVES AND TASK STRUCTURES

The objectives of a cooperative-project-oriented safety program are the following:

- To establish the basic public and operational safety requirements early in the system development phases in an impartial and unquestionable manner;
- To assist the design and production organizations in meeting these requirements in a cost effective fashion; and
- To continuously verify that safety requirements are being met and to provide feedback to the designer.

These objectives can be realized for space reactor systems by implementing the following general tasks:

Task 1 Organize separate design safety and independent safety groups and define their specific roles. This task should be accomplished expeditiously, at least by the time the concept design teams are formed. Since the designer is ultimately responsible for system safety, the need for in-depth involvement of a design safety organization is readily apparent. The design safety group should take the lead in accomplishing objective number 2, above. However, the safety program will be considerably weakened if the in-depth safety assessments are made only by the organization having design responsibility. In-depth safety assessments conducted by both the reactor designer and an independent organization are required to assure that all important aspects of public and operational health and safety are fully considered. An independent safety organization is required to:

- a) Provide completely unbiased safety assessments;
- b) Bring an independent safety viewpoint to the project that will be perceived as such by review groups, users, and the public; and
- c) Guarantee full consideration of safety early in the project while the design is still flexible.

Substantial involvement of an independent safety organization in all aspects of the reactor development and production cycle is essential for establishing a credible safety program. The independent safety organization is involved in the day-to-day project activities

and provides up-to-date, unbiased assessments to the safety review panels, the user, and the public. This function cannot be adequately implemented by simply reviewing the work of others but requires continuing in-depth technical involvement and the insights gained from that involvement. In addition, an independent organization with independent funding is required so that safety funds and manpower are not diverted to meet design needs. Finally, it is important to realize that certifiable independence can be achieved only by careful selection of an independent safety organization which has nearly complete control in implementing its function. To maintain strict independence, an organization must not be constrained or biased due to conflict of interest, funding source, or its reporting and management structure. This infers that the company or organization responsible for independent safety must:

- a) Not be responsible for designing, selecting, procuring or promoting the power system;
- b) Obtain funding from, and report to, a level within the program that is not involved with the physical design;
- c) Have responsibility for management of the independent safety program. (A program managed by others cannot be independent);
- d) Not be the system user.

Task 2 Develop a definitive set of safety criteria for space nuclear reactors. This also must be accomplished early in the program but not without a considerable amount of technical input. Task efforts should focus on developing a consistent set of criteria that can be agreed upon by all the safety review agencies. The safety criteria and the safety plan discussed later should be developed as distinct tasks. However, user requirements for surety (security or safeguards, reliability, and safety) should be included along with the basic safety criteria. Existing requirements should be evaluated for applicability and amended as necessary. Since it is extremely expensive to design to constantly changing specifications, safety and safeguards criteria should be relatively fixed with time.

As a result, documents outlining these criteria must not delve into design considerations by specifying how the criteria are to be met but must address the basic requirements for assuring public health and safety. For example, a basic safety criterion might state that

"Analysis using Code 'ZZ' must show that use of these reactors will not cause any member of the general public to ingest more than 'X' curies of radioactive material annually." As another example, safeguards may require that "Any special nuclear material that randomly reenters the earth's atmosphere within the next 'Y' years shall be dispersed in part sizes weighing less than 'W' grams over an area greater than 'Q' square miles."

The designer must also be given some guidance concerning acceptable risk indices. In the final analysis, acceptable risk indices are determined by the Inter-agency Nuclear Safety Review Panel (INSRP) and ultimately by the President of the United States based on the importance of each mission. However, in the absence of fixed safety goals, any guidelines that exist in this area should be made available.

Task 3 Develop a safety plan. This task incorporates safety in the design by outlining a plan and suggesting methods for meeting the safety criteria developed in Task 2. The safety plan should assist the designer in interpretation of safety requirements, describe the safety review process in detail, and define the processes available for resolving safety problems. The safety plan also identifies required subsystem and system safety demonstration tests along with the objective of each test. If possible, the plan prescribes safety-related design philosophies for design guidance. It is important to understand the differences between basic safety criteria and safety-related design philosophies. The two have considerably different effects on the design process. In general, basic safety criteria are mission independent requirements for protecting the public health and safety. They tell the designer what is expected.

As mentioned earlier, the safety plan describes how safety concerns will be analyzed and proposes methods for meeting the basic safety criteria. These proposals are to be treated only as suggestions; not design requirements. In almost all cases, the designer must have the option to choose the method for achieving a safety objective. Because of his in-depth understanding of the design, he has a great advantage over others in deriving cost-effective solutions to safety problems. In rare instances, safety-related design philosophies rather than basic safety criteria may be prescribed by funding agencies. However, since they limit the designer's options, extreme caution must be exercised when prescribing such philosophies to assure

that they do indeed specify an appropriate solution. (See Section 5.0 for more detail on this subject.)

If public perception of risk is considered an important factor in the outcome of these projects, then methods of assessing and addressing public awareness should also be delineated in the safety plan. The safety plan should be a "living" document that can be amended, adding the appropriate level of detail as the design evolves.

Task 4 Provide risk assessments to help the designer understand and plan for the important problem areas. The scope of these assessments must be kept appropriate to the level of design detail, becoming progressively more definitive as the project proceeds from conceptual design to hardware testing. These assessments of necessity involve only gross detail in the conceptual design stages. Since the risk for a given accident is the product of the accident probability and the population dose for that accident, these risk assessments will be based on accident probability models and consequence models.

Accident probability models should be based on event tree logic and will require development of accident scenarios and probabilities for each of the fabrication-to-end-of-life sequences in the development of the power system. Event probabilities should be estimated based on existing data. Use of detailed fault trees to establish event probabilities is not envisioned in these projects. Insufficient data exists for new systems to warrant that level of detail.

Consequence modeling is concerned with the development of models to simulate the phenomena and environments that result from given operating and accident situations. It is an essential step in the overall risk assessment process. These analyses also provide valuable guidance to the designer; guidance that will help him design to meet safety criteria. For example, it may be essential for the designer to have information concerning dispersal of beryllium in a launch pad accident. This is part of the information required to estimate the risk from such an accident. If the risk to the public must be reduced, insights gained from the consequence model can assist the designer in this task.

Task 5 Develop safety technology in parallel with design technology. The safety technology development process is not as well defined as the design technology development process. Since safety analyses are often concerned with system behavior beyond normal operating

requirements, new phenomenological data and/or modeling techniques may have to be developed to complete the required analyses. It is important that the project manager realize that some of the data needs identified in this task may influence system test planning. Since the development of safety technology may be a lengthy and expensive process, costs and schedules for these efforts must be identified and included in the project costs as early as possible.

Task 6 Conduct tests to verify the safety models and demonstrate subsystem and system safety. When new models are developed or when established models are implemented for new applications, it is often essential that physical tests be conducted to assure that all important phenomena have been included in the models. Since all modeling techniques have their limitations, major subsystem and system tests will also be required to demonstrate final product safety.

Task 7 Plan for a coordinated effort among the various program and project groups. The safety analyst must have a working knowledge of the design before he can conduct analyses. Results of these analyses may precipitate design changes, and so on. Therefore, the safety and design groups must interact in an iterative fashion and work closely throughout the project. In general, if designers must await preparation of formal safety reports or vice-versa, the safety and design programs will be out of sync. This necessitates participation in informal meetings where the day-to-day participants in mission planning, project, design, design safety, independent safety, and user groups can exchange information. This does not preclude the preparation of formal safety analysis reports and independent safety reports as required by the INSRP. In addition, periodic safety presentations should be made to combined meetings of the INSRP and/or concerned safety advisory groups.

Task 8 Provide continuity for the safety effort from concept through flight phases.

IV. ASSIGNMENT OF SAFETY PROGRAM TASKS

The above tasks generally depict a programmatic overview of what should be done to implement a safety program. It is equally important to consider how these tasks should be implemented. Distribution of task assignments between the design safety and independent safety organizations is a program management challenge that must balance the need for adequate safety assessments against the possibility of excessive redundancy. Consideration of any and all safety issues is within the purview of

both the independent and the design safety organizations. Therefore, care should be taken in placing confines on the specific tasks to be undertaken by each organization. However, the task structure for each group must be analyzed to minimize total program costs. This infers that one group or the other should be designated the lead organization for certain safety tasks. In general, the independent safety group should be responsible for specifying basic safety criteria and verifying that those criteria are being met while the design safety group concentrates on meeting the criteria. In all cases, the designer always has the ultimate responsibility for safety and must function as if an independent safety group did not exist. Nothing would be more detrimental to safety than to imply that another organization would be responsible for uncovering the designer's safety errors. While the independent safety group should offer advice when appropriate, it is the responsibility of the designer to act on or reject that advice. Within these rather broad guidelines, plausible areas of responsibility for the general tasks are indicated below:

- Task 1 Organization of separate safety groups is the responsibility of the program office.
- Task 2 Specification of basic safety criteria must be performed in a manner that would not only be deemed impartial by user, review and public organizations but would, in fact, avoid any conflict of interest. This is a program office responsibility with review and comment provided by the design and independent safety groups. The funding, use, and flight approval organizations are, of course, responsible for approving these criteria.
- Task 3 Development of the safety plan is a design safety responsibility. The independent safety group provides review and comment. The safety plan specifies how safety criteria are to be met and is clearly within the designer's purview. Development of this plan should assure early participation of the design contractor in the safety effort.
- Task 4 Risk assessments must be performed by both groups because both must have considerable leeway to provide the analyses that have been historically required. The design safety group is required to submit contractor safety analysis reports to INSRP. These three reports (preliminary, updated, and final) are key to obtaining flight approval and require a concerted effort in all aspects of analysis, testing, and technology development. In addition, the independent safety group provides INSRP with independent analyses and test information.

The design safety group might emphasize modeling of operating situations while the independent safety group could emphasize accidents. Considerable similarity of effort should be expected, however, and even required in accomplishing Task 4 objectives. Since separate organizations generally do not use identical tools and assumptions in modeling a given situation, similar analyses are a means of obtaining quality assurance in that they provide a much needed cross-check on analytical results. Moreover, the qualitative information gained by performing safety studies will provide both organizations with valuable insights into the potential problem areas and solutions. This quality assurance might pay for itself by avoiding future hardware changes; changes that could be incurred if the basic analyses were later proved incorrect.

Task 5 Development of safety technology is similar to Task 4 in that both safety organizations should share the responsibility for this task. Each organization will identify safety technology that must be developed to complete Task 4. If new models are required, each group must independently develop its own. However, if new phenomenological data must be made available, it might be reasonable for the design safety group to acquire operational data and the independent safety group to acquire accident data.

Task 6 Safety Testing. The project manager faces an interesting challenge when deciding how to minimize costs without compromising safety. Whereas analyses are generally much less costly than physical tests and a reasonable amount of analytical similarity will be healthy and cost effective, the same is not necessarily true for tests. Tests are usually very expensive, therefore, duplication should be avoided whenever possible. This, of course, is at odds with legitimate requirements that both safety organizations do "hands-on" hardware testing. Pure "paper studies" on the part of either organization will not yield adequate safety assessments. Physical tests are always required to better understand phenomena, component behavior, or component and subsystem interactions associated with specific environments. Much of the test funding for both organizations must be discretionary if testing is to keep pace with the more responsive analytical efforts. This discretionary funding also provides either group the flexibility to re-examine portions of the other's tests. Usually these re-examinations will complement, not duplicate, previous tests.

Safety testing addresses two general areas: 1) tests designed to verify safety models; and 2) tests designed to demonstrate major subsystem or total system safety. Certainly both groups must conduct tests of the first type. For the design group, this requires testing in abnormal environments in addition to "proof of operation" tests in normal environments. The independent group then emphasizes testing in accident environments.

It is much more difficult to assign responsibility for the major safety demonstration tests. However, the following facts must be considered when making that assignment:

1. These tests provide direct verification of safety, a major function of the independent safety group; and
2. They must be conducted on a completely impartial basis for the results to be credible; i.e., test conduct must avoid actual conflict of interest and any situation that could appear to cause such conflict.

Another very important fact to bear in mind is that the testing organization always influences the outcome of a development test to some degree, no matter who has done the test planning or who supervises the tests. Test procedures can never be completely detailed in development tests. There are too many unknowns encountered in such tests to make complete detail possible. This means that a portion of the procedures and other test specifics will be developed on an ad hoc basis by the personnel performing the tests. In addition, the procedures will obviously be affected by the test equipment available in terms of instrumentation, data acquisition rates, test duration, etc. Documentation of these ad hoc procedures, instrumentation and control configurations, and many other test specifics depend on local QA programs, available time and funding, and mainly on the dedication of the test personnel to this sort of task. Therefore, it may be concluded that the test conduct and outcome is dependent on the experience and dedication of the personnel doing the day-to-day test work and on the equipment available to them. User understanding of the test is equally dependent on these same individuals.

While it is not reasonable to isolate the designer from these major tests, neither is it reasonable to expect the public, review groups, or the system user to place total confidence in tests conducted by the design

organization. Test specification and planning can be shared by design and independent safety groups, but actual test conduct is another matter. Some sort of reasoned compromise is required in this area on a case by-case basis. It may often be advantageous to have these major safety demonstration tests controlled by the using or funding organization. In any case, since only one set of these tests can be performed, extensive input is required from both design and independent safety groups.

- Task 7 Coordination of design and safety efforts is a project office responsibility in terms of scheduling meetings and providing the mechanism for information exchange. Once this is established, however, the individual participants must provide for informal dialogue between scheduled meetings to obtain the maximum benefit from the combined efforts of the various groups within the project.
- Task 8 Continuity in safety work should be shared since it would certainly be advantageous to have continuity from both safety groups.

V. SAFETY-RELATED DESIGN PHILOSOPHIES

Two safety-related design philosophies that have proven useful in other nuclear power programs are described below. These philosophies are products of safety programs and are simple, unerring, and unchanging guidelines for the designer. These philosophies must: (1) be based on extensive technical system analyses; (2) be clearly and completely defined (including the logic leading to the philosophy); and (3) be no more prescriptive than necessary. If philosophies such as these can be developed, they will promote increased safety and considerably reduce program costs. As with most safety work, the greatest positive effect is produced if the results are available in the concept through prototype development phases where the design is still relatively flexible.

As an example, the multiple barrier containment philosophy is a safety-related design philosophy that applies to terrestrial nuclear reactors.¹ It evolved in response to the need for minimizing the risk of potentially hazardous fission product release to the general environment. Here, the fuel is the first barrier, therefore, it is formed into particles designed for a high degree of fission product retention. The second barrier is

1. Nuclear Energy Technology, Knief, Ronald Allen, McGraw Hill, 1981, p. 14.

typically an encapsulation capable of holding fission products that do escape the fuel. The reactor vessel and primary coolant loop form the third barrier while containment buildings or structures serve as additional barriers. Naturally, these principles have major impact on fuel assembly designs. For example, since uranium dioxide and uranium carbide are relatively dense ceramic materials with good ability to retain fission products, they are favored fuel forms.

The multiple barrier containment philosophy is very similar to the "intact through impact" safety-related design philosophy used for the most recent radioisotope-fueled space power supplies. This design philosophy uses multiple barriers to reduce the risk of radioisotope release in all abnormal environments including reentry into the earth's atmosphere and impact on its surface.

These safety design philosophies have been included only as examples. They may or may not be applicable to space reactors.

VI. SUMMARY

Programs that develop nuclear reactor systems for use in space have a unique opportunity to include safety as an integral part of the design and development process. These are new programs without the legacy of an established design. As a result, the safety effort should not result in retrofits as it did in some commercial reactor programs. Safety input provided early will more than pay for itself in assistance to the designers. Conversely, safety input late in the program results in an adversary relationship between design and safety groups, causes costs to skyrocket, and results in an inferior design for safety. It is often said that with design engineers, safety is an afterthought; performance is foremost in their minds. In fact, many times safety is an afterthought in the budgeting and planning process and the designer simply has insufficient safety criteria until too late in the development cycle.

The program manager is responsible for instituting and executing a properly balanced program which ensures that safety is given adequate consideration without imposing unreasonable constraints on the system design. The structure of and funding for the safety program must be carefully considered. Enough analysis and testing must be performed to clearly demonstrate system safety. A portion of this analysis and testing must be rigorously independent and perceived as such by all parties who influence flight approval.

Safety, properly emphasized and implemented, can help get the program objectives completed, better, cheaper, and faster. This includes helping to guarantee that a reactor can be flown after it is built.

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