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INTEGRATED SYSTEMS PERFORMANCE ASSESSMENT FOR THE EVALUATION OF SPACE NUCLEAR REACTOR DESIGN CONCEPTS (PHASE 1: DEMONSTRATION OF THE METHODOLOGY)

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This technical report has been reviewed and is approved for publication.

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13. Supplementary Notes

14. Abstract Science Applications International Corporation has developed an Integrated Systems Performance Assessment (ISPA) model for the evaluation of space nuclear reactor design concepts. This modeling effort has been undertaken in support of the Space Power and Thermal Management Division of the U.S. Air Force Phillips Laboratory. The goal of Phase I of this project was to demonstrate the ISPA methodology by developing a simple model that quantitatively evaluates the performance of conceptual space nuclear reactor designs while considering the complexities and interdependencies among established evaluation criteria. The model that has been developed is capable of quantitatively assessing the performance of two proposed space nuclear reactor design concepts by considering the individual and integrated performance of twenty-eight design attributes and using those results to evaluate thirty-eight weighted acceptance criteria.

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Acronym List

DOE	U.S. Department of Energy
ISPA	Integrated Systems Performance Assessment
PL	Phillips Laboratory
PSA	Probabilistic Safety Assessment
QFD	Quality Functional Deployment
SAIC	Science Applications International Corporation
SNL	Sandia National Laboratories
SNPS	Space Nuclear Power System
TFE	Thermionic Fuel Element
TQM	Total Quality Management
USAF	U.S. Air Force

1.0 INTRODUCTION

The U.S. Air Force (USAF) Phillips Laboratory (PL) has identified five basic research areas in Space Power and Thermal Management where the development of innovative technologies has been requested. These technologies are anticipated to provide significant payoff to the performance, survivability, and affordability of important systems. The first basic research area is Space Nuclear Power. This report discusses the development and application of an innovative approach to systems performance assessment for the evaluation of space nuclear reactor design concepts. The approach described is anticipated to provide an important tool for guiding the assessment of component and system performance. The extension of this approach to provide a framework for design optimization is also envisioned.

1.1 Space Nuclear Power Systems

PL's objectives for research in the area of space nuclear power are directed towards experimental and analytical development of advanced space nuclear power systems (SNPSs) for future USAF spacecraft. Specifically, PL's focus is on advancing the state-of-the-art technology in SNPS materials, components, subsystems, and systems for power generation, conversion, and distribution, as well as heat transport/rejection for existing and proposed system concepts. To achieve these objectives, PL has identified the following specific areas for research:

- Increase thermal to electric conversion efficiency
- Reduce production costs
- Increase lifetime
- Reduce system mass
- Increase reliability
- Identify and analyze mission applications and their attendant requirements
- Develop improved numerical and analytical techniques for designing and assessing space power systems
- Reduce development cost
- Reduce testing risk, cost, and schedule

Each of these research areas involves independent assessment and subsequent integration of individual components or subsystems into an SNPS. The proposed system designs are largely conceptual, and many of the proposed materials, physical processes, and components have limited modeling, testing, and validation on which to base the assessment of their performance within the overall system. This lack of information relative to certain aspects of conceptual designs gives rise to uncertainty relative to the overall performance of the system. Therefore, a potentially high degree of uncertainty can exist with regard to ultimate performance (i.e., power output and capacity), mission application, reliability, lifetime, development cost, and testing risk. This uncertainty has been termed "technology risk."

PL has identified two specific space nuclear reactor design concepts to be evaluated using Integrated Systems Performance Assessment (ISPA) methodology: the S-PRIME concept designed by Rockwell International and the SPACE-R concept designed by Space Power Incorporated. Each design is characterized by a moderated core, a NaK pumped loop primary coolant system, and a potassium heat pipe radiator as the ultimate heat sink. The most significant difference between the two concepts is in the design of the in-core Thermionic Fuel Elements (TFEs). The S-PRIME concept proposes the use of multi-cell TFEs, while the SPACE-R concept proposes the use of core-length single-cell TFEs.

The TFE design and performance specifications have a significant impact on the assessment of overall system performance. The TFE design could affect the system cost, demonstrable reliability, scalability, power, etc. The impact on the overall system performance could be either positive or negative, depending on the evaluation criteria being considered. This is an example of only one component of a complex system. A fully integrated engineered system could potentially have hundreds of components, each of whose individual performance is dependent on the performance of others. To effectively evaluate overall system performance, an integrated model that considers both multiple levels of dependencies and weighted evaluation criteria is required.

1.2 Integrated Systems Performance Assessment

SAIC has coined the term ISPA to refer to the application of an inductive probabilistic modeling framework to the assessment of the overall performance of engineered systems. This framework provides PL with the appropriate tool for the application of existing models for physical processes and component performance to an integral assessment of SNPSs that enables the assessment of performance combined with a consistent evaluation of technology risk.

Inductive modeling begins by characterizing the system performance in terms of acceptance criteria (e.g., maximum power output, mass, and reliability) and/or its response to events (e.g., failure of a component or exposure to excessive heat). The analyst then describes the causal relationships between these performance criteria and relevant events. The system is then designed based on inductive reasoning. Event trees have been used in reliability engineering and safety assessments to represent these causal relationships. Specifically, the analyst indicates, using the event-tree structure, the sequence of design features, physical processes, and component performance required to attain a certain performance goal, either with respect to each acceptance criterion or in response to an event. The structure of the tree indicates the causal relationships that the analyst believes exist. Because the event-tree modeling framework is probabilistic, the analyst can indicate, within the context of the model, his or her confidence that a particular causal relationship is accurate. Multiple relationships with varying levels of confidence can be indicated if the analyst identifies more than one potential cause-effect relationship. The event-tree framework provides a rigorous, traceable method for performing the evaluation that allows a fully consistent parallel assessment of technology risk.

The EVNTRE[1] code, developed by Sandia National Laboratories (SNL) for use in nuclear plant safety assessments, is used to evaluate the event tree models for the performance of each conceptual design. EVNTRE is extremely powerful in this regard because it allows the inclusion of any user-supplied code to evaluate any branch point (i.e., performance indicator). It also allows the use of parameters (e.g., temperatures, flow rates, and heat fluxes) within the framework to characterize the interactions and dependencies between models.

1.3 Report Organization

This report describes the development of an ISPA model for the evaluation of two space nuclear reactor design concepts. Section 1.0 (this section) introduces the problem of evaluating complex engineered systems and the ISPA methodology. Section 2.0 describes the ISPA methodology. Section 3.0 describes the Phase I ISPA model development, including a description of the evaluation criteria and the parameters used to assess the success or failure to achieve specific design goals. Section 4.0 discusses the results of the assessment and identifies how key uncertainties and sensitivities may be identified. Finally, Sections 5.0 and 6.0 provide a summary of the results and outline the tasks associated with Phases II and III of the ISPA project.

1 Greismeyer, J. M., and L. N. Smith, *A Reference Manual for the Event Progression Analysis Code (EVNTRE)*, NUREG/CR-5174.

2.0 EVALUATION OF SPACE NUCLEAR REACTORS

Evaluation of complex engineered system performance with respect to a given set of criteria requires an integrated assessment that considers physical processes, component behavior, and constraints imposed by the intended application (e.g., size and mission time). Dependencies between these considerations lead to the requirement for an integrated model. Since some models already exist for assessing component behavior and the associated physical processes, a framework that allows integration of individual models is particularly appealing. The ISPA methodology provides such a framework. Furthermore, since uncertainty exists with respect to both the appropriateness (or correctness) of models for some physical processes and the performance of components under certain conditions, the ability to reflect that uncertainty within the integrated assessment provides a particularly powerful tool. Because ISPA is based on probabilistic modeling methodology, it enables the simultaneous modeling of system performance (based on process and component performance models) and assessment of technology risk (i.e., the confidence or likelihood of attaining the level of performance indicated by a particular combination of models).

2.1 Integrated Analysis Requirements

The focus of analysis efforts with regard to commercial nuclear power plants, and more recently the U.S. Department of Energy's (DOE's) nuclear material production facilities, has been safety assessment. It should be recognized, however, that safety assessment is the assessment of reactor system performance in response to anticipated events and equipment failures. The methods that have been developed are thus equally applicable, and perhaps of greater overall value, in the assessment of system performance relative to established criteria other than safety. Such criteria may include power produced, reliability, survivability, and others related to suitability for the intended mission.

Experience derived from more than two decades of effort to characterize the safety performance of commercial nuclear plants suggests that such efforts must consider the whole system. Efforts that have considered each component individually, or based on a limited characterization of its interaction with the other system components, have generally been shown to be less than adequate. It is frequently the case that a seemingly minor aspect of the design or operation of one component can have a significant effect on the performance of another. Inductive modeling techniques that focus the analyst's attention on cause and effect relationships within the system have become an important tool in the assessment of existing nuclear reactor systems. These types of analyses draw on results obtained from integrated mechanistic tools, component models, detailed analysis of specific phenomena, and test results to develop a more complete picture of system performance.

Nuclear power systems have been studied for more than three decades. Even with the large body of performance data and models that have resulted, significant areas remain where knowledge is less than complete. As a consequence, significant performance uncertainties remain. The probabilistic modeling framework of the ISPA methodology allows treatment of these uncertainties in a manner that permits the analyst to evaluate their potential effect on system performance. Of even greater benefit is the fact that system models constructed within this framework can be readily modified to evaluate design or operational adjustments that minimize the potential effect of these uncertainties on system performance. Techniques have also been developed to allow the analyst to identify which uncertainties included in the model have the greatest impact on the uncertainty in system performance. This information can be used to focus model development and component testing so as to gain the greatest benefit in minimizing technology risk.

2.2 Description of the ISPA Methodology

ISPA is a term that has been recently adopted by Science Applications International Corporation (SAIC) to describe a methodology that we have adapted from the nuclear plant risk assessment field for more general application to the assessment of engineered systems. The ISPA methodology has been designed to address the needs that currently exist in several technological areas with respect to developing models for the performance of complex engineered systems. ISPA provides a framework within which the analyst can develop a model for the dependencies and interactions between components, phenomena, and human or computer controls. That framework allows the analyst to develop a system model by importing models for physical phenomena (e.g., heat transfer correlations), component performance (e.g., heat pipe performance code), and component reliability (e.g., fault trees), and combining them based on identified interactions and dependencies. ISPA also allows for assessment of system performance uncertainty that may be inherent due to uncertainties related to the appropriateness or accuracy of the imported models.

This section provides a brief background of the methodology, discusses the specific benefits of this approach for the performance assessment of space reactor design concepts, and describes the modeling approach.

History

ISPA is based on the application of software developed by SNL to support probabilistic assessments of the safety of nuclear power plants. The software consists of two computer codes: EVNTRE, the principal code, and PSTEVNT, which is a utility code that facilitates the analysis of EVNTRE results. Both codes are documented in the open literature and are available to all domestic (U.S.) concerns.

EVNTRE provides a framework for the development of inductive models for system performance. Its structure allows relationships between physical phenomena, component performance, and human or control system interaction to be expressed in a completely general fashion. Boolean expressions are used within the framework to express these relationships in a manner similar to that used in conventional reliability analysis software. EVNTRE represents a significant advance over reliability software in that it allows the inclusion of mechanistic models to evaluate any aspect of system performance that may be required. In existing applications, these models are typically correlations or tabulations of the results obtained from more sophisticated computer models. However, incorporation of detailed mechanistic models is possible.

Inductive modeling begins with the identification of performance criteria or goals. Initially, deductive reasoning is used to identify the component performance measures that allow evaluation of performance relative to these goals or criteria. This process can be described as the analyst asking which components must function at what level to achieve the desired performance. The inductive process is then applied to include consideration of system effects. This part of the modeling process involves asking questions about the effect of an anticipated or potential behavior of one subsystem or component on the behavior of another. These questions, and the methods used to evaluate the answers, constitute the event tree model that the EVNTRE code will then evaluate. The framework is sufficiently flexible to allow easy enhancement by adding additional questions, including newly recognized dependencies, and enhancing the mechanistic models used to evaluate physical processes or component behavior.

This approach to system performance modeling parallels decision analysis techniques that have been developed to assist in technical management. The event tree that is formed by the series of questions posed by the analyst defines the context for each subsequent answer. The set of answers to previous questions in the analysis thus defines the context in which each question is answered. Rules for the evaluation of each question based on this context are then defined. Rule-dictated evaluation is the key element in decision analysis and is the core of the proposed methodology. This methodology, which combines mechanistic component modeling, probabilistic assessment, and decision analysis into an integrated performance model, is ideally suited for the performance assessment of complex conceptual designs.

Description

The ISPA framework is best represented by an event tree. Event trees have been used extensively, and successfully, to evaluate system performance and response to off-normal events. They can reflect interdependencies and treat significant uncertainties. The ISPA methodology is a logical extension of Probabilistic Safety Assessment (PSA). The difference between the two is that performance measures other than accident consequences are the desired results. The ISPA model developed for PL is an event tree with various SNPS performance criteria as top events. Each top event is characterized in terms of discrete levels (e.g., high, medium, or low) of performance. Each level corresponds to a specific range in the value of a parameter that characterizes performance for a specific criterion and is represented by a branch in the tree. Evaluating (or quantifying) the tree requires evaluating the parameter values corresponding to each level and assigning a split fraction (i.e., confidence that the outcome indicated by that branch is correct) to that branch. By multiplying the branch split fractions together along a pathway through the tree (typically referred to as a sequence), the frequency of each path through the tree (which indicates a certain level of performance relative to each criterion) is evaluated.

This approach offers significant advantages in the way the split fractions are evaluated relative to conventional event tree tools. Determination of the importance or significance of uncertainties in the performance of a system or component is facilitated. The top event split fractions can be evaluated independently, as a function of the outcome of previous events, or based on the results of an external user-defined function. Dependencies between systems can be handled within the model through the use of Boolean expressions that define the relationship. Also, independent component models can be linked with the tree for a detailed, systematic evaluation of key parameters that describe component performance. Multiple user functions that perform this type of evaluation are possible, facilitating the assessment of individual systems with various models. Evaluation of the sensitivity of the prediction of system performance to the various models can be evaluated as an integral part of the assessment.

Final evaluation of a particular space nuclear reactor design concept is performed by "scoring" each individual sequence. Each performance indicator will be assigned a weighting factor representing the importance of the characteristic to mission success. For example, sequences that indicate demonstrable reliability are assigned a higher weight than sequences characterized by no demonstrable reliability. The score of a particular sequence is the sum of its performance indicator weighting factors. The magnitude of the score is representative of the probability that a particular sequence will achieve the desired result. Multiplying each sequence score by its calculated frequency and summing over all sequences results in an overall score or an evaluation of the design concept. This method combines measures for system performance and technology risk. Other approaches to producing an overall score are also possible.

Benefits of ISPA

Using the ISPA methodology provides an exceptional tool for evaluating the effect of uncertainties in individual systems to the integrated system performance. ISPA models can be modified and exercised quickly and inexpensively. By modifying uncertain parameters and quantifying the model, the analyst can determine the frequency change of selected performance evaluation criteria. The effect of individual design parameters, components, or features on the overall performance of the integrated system can therefore be assessed. This process provides the necessary information to increase the overall system reliability, increase the lifetime, and analyze specific mission applications, and it provides a basis for reducing development cost and assessing risk. Specific advantages include the following:

- The methodology encourages careful consideration of component dependencies and interactions that have been shown to have significant implications for nuclear reactor system performance.
- Existing models for component performance can be incorporated in the model, either directly or by summarizing the results.
- Technology risk and system performance are assessed simultaneously, providing greater assurance of consistency.
- The evaluation is traceable and reproducible since it is based on an integrated system model rather than individual evaluations against diverse, and sometimes subjective, performance criteria.
- The resulting system model is easily modified providing significant flexibility in reflecting new insights or adding more detail to the performance evaluation.
- Once a system model has been developed, the evaluation of design tradeoffs, the effectiveness of testing in reducing technology risk, and the enhancement of the model to enable more detailed predictions of system performance is facilitated.

3.0 PHASE I ISPA MODEL DEVELOPMENT

Phase I of the PL ISPA project consists of the development of a simple model for the overall system performance assessment of a space nuclear reactor design concept. The goal of Phase I is to demonstrate the ISPA methodology and its potential as an integrated assessment tool. The following sections describe the selection of evaluation criteria; the identification of individual systems or components to be included in the model; and, finally, their integration into an ISPA model.

3.1 Evaluation of Space Nuclear Power Systems

As described earlier in this document, the first step in developing a model for systems performance assessment is to establish the evaluation criteria. These criteria provide the quantitative basis for the performance assessment.

3.1.1 Quality Functional Deployment (QFD) Analysis

As part of a Total Quality Management (TQM) exercise, PL has initiated a Quality Functional Deployment (QFD) process to assist in identifying important characteristics of an SNPS. The QFD process consisted of establishing a list of "wants" in a thermionic space power system (through a brain-storming exercise) and ranking those "wants" by systematically evaluating (through expert elicitations) their importance. The results of the QFD process provide two key pieces of information required for the ISPA model: (1) the list of "wants" in a thermionic SNPS establishes the evaluation criteria, and (2) the ranking of those "wants" provides their relative weight or importance. Table 1 lists the results of the brain-storming exercise (i.e., the "wants") and groups them into eleven primary evaluation criteria categories. Table 2 lists the eleven primary evaluation criteria and their relative importance based on the ranking each received.

Table 1. "Wants" in a Thermionic Space Power System

Evaluation Criteria Group[a]	"Wants"[b]
Attractive Costs	1. Low up front development costs 2. Affordable demonstration costs (fabrication, qualification, and first flight) 3. Low life cycle costs
Flexible Operation	4. Start up and forget 5. Off design power operation (short term; e.g., days) 6. Multiple startups and shutdowns on orbit 7. Operate in a variety of environments or orbits, such as the surface of the Moon and Mars, without changing design (costs acceptable; parasitic vacuum vessel not allowed)
Easy to Build, Handle, and Maintain	8. Easy to fabricate 9. Transportable, easy to move 10. Repairable until launch 11. Repairable on orbit
Compatible with Satellite/ Mission Objectives	12. Minimal negative impact on satellite 13. Improve operational performance of satellite 14. Allow use of smaller launch vehicle 15. Ability to support secondary function 16. Standard interface for coupling to satellite (e.g., electrical and mechanical)
Enhance Survivability of Satellite	17. Avoid detection (i.e., hideability—small signature design) 18. Avoid attack (i.e., ability to withstand maneuvering) 19. Survive attack 20. Operate through attack
Reliable Design	21. Demonstrate reliability 22. No credible mission-ending single point failures
Flexible/Scalable Design	23. Scalable over small power range with no design changes 24. Scalable over medium power range with no technology or component design changes 25. Scalable technology over large power range 26. Simplicity—use common components within same reactor 27. Simplicity—use common components while scaling power 28. Ability to easily incorporate technological advancements
Safety and Public Acceptance	29. Low radiological risk to biosphere 30. Saleable to public (safety, cost, and benefit) 31. Man-rated
Schedule	32. Key technologies demonstrated by 10/94 33. Fly by 10/99
Acceptable Program Risk	34. Acceptable development risk (high probability that development will be successful—technical, cost, schedule) 35. Performance must be assessable when satellite is in orbit 36. Testable—full system qualification and acceptance
Attractive Lifetime	37. Long operational life 38. Lifetime tailorable to mission

[a] Also referred to as Level 1 evaluation criteria
[b] Also referred to as Level 2 evaluation criteria

Table 2. Ranking of Space Nuclear Power System ISPA Evaluation

Evaluation Criteria Group	Group Ranking and Weight
Reliable Design	8.52
Safety and Public Acceptance	7.71
Acceptable Program Risk	7.60
Attractive Costs	6.95
Compatible with Satellite	6.61
Flexible/Scalable Design	6.20
Attractive Lifetime	5.98
Flexible Operation	5.59
Enhance Survivability	5.32
Easy to Build, Handle, and Maintain	5.29
Schedule	5.25

3.2 ISPA Event Tree Model

The ISPA model for the evaluation of space nuclear reactor design concepts was developed in three stages. The first stage was to develop an event tree with the eleven evaluation criteria (referred to as Level 1 evaluation criteria) listed in Table 1. Figure 1 shows a small part of the event tree containing the first three evaluation criteria.

Each sequence in the event tree has an associated frequency. The frequency indicates the probability that the outcome is characterized by the combination of successes and failures that characterize that sequence. Quantifying the tree (or evaluating each sequence frequency) is performed by multiplying each of the event node branch split fractions together. As described earlier, the branch split fractions indicate the analysts' confidence that the outcome indicated by the corresponding branch is indeed correct. If the split fractions for each of the three top events shown in Figure 1 were 0.5, the frequency of each sequence (labeled 1 through 8) would be 0.5^3 (0.125).

Stage 2 of the ISPA model development was to enhance the event tree by including sub-event trees to evaluate the top event (evaluation criteria) split fractions. To evaluate the success or failure of the evaluation criteria top events, the original "wants" used to establish the criteria were used.

Table 1 listed the evaluation criteria groups and the associated "wants" contained within each group. The logic structure input to the ISPA model permitted success of the group evaluation criteria only if each of the "wants" contained within that group were also successful.

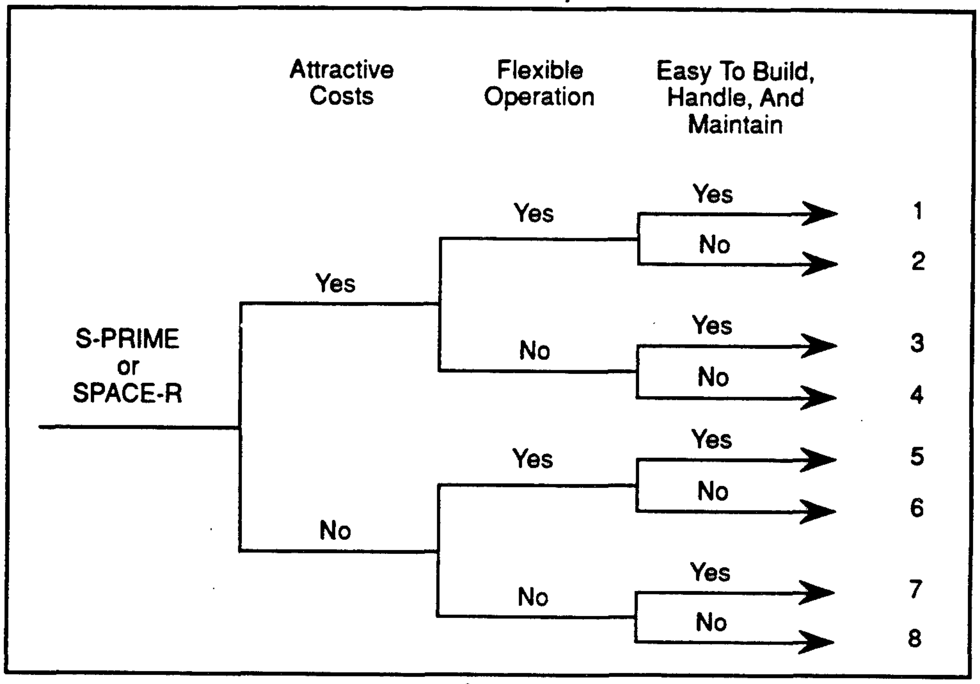


Figure 1. First Three Evaluation Criteria in Event Tree Format

Figure 2 illustrates a subtree model for the first evaluation criteria (Attractive Costs).

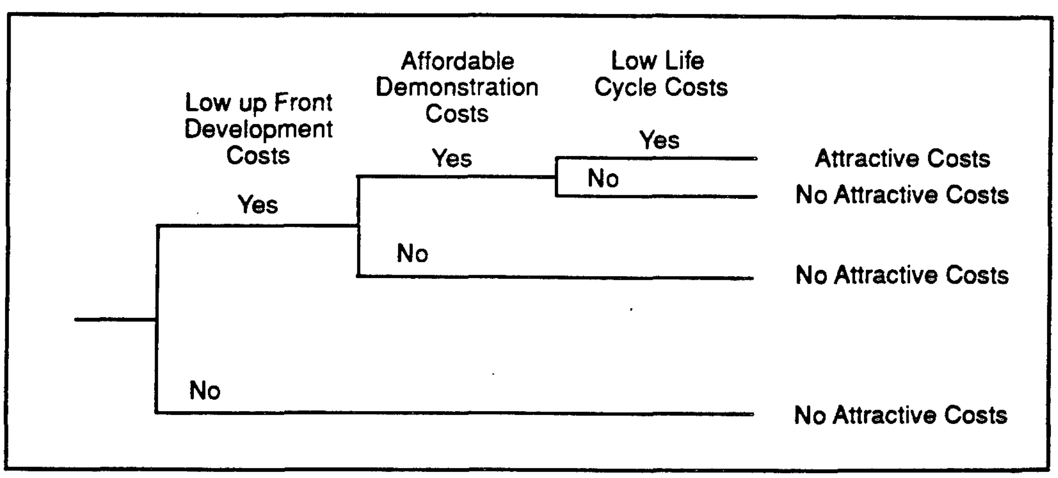


Figure 2. Attractive Costs Subtree

By assigning or calculating a split fraction for each of the event nodes (referred to as Level 2 evaluation criteria) shown in Figure 2, the probability of successfully achieving Attractive Costs can be calculated. This success probability is then assigned to the "yes" branch of the Attractive Costs top event (shown in Figure 1).

The final stage of the ISPA model development was to include the physical attributes necessary to evaluate the success or failure of the Level 2 evaluation criteria. Twenty-eight design parameters were identified through a review of the two proposed design concepts. A list of dependencies was then generated to correlate the physical attributes with the Level 1 and Level 2 evaluation criteria. Table 3 lists the evaluation criteria (Level 1 and Level 2) and provides a cross-reference to the dependent attributes. Table 3 also provides a cross-reference of dependencies between the evaluation criteria. An example of this type of dependency is the requirement of achieving both Attractive Costs and Schedule to achieve an Acceptable Program Risk.

The ISPA model developed through the three-stage process just described is presented in Appendix A of this document. The EVNTRE input deck and the associated binners are listed in Appendix B. The model is a completely integrated performance assessment tool that uses the results of the QFD process as weighted evaluation criteria and systematically considers the integrated performance of nearly thirty components, systems, or design attributes. Although the model is fully integrated, the results are presented in a modular, easy-to-read format (the graphical representation presented in Appendix A). Figure 3 illustrates the general framework of the ISPA model.

3.3 Quantifying Performance

The final step in quantifying overall system performance is to score each event tree sequence based on the success or failure of the evaluation criteria. The magnitude of the score of an individual sequence is an indicator of the degree to which that sequence represents a favorable result (i.e., the higher the score, the more desirable the result). The Phase I ISPA model for the evaluation of space nuclear reactor design concepts includes eleven evaluation criteria (listed in Table 2 with a measure of relative importance). The analyst conducting the performance assessment has virtually unlimited flexibility regarding the scoring of sequences. For this assessment, a simple scoring scheme was used that scored individual branches in a sequence with their appropriate weighting factor (from Table 2) if the branch indicated success. If the branch indicated a failure with respect to a particular evaluation criteria, a score of zero was assumed. The total score for each sequence is evaluated by summing the scores of the individual branches under the evaluation criteria top events in each sequence. For example, the sequence represented by a success for each evaluation criteria will have the maximum score of 71.02 (the total of the evaluation criteria weighting factors).

The overall performance of the system is evaluated by multiplying each sequence score by its associated frequency and summing over all sequences. Figure 4 shows a schematic representation of an ISPA model and how overall system performance is quantified.

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria

	Attractive Costs			Flexible Operation				Easy to Build, Handle, and Maintain			
	Low Up Front Development Costs	Affordable Demonstration Costs	Low Life Cycle Costs	Start-Up and Forget	Off Design Power Operation	Multiple Startups and Shutdowns	Operate in a Variety of Environments	Easy to Fabricate	Transportable	Repairable Up Until Launch	Repairable in Orbit
Attributes											
Proven Technology (TFEs)	✓	✓						✓			
Proven Technology (Core Components)	✓	✓						✓			
Redundancy			✓	✓		✓					
TFE Costs		✓	✓								
Telemetry											
Control Sensors and Controller											
Ground Control				✓							
Small Signature							✓				
Specific Radiator Size							✓		✓		
Modularity								✓	✓	✓	✓
Fission Product Release											✓
Shield Performance											✓
Monitoring and Control											
Specific Power											
Standard Connections											
Structural Integrity									✓		
Armor											
Reliability of Power Subsystem											
Reliability of Primary Coolant System											
Reliability of Reactivity Control System											
Reliability of Heat Removal System											
Reliability of Shield/Structural System											
Reliability of Supporting Systems											
Neutron Spectrum (fast or thermal)											

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Attractive Costs			Flexible Operation				Easy to Build, Handle, and Maintain			
	Low Up Front Development Costs	Affordable Demonstration Costs	Low Life Cycle Costs	Start-Up and Forget	Off Design Power Operation	Multiple Startups and Shutdowns	Operate in a Variety of Environments	Easy to Fabricate	Transportable	Repairable Up Until Launch	Repairable in Orbit
Attributes											
TFE Design (multi- or single cell)											
Shutdown Contingencies (Physics Calculations)											
Safety Requirements											
Level 2 Evaluation Criteria											
Multiple Startups and Shutdowns					✓						
Demonstrable Reliability			✓		✓	✓					
Scalable Power											
Radiological Risk											
Key Technology Demonstrated by 10/94											
Development Risk											
Level 1 Evaluation Criteria											
Attractive Cost											
Flexible Operation											
Flexible/Scalable Design											
Safety and Public Acceptance											
Schedule											

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Compatible With Satellite/Mission Objectives					Enhance Survivability of Satellite				Reliable Design	
	Minimal Negative Impact on Satellite	Improve Operational Performance of Satellite	Allow Use of Smaller Launch Vehicle	Ability to Support Secondary Function	Standard Interface for Coupling to Satellite	Avoid Detection	Avoid Attack	Survive Attack	Operate Through Attack	Demonstrable Reliability	No Credible Mission-Ending Single Point Failures
Attributes											
Proven Technology (TFEs)											
Proven Technology (Core Components)											
Redundancy								✓	✓		✓
TFE Costs											
Telemetry											
Control Sensors and Controller											
Ground Control											
Small Signature						✓					
Specific Radiator Size	✓		✓			✓					
Modularity											
Fission Product Release	✓			✓							
Shield Performance	✓										
Monitoring and Control		✓									
Specific Power			✓								
Standard Connections				✓	✓						
Structural Integrity							✓	✓			
Armor								✓	✓		
Reliability of Power Subsystem										✓	
Reliability of Primary Coolant System										✓	
Reliability of Reactivity Control System										✓	
Reliability of Heat Removal System										✓	
Reliability of Shield/Structural System										✓	
Reliability of Supporting Systems										✓	

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Compatible With Satellite/Mission Objectives					Enhance Survivability of Satellite				Reliable Design	
	Minimal Negative Impact on Satellite	Improve Operational Performance of Satellite	Allow Use of Smaller Launch Vehicle	Ability to Support Secondary Function	Standard Interface for Coupling to Satellite	Avoid Detection	Avoid Attack	Survive Attack	Operate Through Attack	Demonstrable Reliability	No Credible Mission-Ending Single Point Failures
Attributes											
Neutron Spectrum (fast of thermal)											
TFE Design (multi- or single cell)											
Shutdown Contingencies (Physics Calcs)											
Safety Requirements											
Level 2 Evaluation Criteria											
Multiple Startups and Shutdowns		✓		✓							
Demonstrable Reliability											
Scalable Power		✓		✓							
Radiological Risk											
Key Technology Demonstrated by 10/94											
Development Risk											
Level 1 Evaluation Criteria											
Attractive Cost											
Flexible Operation											
Flexible/Scalable Design											
Safety and Public Acceptance											
Schedule											

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Flexible/Scalable Design						Safety and Public Acceptance			Schedule	
	Scalable Over Small Power Range With No Design Changes	Scalable Over Medium Power Range With No Technology or Component Design Changes	Scalable Technology Over Large Power Range	Simplicity—Use Common Components Within Same Reactor	Simplicity—Use Common Components While Scaling Power	Ability to Easily Incorporate Technological Advancements	Low Radiological Risk to Biosphere	Saleable to Public (Safety, Cost, Benefit)	Man-Rated	Key Technologies Demonstrated by 10/94	Fly by 10/99
Attributes											
Proven Technology (TFEs)							✓			✓	
Proven Technology (Core Components)										✓	
Redundancy											
TFE Costs											
Telemetry											
Control Sensors and Controller											
Ground Control											
Small Signature											
Specific Radiator Size											
Modularity				✓	✓	✓					
Fission Product Release							✓				
Shield Performance											
Monitoring and Control											
Specific Power											
Standard Connections											
Structural Integrity							✓				
Armor											
Reliability of Power Subsystem											
Reliability of Primary Coolant System											
Reliability of Reactivity Control System											
Reliability of Heat Removal System											
Reliability of Shield/Structural System											
Reliability of Supporting Systems											

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Flexible/Scalable Design						Safety and Public Acceptance			Schedule	
	Scalable Over Small Power Range With No Design Changes	Scalable Over Medium Power Range With No Technology or Component Design Changes	Scalable Technology Over Large Power Range	Simplicity – Use Common Components Within Same Reactor	Simplicity – Use Common Components While Scaling Power	Ability to Easily Incorporate Technological Advancements	Low Radiological Risk to Biosphere	Saleable to Public (Safety, Cost, Benefit)	Man-Rated	Key Technologies Demonstrated by 10/94	Fly by 10/99
Attributes											
Neutron Spectrum (fast of thermal)	✓	✓	✓								
TFE Design (multi- or single cell)	✓	✓	✓		✓						
Shutdown Contingencies (Physics Calcs)							✓				
Safety Requirements							✓				
Level 2 Evaluation Criteria											
Multiple Startups and Shutdowns											
Demonstrable Reliability											
Scalable Power											
Radiological Risk								✓			
Key Technology Demonstrated by 10/94											✓
Development Risk											
Level 1 Evaluation Criteria											
Attractive Cost								✓			✓
Flexible Operation											
Flexible/Scalable Design											
Safety and Public Acceptance											✓
Schedule											

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Acceptable Program Risk			Attractive Lifetime	
	Acceptable Development Risk (High Probability That Development Will Be Successful—Technical, Cost, Schedule)	Performance Must Be Assessable While Satellite is in Orbit	Testable—Full System Qualification and Acceptance	Long Operational Life	Lifetime Tailorable to Mission
Attributes					
Proven Technology (TFEs)	✓				
Proven Technology (Core Components)	✓				
Redundancy					
TFE Costs					
Telemetry		✓			
Control Sensors and Controller		✓			
Ground Control		✓			
Small Signature					
Specific Radiator Size					
Modularity					
Fission Product Release					
Shield Performance					
Monitoring and Control					
Specific Power					
Standard Connections					
Structural Integrity					
Armor					
Reliability of Power Subsystem					
Reliability of Primary Coolant System					
Reliability of Reactivity Control System					
Reliability of Heat Removal System					
Reliability of Shield/Structural System					
Reliability of Supporting Systems					

Table 3. Cross-Reference of Design Attributes and Level 1 and Level 2 Evaluation Criteria (continued)

	Acceptable Program Risk			Attractive Lifetime	
	Acceptable Development Risk (High Probability That Development Will Be Successful—Technical, Cost, Schedule)	Performance Must Be Assessable While Satellite is in Orbit	Testable—Full System Qualification and Acceptance	Long Operational Life	Lifetime Tailorable to Mission
Attributes					
Neutron Spectrum (fast of thermal)					
TFE Design (multi- or single cell)			✓		
Shutdown Contingencies (Physics Calcs)					
Safety Requirements					
Level 2 Evaluation Criteria					
Multiple Startups and Shutdowns					
Demonstrable Reliability	✓				
Scalable Power					
Radiological Risk					
Key Technology Demonstrated by 10/94					
Development Risk					
Level 1 Evaluation Criteria					
Attractive Cost	✓				
Flexible Operation				✓	✓
Flexible/Scalable Design					✓
Safety and Public Acceptance					
Schedule	✓				

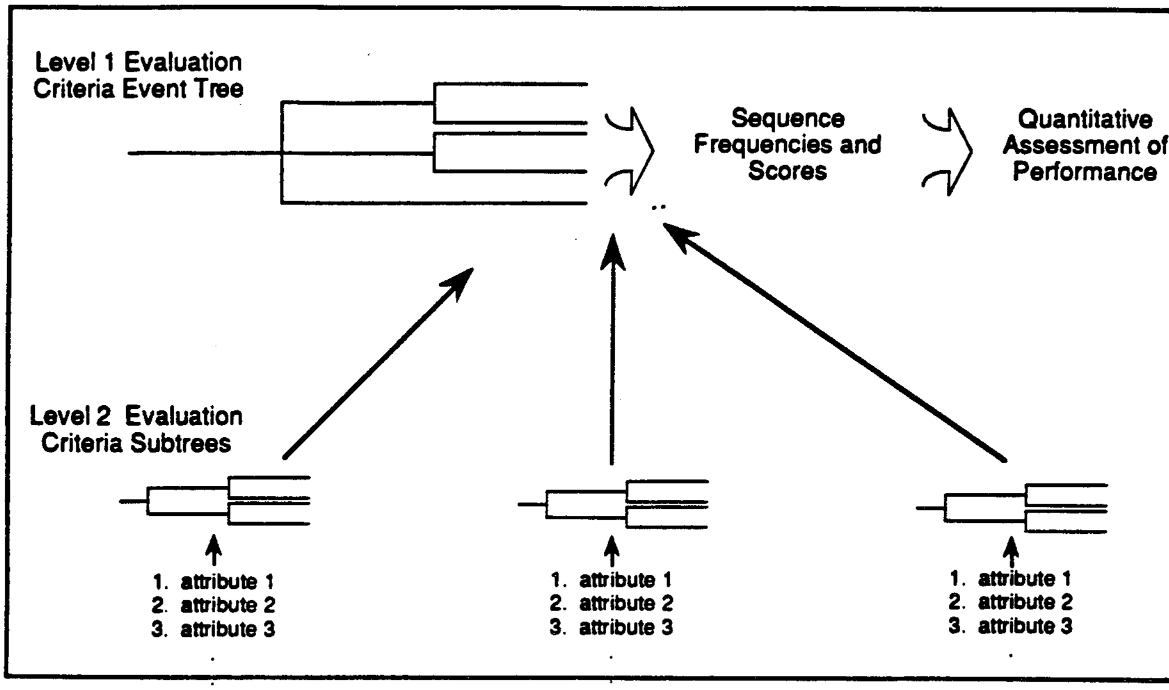


Figure 3. General Framework of the ISPA Model

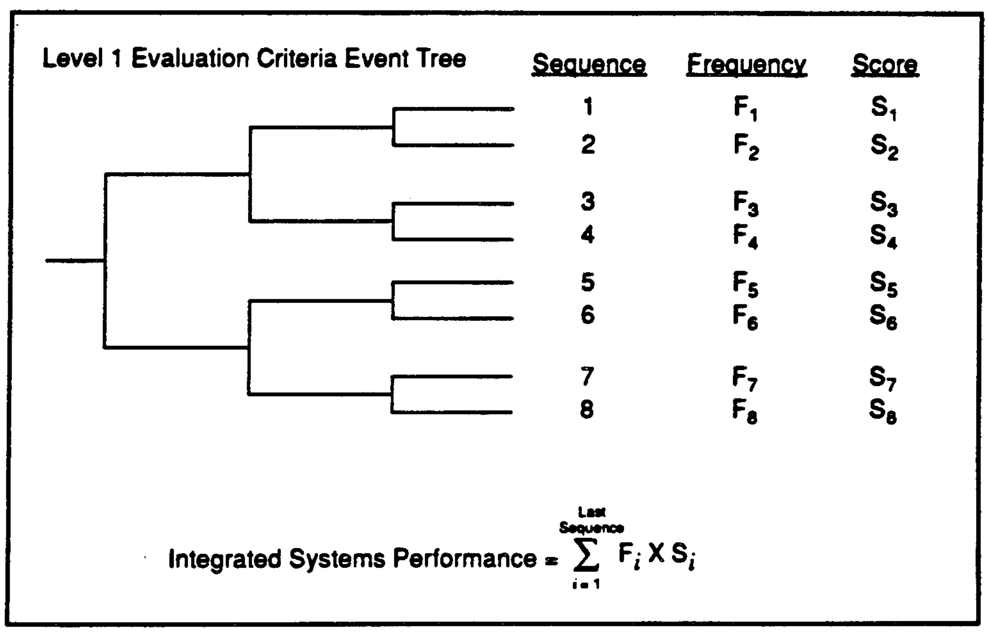


Figure 4. Quantifying Overall System Performance

4.0 RESULTS OF PERFORMANCE ASSESSMENT

Prior to our discussion of the performance assessment results, it is important to note that the split fractions assigned to the branch points representing the physical attributes of this Phase I ISPA model are somewhat arbitrary. The various probabilities that the two space nuclear reactor design concepts will achieve individual design goals have been input by SAIC based on only a limited review of the proposed concepts. Our purpose in this exercise was to illustrate the ISPA concept and produce a model that could provide the starting point for more rigorous evaluation. Therefore, the use of these results as an indicator of performance (i.e., comparing the results of the S-PRIME assessment to the SPACE-R assessment) is inappropriate pending a detailed evaluation of both concepts and formal quantification of the attribute split fractions (Phase II of the ISPA project). However, sensitivity/uncertainty assessments are possible and are provided below to demonstrate the potential of the model to provide insights regarding the importance of the various systems on overall performance.

4.1 Importance Assessment

Table 4 lists the results of the ISPA evaluation for the two proposed space nuclear reactor design concepts; Table 5 lists the success frequencies for each of the eleven evaluation criteria. The data presented in Table 5 provide valuable insights regarding the importance of the evaluation criteria and their potential impact on the overall system performance. The evaluation criterion with the highest weight (or importance) is *Reliable Design*. For both the S-PRIME and SPACE-R concepts, the success frequency is quite high[2] (>90 percent). Because the success frequency is so high, any additional increase in reliability will not likely result in a significant increase in overall system performance. However, looking at the evaluation criterion ranked second (e.g., *Safety and Public Acceptance*), we can see that the success frequency for both design concepts is quite low (~7 to 10 percent). Unlike the reliability evaluation criteria, any increase in the success frequency of the *Safety and Public Acceptance* top event will likely result in a significant increase in overall system performance. This simple application of the ISPA methodology allows the analyst to identify and

2 A design reliability of 95 percent was required by the design specification. Each designer thus attributed this level of reliability to their design. No separate evaluation of this result was made under this effort. The deviation from the original figure results from the subjective assessments made under this effort.

rank the importance or components as they relate to the evaluation criteria, thus providing guidance for the allocation of additional resources or analyses in the most effective manner.

Table 4. Base Case ISPA Results for S-PRIME and SPACE-R

Design	ISPA Result
S-PRIME	16.63
SPACE-R	17.95

Table 5. Success Frequency for the Eleven Evaluation Criteria

	SPACE-R	S-PRIME
Evaluation Criteria	Success Frequency	Success Frequency
Attractive Costs	0.534	0.341
Flexible Operation	0.189	0.171
Easy to Build, Handle, and Maintain	0.158	0.159
Flexible/Scalable Design	0.208	0.354
Compatible with Satellite/Mission Objectives	0.04	0.07
Enhance Survivability of Satellite	0.12	0.108
Reliable Design	0.92	0.912
Safety and Public Acceptance	0.108	0.069
Schedule	0.11	0.069
Acceptable Program Risk	0.09	0.028
Attractive Lifetime	0.04	0.063

4.2 Sensitivity Assessment

Four additional assessments were performed to determine the sensitivity of the overall system performance to uncertain parameters. The SPACE-R concept was arbitrarily selected for the sensitivity assessment; the results are summarized in Table 6. The first sensitivity assessment involved decreasing confidence from 0.95 to 0.5 that the TFE technology is proven. The result was a decrease in overall system performance of 17.3 percent. This significant decrease in the system's performance occurs because of the importance (i.e., high weight assigned) of the *Proven Technology (TFEs)* attribute among the evaluation criteria. Referring to Table 3, we can see that the success or failure of six Level 2 evaluation criteria is dependent on proven TFE technology. These six Level 2 evaluation criteria then affect the success or failure of the following Level 1 evaluation criteria:

- Attractive Costs.
- Easy to Build, Handle, and Maintain.
- Safety and Public Acceptance.
- Schedule.
- Acceptable Program Risk.

Table 6. Results of SPACE-R Sensitivity Assessment

Performance Assessment	Score	Change Relative to Base Case
SPACE-R Base Case	17.95	--
Sensitivity Cases		
Decrease confidence that the TFE technology is proven (from 0.95 to 0.5)	14.84	-17.3%
Decrease confidence that the power subsystem will be reliable (from 0.982 to 0.8)	15.11	-15.8%
Increase confidence that the reactor will have a small signature (from 0.5 to 1.0)	19.88	+10.8%
Increase confidence that there will be mission-ending single point failures (from 0.01 to 0.1)	17.2	-4%
Increase confidence from 0.5 to 0.75 that TFE costs are low and simultaneously decrease confidence that there are no mission-ending single point failures from 0.01 to 0.1	18.39	+2.5%

The second sensitivity assessment once again demonstrates the importance that a single attribute can have on overall system performance. For this calculation, the confidence in the reliability of the power subsystem was decreased from 0.982 to 0.8. This resulted in a decrease in system performance of 15.8 percent.

The final sensitivity assessment was designed to reflect a somewhat more realistic situation in which the effect of multiple dependencies on the overall system performance is not intuitively obvious. The assessment assumed that a proposed decrease in TFE costs (an increase in confidence from 0.5 to 0.75 that the TFE costs will be low) would result in an order of magnitude increase in the probability of a mission-ending single point failure (assumed to be some common mode failure of the TFEs). Because of the multiple levels of dependencies (TFE costs affect the Attractive Costs evaluation criteria that in turn affects several other evaluation criteria, such as Safety and Public Acceptance, and Acceptable Program Risk) and the different weights applied to the various evaluation criteria, the effect of this design trade-off on overall system performance would be extremely difficult (if not impossible) to assess without an integrated model. The result of the ISPA evaluation showed a 2.5 percent increase in overall system performance.

5.0 SUMMARY OF PHASE I ISPA

The goal of Phase I of the PL ISPA project to evaluate space nuclear reactor design concepts is to demonstrate the ISPA methodology and the ability to perform integrated performance assessments where multiple dependencies and significant uncertainties exist. An ISPA model has been developed to evaluate two proposed space nuclear reactor design concepts: S-PRIME and SPACE-R. The weighted criteria for evaluating the performance of the two conceptual designs are based on the results of a QFD exercise in which expert elicitations were used to identify and rank "wants" in a thermionic space power system. The ISPA model considers twenty-eight design attributes and evaluates the success or failure of the evaluation criteria based on the level of confidence the analysts place in each concept to achieve specific design goals. The model is capable of quantitatively evaluating the performance of each design concept in a systematic, self-consistent manner. Dependencies both between the criteria and between components included in the design are represented in the model.

At this phase of the project, a thorough review and independent assessment of the two proposed design concepts has not been performed. The confidence level split fractions input to the model (e.g., the likelihood that the heat rejection system will be reliable, the likelihood that the system will be fully testable, etc.) are estimates based on a preliminary review of the proposed designs. Pending a thorough design review and formal quantification of the ISPA model, any comparison of the S-PRIME performance to the SPACE-R performance based on the material presented herein is inappropriate. However, relative changes in overall performance can be assessed for the purposes of demonstrating the methodology and identifying and evaluating the importance of sensitive or uncertain parameters.

Initial results of the ISPA evaluation indicate that significant impacts on overall system performance can result from relatively small perturbations in confidence related to evaluation criteria that have a low probability of success. Conversely, only limited performance effects will result from relatively large perturbations in confidence related to criteria that initially have a high probability of success. These results provide the analyst with insights into the most effective way to allocate time or resources in efforts associated with improving the design of a SNPS.

The most effective demonstration of the ISPA methodology is in its application as a decision analysis tool to a realistic performance assessment problem. Calculations have been performed that demonstrate the model's ability to effectively quantify the net performance increase or decrease from proposed design changes where those changes influence multiple systems (either in a positive or negative manner) that are not of equal importance. Quantifying the effect of complex design changes or performing design trade-off studies would be extremely difficult without an integrated model.

6.0 PHASES II AND III ISPA

As stated in Section 4.0 of this report, the attribute split fractions (indicting the level of confidence that the outcome is indeed correct) input to the Phase I ISPA model are based on a preliminary review of the two proposed space nuclear reactor design concepts. The practical value of the ISPA approach will only be realized when results obtained from the mechanistic modeling tools applied by the PL (e.g., heat, pipe models, structural analysis, and core neutronics evaluation) are used within this framework. This merger will facilitate a realistic evaluation of the conceptual designs. Use of an integrated framework in this evaluation will help ensure a systematic and self-consistent evaluation of each design. The fact that both designs are evaluated within the same framework will help ensure that the potential for analytical bias will be reduced. Finally, the ability to reflect both the PL's evaluation and the designer's evaluation within a single model framework will allow direct assessment of the impact of modeling differences. This will assist in the direction of future research and development resources toward areas that will provide the greatest payback in terms of reducing technology risk.

Phase II of the ISPA project involves using the model developed under Phase I to quantitatively evaluate the two concepts. This task will involve the following: (1) a thorough review of the ISPA model by PL personnel to ensure that all relevant design attributes and evaluation criteria have been included; (2) a review of the design attribute/evaluation criteria cross-reference matrix to ensure that all dependencies are being modeled correctly; and (3) an analytical evaluation of the two proposed design concepts to facilitate quantification of the design attribute split fractions. Once these three tasks are completed, final quantitative ISPA evaluations will be made. These results will be suitable for direct comparison and should provide PL with valuable insights regarding final selection and design enhancements of a space nuclear reactor concept.

Phase III of the ISPA project involves developing an enhanced ISPA model for one (or both) of the concepts being evaluated. This will be performed by refining the Phase II ISPA model to more accurately represent systems or phenomena identified as sensitive regarding the final performance evaluation. The Phase III enhanced model will be used for complete evaluation of a selected design and the evaluation of design trade-offs. In addition to evaluation of the reactor design concepts, the Phase III ISPA model will also be used to support assessments of the following:

- Design innovations to extend useful lifetime.
- Design changes to enhance reliability.

- Performance with respect to a range of mission applications.
- Effects of design choices on development costs.
- Testing risk, cost, and schedule.

In summary, the Phase I ISPA model should be regarded only as a proof-of-concept study. In keeping with this objective, costs have been held to a minimum. However, the real payback to this modeling initiative will be realized in the actual application.

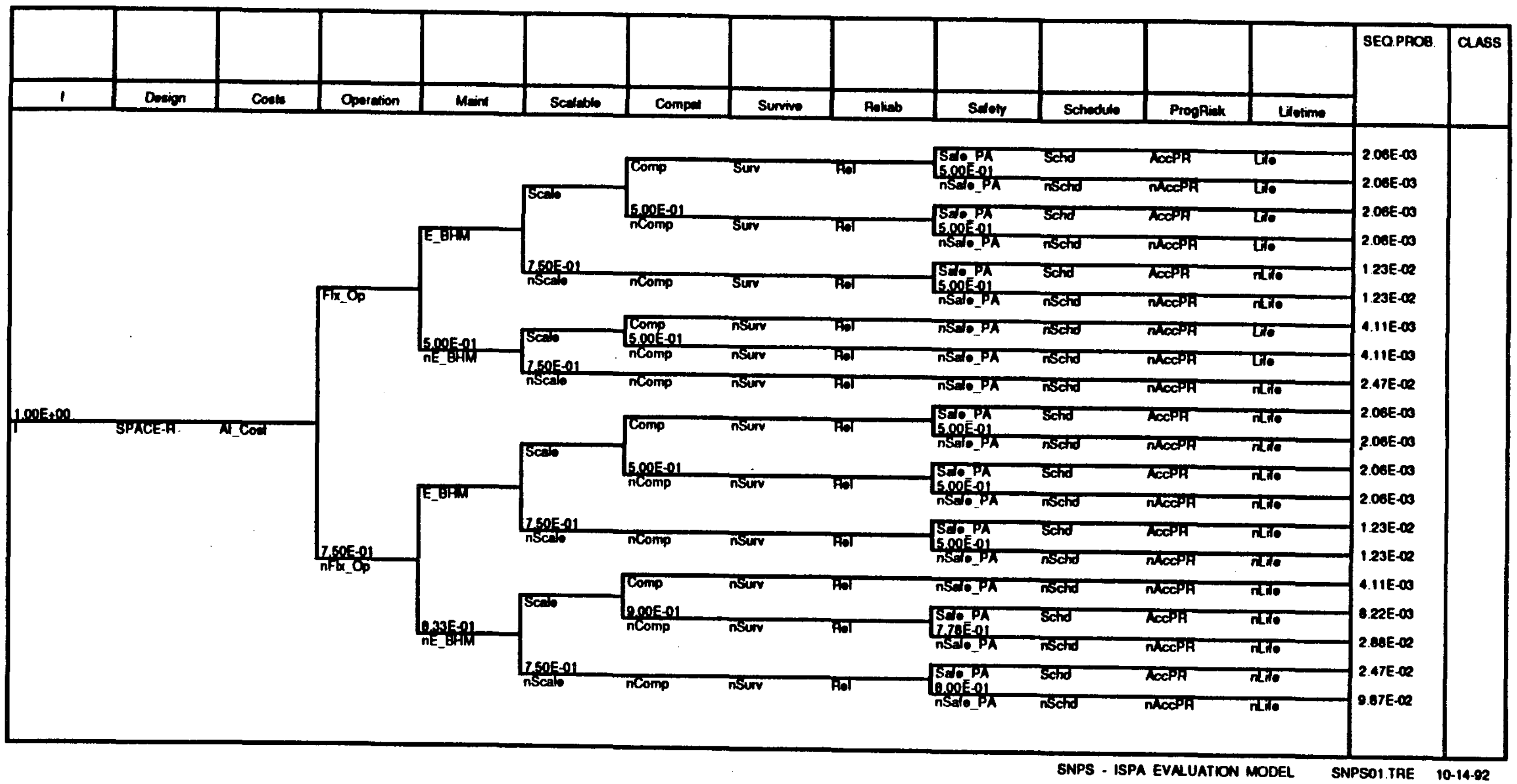


Figure A-1. Level 1 Evaluation Criteria Event Tree

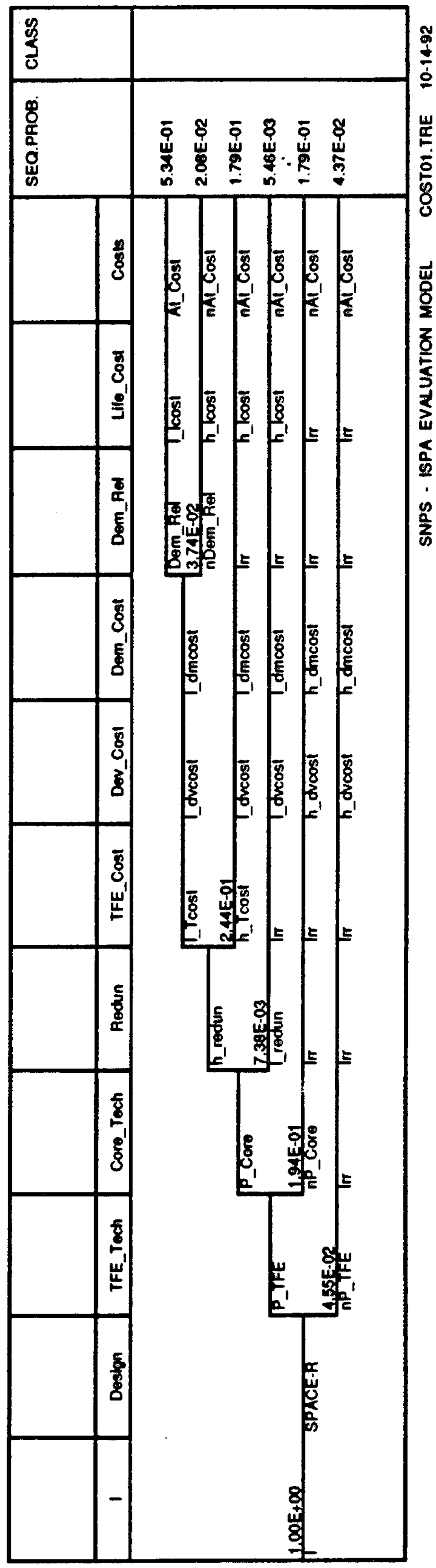


Figure A-2. Attractive Costs Subtree

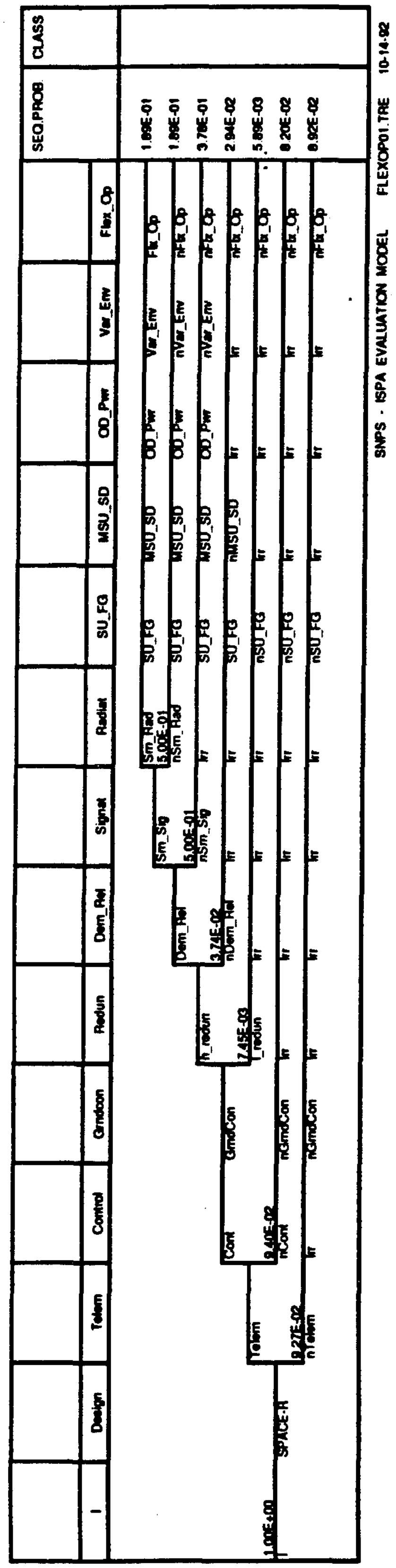


Figure A-3. Flexible Operation Subtree

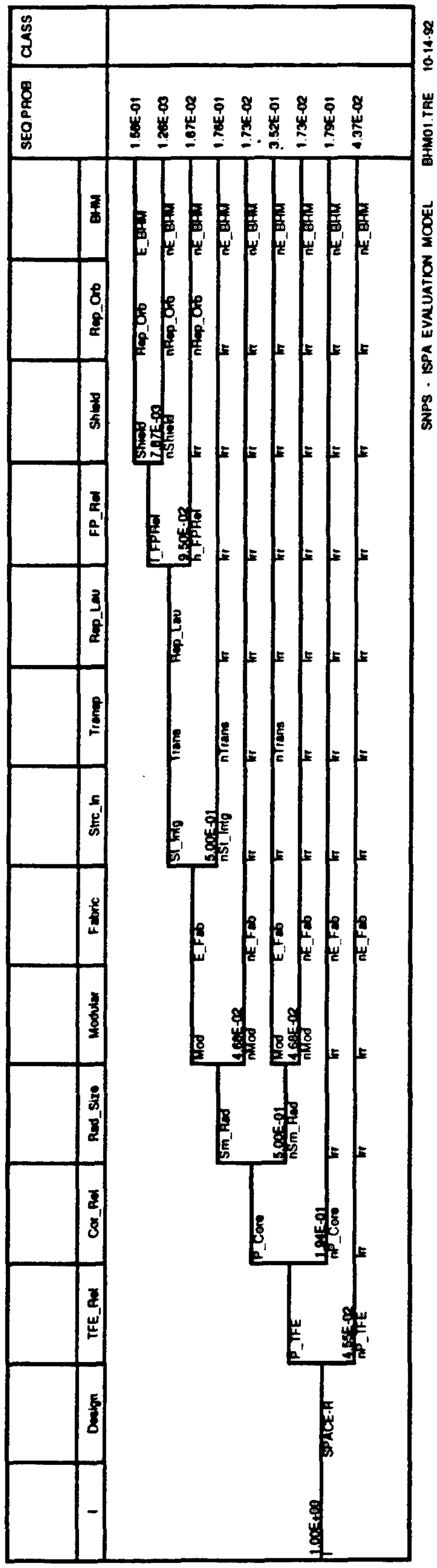


Figure A-4. Easy to Build, Handle, and Maintain Subtree

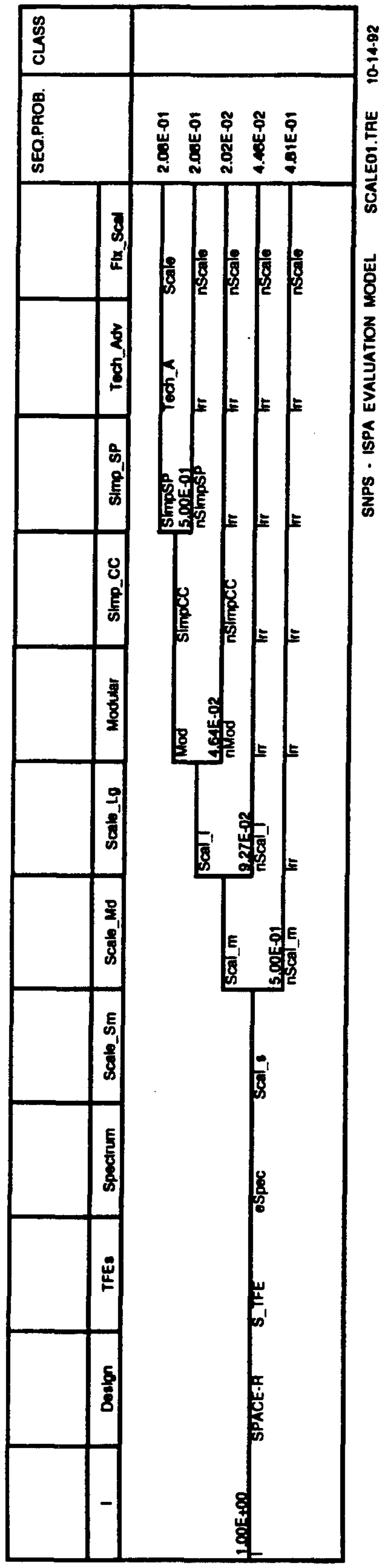


Figure A-5. Scalable Subtree

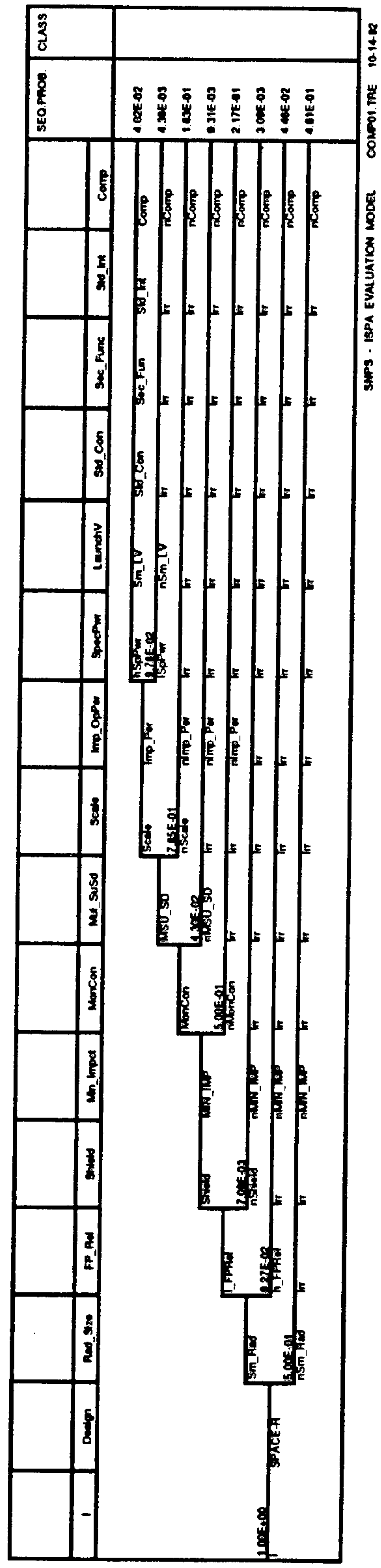


Figure A-6. Compatible with Satellite Subtree

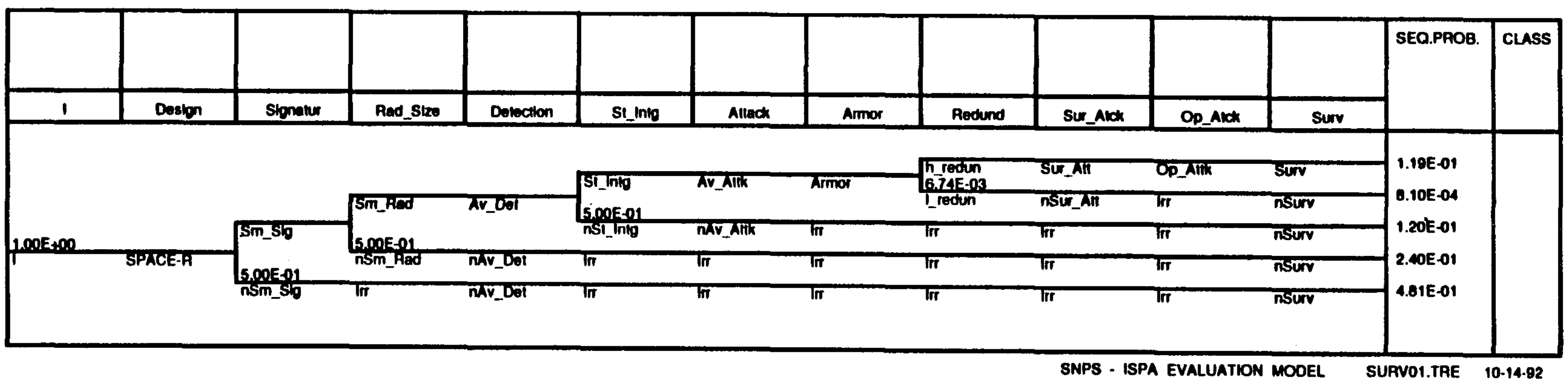


Figure A-7. Survivability Subtree

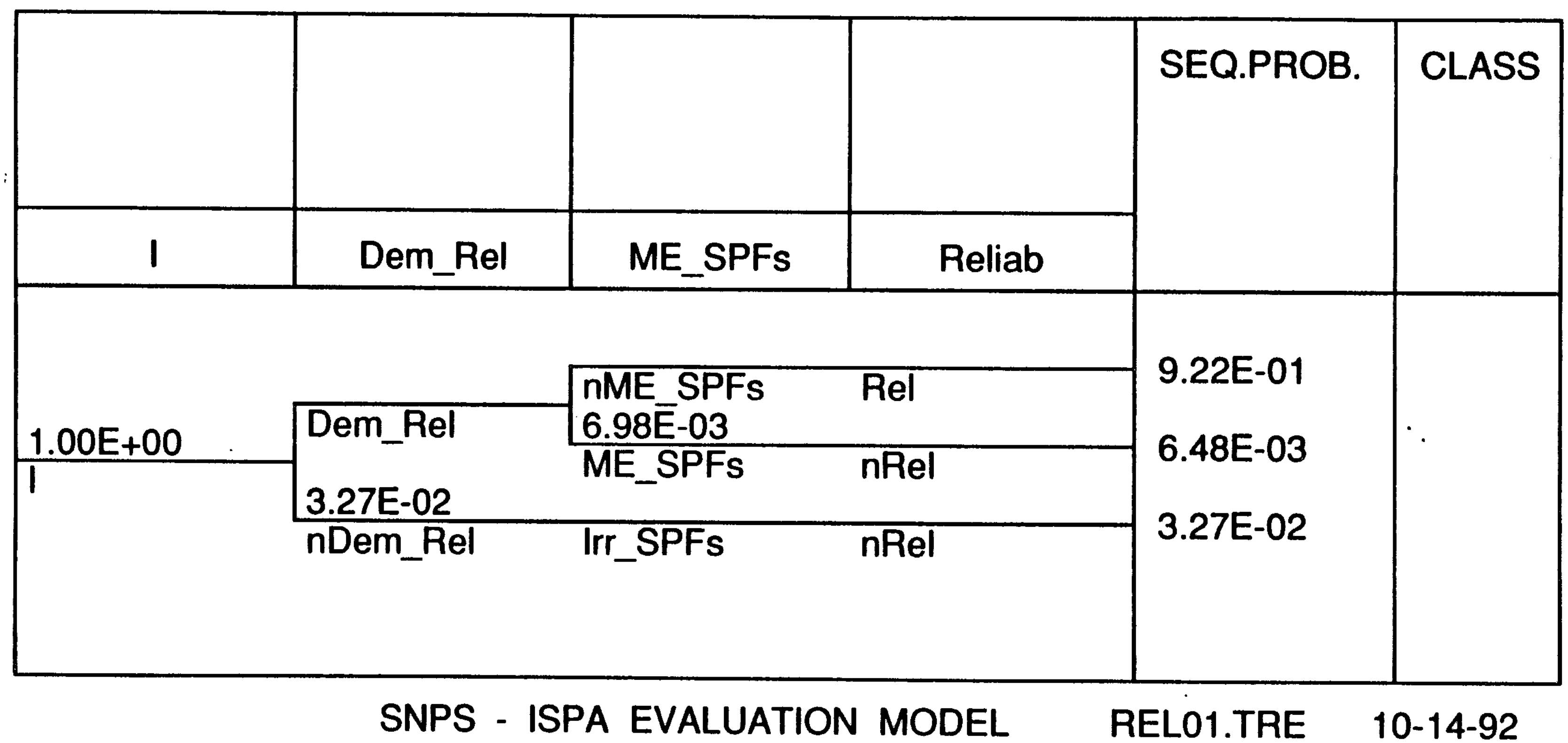


Figure A-8. Reliable Design Subtree

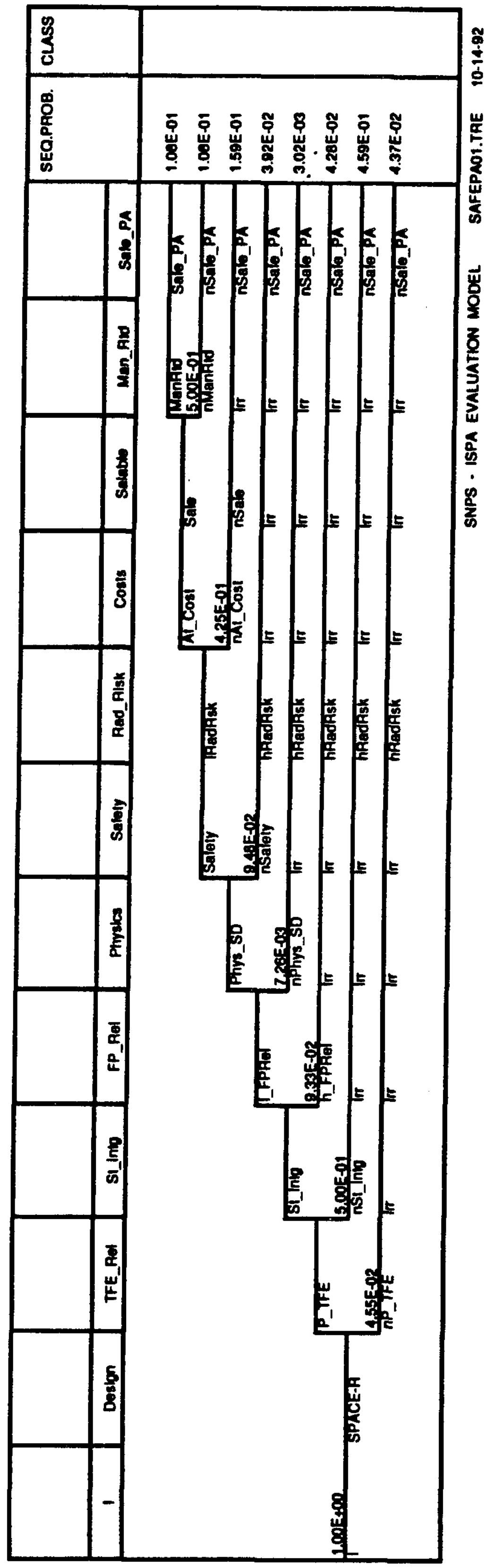


Figure A-9. Safety and Public Acceptance Subtree

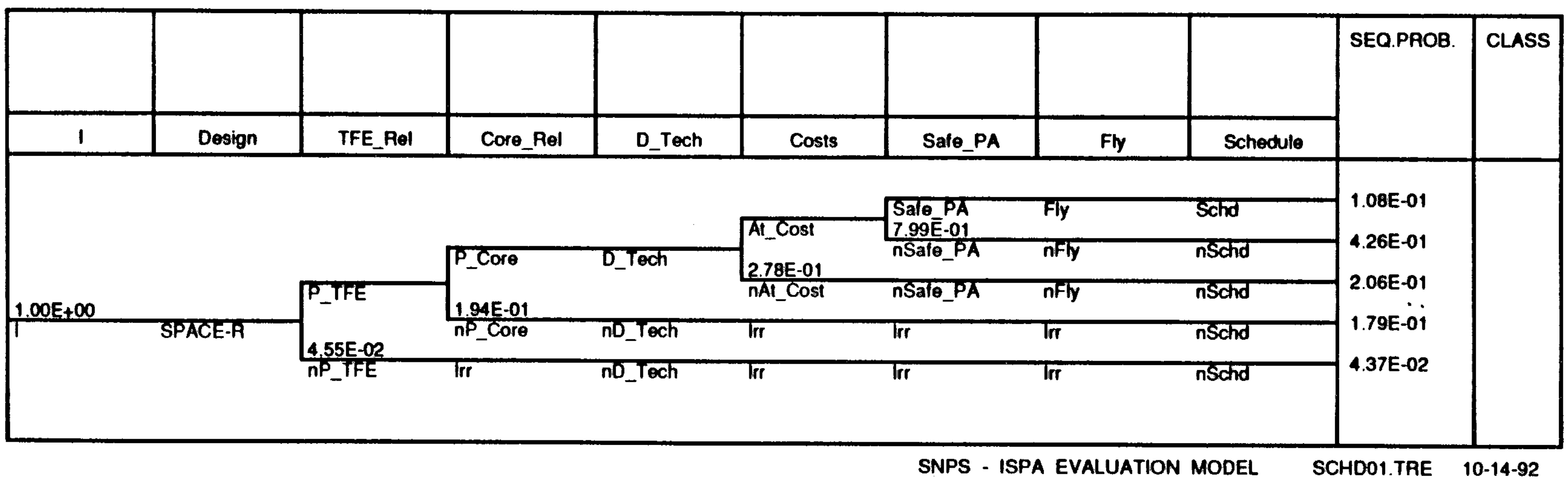


Figure A-10. Schedule Subtree

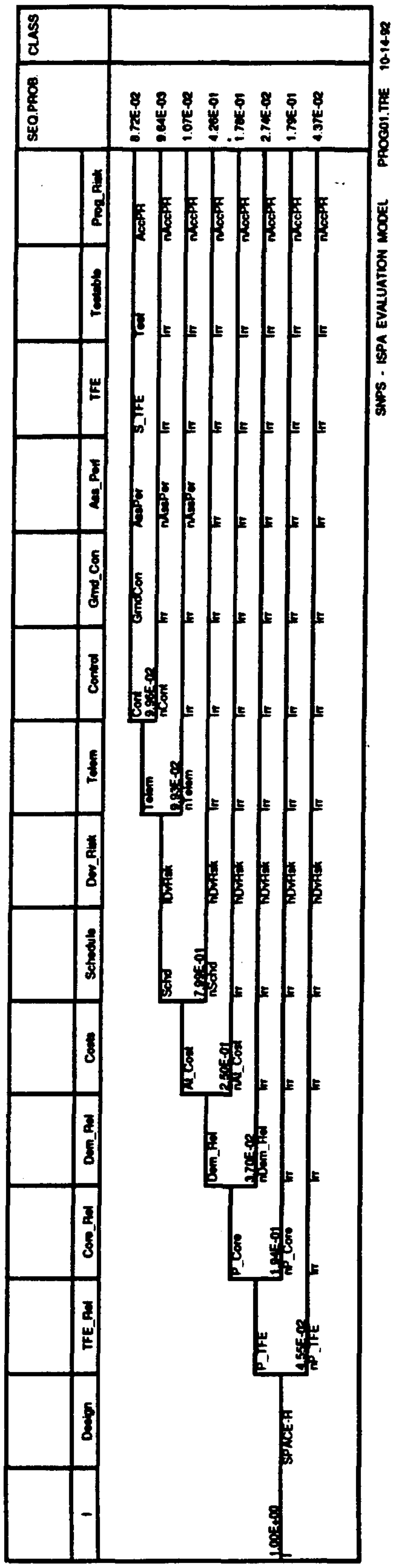
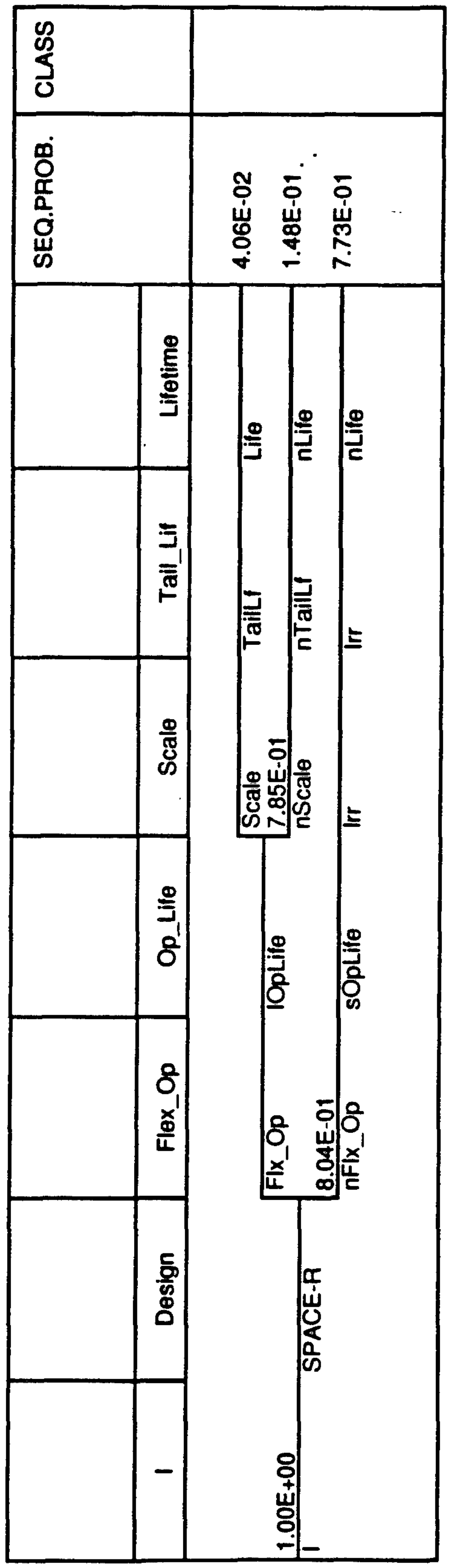


Figure A-11. Acceptable Program Risk Subtree



SNPS - ISPA EVALUATION MODEL LIFE01.TRE 10-14-92

Figure A-12. Attractive Lifetime Subtree

```
SNPS - ISPA EVALUATION MODEL
     77
     NQ
      1    1.000
    SNPS Design Assessment
  1 What is Design Concept?
      2   S-PRIME   SPACE-R
      1         1         2
           0.000     1.000
  2 Is the TFE design multi- or single-cell?
      2     S_TFE     M_TFE
      2         1         2
      3
      1         1
                1
        S-PRIME
           0.000     1.000
      1         1
                2
        SPACE-R
           1.000     0.000
         Otherwise - Not Used
           1.000     0.000
  3 Is the neutron spectrum fast, thermal, or either?
      3     fSpec     tSpec     eSpec
      2         1         2         3
      3
      1         1
                1
        S-PRIME
           0.000     0.000     1.000
      1         1
                2
        SPACE-R
           0.000     0.000     1.000
         Otherwise - Not Used
           1.000     0.000     0.000
  4 Is the TFE technology proven?
      2     P_TFE    nP_TFE
      2         1         2
      3
```

```
    1        1
             1
       S-PRIME
         0.900    0.100
    1        1
             2
       SPACE-R
         0.950    0.050
      Otherwise - Not Used
         1.000    0.000
5 Is the core component technology proven?
    2    P_Core  nP_Core
    2        1        2
    3
    1        1
             1
       S-PRIME
         0.900    0.100
    1        1
             2
       SPACE-R
         0.800    0.200
      Otherwise - Not Used
         1.000    0.000
6 What is the level of redundancy?
    2   h_redun  l_redun
    2        1        2
    3
    1        1
             1
       S-PRIME
         0.900    0.100
    1        1
             2
       SPACE-R
         0.990    0.010
      Otherwise - Not Used
         0.000    1.000
7 What is the reliability of the power subsystem?
    2   Rel_Pwr nRel_Pwr
    2        1        2
    3
```

```
                1        1
                         1
                   S-PRIME
                     0.997    0.003
                1        1
                         2
                   SPACE-R
                     0.982    0.018
                  Otherwise - Not Used
                     1.000    0.000
            8 What is the reliability of the primary coolant system?
                2  Rel_NaK nRel_NaK
                2        1        2
                3
                1        1
                         1
                   S-PRIME
                     0.995    0.005
    $Case  1
                1        1
                         2
                   SPACE-R
                     0.997    0.003
    $Case  2
                  Otherwise - Not Used
                     1.000    0.000
    $Case  3
            9 What is the reliability of the reactivity control
system?
                2   Rel_RC  nRel_RC
                2        1        2
                3
                1        1
                         1
                   S-PRIME
                     0.963    0.037
    $Case  1
                1        1
                         2
                   SPACE-R
                     0.983    0.017
    $Case  2
```

```
                   Otherwise - Not Used
                      1.000    0.000
$Case  3
          10 What is the reliability of the heat removal components?
               2   Rel_HX  nRel_HX
               2        1        2
               3
               1        1
                        1
                  S-PRIME
                    0.995    0.005
$Case  1
               1        1
                        2
                  SPACE-R
                    0.997    0.003
$Case  2
                   Otherwise - Not Used
                      1.000    0.000
$Case  3
          11 What is the reliability of the shield and structures?
               2   Rel_SS  nRel_SS
               2        1        2
               3
               1        1
                        1
                  S-PRIME
                    1.000    0.000
$Case  1
               1        1
                        2
                  SPACE-R
                    0.997    0.003
$Case  2
                   Otherwise - Not Used
                      1.000    0.000
$Case  3
          12 What is the reliability of the supporting systems
(wiring, TFE inte
               2  Rel_Sup nRel_Sup
               2        1        2
               3
```

```
                1         1
                          1
                      S-PRIME
                        0.999    0.001
    $Case   1
                1         1
                          2
                      SPACE-R
                        0.995    0.005
    $Case   2
                     Otherwise - Not Used
                        1.000    0.000
    $Case   3
            13 What is the demonstrable reliability of the design?
                2   Dem_Rel nDem_Rel
                2         1        2
                2
                6         7        8        9        10        11
12
                          1        1        1         1         1
 1
                    Rel_Pwr  Rel_NaK    Rel_RC     Rel_HX     Rel_SS
Rel_Sup
                        1.000    0.000
    $Case   1
                     Otherwise - No Demonstrable Reliability
                        0.000    1.000
    $Case   2
            14 What are the TFE costs?
                2   l_Tcost  h_Tcost
                2         1        2
                3
                1         2
                          1
                        S_TFE
                        0.750    0.250
    $Case   1
                1         2
                          2
                        M_TFE
                        0.500    0.500
    $Case   2
```

```
               Otherwise - Not Used
                  0.000    1.000
$Case  3
          15 Are the up front development costs low?
               2 l_dvcost h_dvcost
               2        1        2
               2
               2        4        5
                        1        1
                  P_TFE   P_Core
                  1.000    0.000
$Case  1
               Otherwise - High Up Front Development Costs
                  0.000    1.000
$Case  3
          16 Are the demonstration costs affordable?
               2 l_dmcost h_dmcost
               2        1        2
               2
               2        4        5
                        1        1
                  P_TFE   P_Core
                  1.000    0.000
$Case  1
               Otherwise - High Demonstration Costs
                  0.000    1.000
$Case  3
          17 Are the life cycle costs < 500/We
               2  l_lcost  h_lcost
               2        1        2
               2
               3        6       13        14
                        1        1         1
                h_redun  Dem_Rel  l_Tcost
                  1.000    0.000
$Case  1
               Otherwise - High Life Cycle Costs
                  0.000    1.000
$Case  2
          18 How attractive are the costs?
               2  At_Cost nAt_Cost
               2        1        2
```

```
                 2
                 3       15       16       17
                          1        1        1
                   l_dvcost l_dmcost  l_lcost
                      1.000    0.000
$Case  1
                   Otherwise - Costs Not Attractive
                      0.000    1.000
$Case  2
             19 Is there adequate telemetry?
                 2    Telem   nTelem
                 2        1        2
                 3
                 1        1
                          1
                   S-PRIME
                      0.900    0.100
$Case  1
                 1        1
                          2
                   SPACE-R
                      0.900    0.100
$Case  2
                   Otherwise - Not Used
                      0.000    1.000
$Case  3
             20 Are the control sensors and controller reliable?
                 2     Cont    nCont
                 2        1        2
                 3
                 1        1
                          1
                   S-PRIME
                      0.900    0.100
$Case  1
                 1        1
                          2
                   SPACE-R
                      0.900    0.100
$Case  2
                   Otherwise - Not Used
```

```
                    0.000     1.000
$Case  3
         21 Are there means for adequate ground control?
              2   GrndCon nGrndCon
              2         1        2
              2
              2        19       20
                        1        1
                    Telem     Cont
                    1.000     0.000
$Case  1
                 Otherwise - Not Adequate Ground Control
                    0.000     1.000
$Case  2
         22 Does the reactor have a small signature?
              2    Sm_Sig  nSm_Sig
              2         1        2
              3
              1         1
                        1
                  S-PRIME
                    0.500     0.500
$Case  1
              1         1
                        2
                  SPACE-R
                    0.500     0.500
$Case  2
                 Otherwise - Not Used
                    0.000     1.000
$Case  3
         23 Is the specific radiator size small?
              2    Sm_Rad  nSm_Rad
              2         1        2
              3
              1         1
                        1
                  S-PRIME
                    0.500     0.500
$Case  1
              1         1
                        2
```

```
                     SPACE-R
                       0.500    0.500
$Case  2
                    Otherwise - Not Used
                       0.000    1.000
$Case  3
             24 Can the reactor operate in start-up and forget mode?
                  2     SU_FG   nSU_FG
                  2         1        2
                  2
                  2         6       21
                            1        1
                      h_redun  GrndCon
                        1.000    0.000
$Case  1
                    Otherwise - No Start-Up and Forget
                       0.000    1.000
$Case  2
             25  Is  the  reactor  capable  of  multiple  startups  and
shutdowns?
                  2    MSU_SD  nMSU_SD
                  2         1        2
                  2
                  2         6       13
                            1        1
                      h_redun  Dem_Rel
                        1.000    0.000
$Case  1
                    Otherwise - No Multiple Startups and Shutdowns
                       0.000    1.000
$Case  2
             26 Is the reactor capable of off-design power operation?
                  2    OD_Pwr  nOD_Pwr
                  2         1        2
                  2
                  2        13       25
                            1        1
                      Dem_Rel   MSU_SD
                        1.000    0.000
$Case  1
                    Otherwise - No Off-Design Power Operation
```

```
                  0.000     1.000
   $Case  2
           27 Is the reactor capable of operating in a variety of
environments?
                 2   Var_Env nVar_Env
                 2         1        2
                 2
                 2        22       23
                           1        1
                      Sm_Sig   Sm_Rad
                       1.000    0.000
   $Case  1
                Otherwise  -  No  Operation  in  a  Variety  of
Environments
                       0.000    1.000
   $Case  2
           28 How flexible is the operation of the reactor?
                 2    Flx_Op  nFlx_Op
                 2         1        2
                 2
                 4        24       25       26       27
                           1        1        1        1
                       SU_FG   MSU_SD   OD_Pwr  Var_Env
                       1.000    0.000
   $Case  1
                Otherwise - No Flexible Operation
                       0.000    1.000
   $Case  2
           29 Is the design modular?
                 2       Mod     nMod
                 2         1        2
                 3
                 1         1
                           1
                     S-PRIME
                       0.900    0.100
   $Case  1
                 1         1
                           2
                     SPACE-R
                       0.950    0.050
   $Case  2
```

```
                Otherwise - Not Used
                   0.000    1.000
$Case  3
          30 Will the reactor be easy to fabricate?
               2    E_Fab   nE_Fab
               2        1        2
               2
               3        4        5        29
                        1        1         1
                    P_TFE   P_Core       Mod
                    1.000    0.000
$Case  1
                Otherwise - Not Easy to Fabricate
                   0.000    1.000
$Case  2
          31 Does the reactor have structural integrity?
               2  St_Intg nSt_Intg
               2        1        2
               3
               1        1
                        1
                  S-PRIME
                    0.500    0.500
$Case  1
               1        1
                        2
                  SPACE-R
                    0.500    0.500
$Case  2
                Otherwise - Not Used
                   0.000    1.000
$Case  3
          32 Is the reactor transportable?
               2    Trans   nTrans
               2        1        2
               2
               3       23       29        31
                        1        1         1
                   Sm_Rad      Mod   St_Intg
                    1.000    0.000
$Case  1
                Otherwise - Not Transportable
```

```
                 0.000    1.000
$Case  2
          33 Is the reactor repairable up until launch?
               2  Rep_Lau nRep_Lau
               2        1        2
               2
               1       29
                        1
                      Mod
                 1.000    0.000
$Case  1
                Otherwise - Not Repairable Up Until Launch
                 0.000    1.000
$Case  2
          34 Will the fission product release be low?
               2  l_FPRel  h_FPRel
               2        1        2
               3
               1        1
                        1
                  S-PRIME
                 0.900    0.100
$Case  1
               1        1
                        2
                  SPACE-R
                 0.900    0.100
$Case  2
                Otherwise - Not Used
                 0.000    1.000
$Case  3
          35 Will the shield performance be adequate?
               2   Shield  nShield
               2        1        2
               3
               1        1
                        1
                  S-PRIME
                 0.990    0.010
$Case  1
               1        1
                        2
```

```
                SPACE-R
                  0.990    0.010
$Case  2
               Otherwise - Not Used
                  0.000    1.000
$Case  3
         36 Is the reactor repairable in orbit?
              2  Rep_Orb nRep_Orb
              2        1        2
              2
              3       29       34       35
                       1        1        1
                     Mod  1_FPRel   Shield
                   1.000    0.000
$Case  1
               Otherwise - Not Repairable In Orbit
                   0.000    1.000
$Case  2
         37 Is the reactor easy to build, handle, and maintain?
              2    E_BHM   nE_BHM
              2        1        2
              2
              4       30       32       33       36
                       1        1        1        1
                   E_Fab    Trans  Rep_Lau  Rep_Orb
                   1.000    0.000
$Case  1
               Otherwise - Not Easy to Build, Handle, and Maintain
                   0.000    1.000
$Case  2
         38 Is the power scalable - small range?
              2   Scal_s  nScal_s
              2        1        2
              2
              2        3        3
                      (2    +    3)
                   tSpec    eSpec
                   1.000    0.000
$Case  1
               Otherwise - Not Scalable - Small Power Range
                   0.000    1.000
$Case  2
```

```
          39 Is the power scalable - medium range?
                2    Scal_m   nScal_m
                2         1         2
                3
                2         3         2
                          3         1
                      eSpec     S_TFE
                      0.500     0.500
$Case   1
                2         3         2
                          3         2
                      eSpec     M_TFE
                      0.900     0.100
$Case   2
                   Otherwise - Not Scalable - Medium Power Range
                      0.000     1.000
$Case   3
          40 Is the power scalable - large range?
                2    Scal_l   nScal_l
                2         1         2
                2
                2         3         3
                         (1    +    3)
                      fSpec     eSpec
                      0.900     0.100
$Case   1
                   Otherwise - Not Scalable - Large Power Range
                      0.000     1.000
$Case   2
          41 Simplicity - Use common components (CC) within same
reactor?
                2    SimpCC   nSimpCC
                2         1         2
                2
                1        29
                          1
                        Mod
                      1.000     0.000
$Case   1
                   Otherwise - No Common Components Within Same Reactor
                      0.000     1.000
$Case   3
```

```
          42 Simplicity - Use common components while scaling power?
                2    SimpSP  nSimpSP
                2         1        2
                3
                2         2       29
                          2        1
                      M_TFE      Mod
                      0.500    0.500
   $Case  1
                2         2       29
                          1        1
                      S_TFE      Mod
                      0.500    0.500
   $Case  2
                   Otherwise - No Common Components While Scaling Power
                      0.000    1.000
   $Case  3
          43 Can the design incorporate technological advances?
                2    Tech_A  nTech_A
                2         1        2
                2
                1        29
                          1
                        Mod
                      1.000    0.000
   $Case  1
                   Otherwise - Can't Incorporate Technological Advances
                      0.000    1.000
   $Case  2
          44 Is the design flexible/scalable?
                2     Scale   nScale
                2         1        2
                2
                6        38       39       40       41       42
43
                          1        1        1        1        1
 1
                    Scal_s   Scal_m   Scal_l   SimpCC   SimpSP
Tech_A
                      1.000    0.000
   $Case  1
                   Otherwise - Not Flexible/Scalable
```

```
                    0.000     1.000
    $Case   2
            45 Is there a minimal negative impact on the satellite?
                 2   MIN_IMP nMIN_IMP
                 2         1        2
                 2
                 3        23       34       35
                           1        1        1
                      Sm_Rad  1_FPRel   Shield
                       1.000    0.000
    $Case   1
                   Otherwise - Negative Impact on Satellite
                       0.000    1.000
    $Case   2
            46 Is there adequate monitoring and control?
                 2    MonCon  nMonCon
                 2         1        2
                 3
                 1         1
                           1
                     S-PRIME
                       0.500    0.500
    $Case   1
                 1         1
                           2
                     SPACE-R
                       0.500    0.500
    $Case   2
                   Otherwise - Not Used
                       0.000    1.000
    $Case   3
            47 Will the reactor improve the operational performance of
the satelli
                 2   Imp_Per nImp_Per
                 2         1        2
                 2
                 3        25       46       44
                           1        1        1
                      MSU_SD   MonCon    Scale
                       1.000    0.000
    $Case   1
```

```
                   Otherwise    -   No   Improvement   in   Operational
Performance
                      0.000    1.000
   $Case  2
           48 Is the specific power high?
                2    hSpPwr   lSpPwr
                2         1        2
                3
                1         1
                          1
                   S-PRIME
                     0.950    0.050
   $Case  1
                1         1
                          2
                   SPACE-R
                     0.900    0.100
   $Case  2
                  Otherwise - Not Used
                     0.000    1.000
   $Case  3
           49 Will the design allow use of a smaller launch vehicle?
                2     Sm_LV   nSm_LV
                2         1        2
                2
                2        23       48
                          1        1
                    Sm_Rad   hSpPwr
                     1.000    0.000
   $Case  1
                  Otherwise - No Smaller Launch Vehicle
                     0.000    1.000
   $Case  2
           50 Are the connections used standard?
                2  Std_Con nStd_Con
                2         1        2
                3
                1         1
                          1
                   S-PRIME
                     1.000    0.000
   $Case  1
```

```
                1       1
                        2
                  SPACE-R
                    1.000    0.000
   $Case   2
                 Otherwise - Not Used
                    0.000    1.000
   $Case   3
           51 Does the design have the ability to support a secondary
function?
                2  Sec_Fun nSec_Fun
                2        1        2
                2
                4       25       34       44       50
                         1        1        1        1
                    MSU_SD  1_FPRel    Scale  Std_Con
                     1.000    0.000
   $Case   1
                 Otherwise - Can't Support a Secondary Function
                     0.000    1.000
   $Case   2
           52  Is  there  a  standard  interface  for  coupling  to  the
satellite?
                2  Std_Int nStd_Int
                2        1        2
                2
                1       50
                         1
                   Std_Con
                     1.000    0.000
   $Case   1
                 Otherwise - No Standard Interface
                     0.000    1.000
   $Case   2
           53 How compatible with satellite/mission objectives?
                2     Comp     nComp
                2        1        2
                2
                5       45       47       49       51       52
                         1        1        1        1        1
                   MIN_IMP  Imp_Per    Sm_LV  Sec_Fun  Std_Int
```

```
                     1.000    0.000
   $Case  1
                  Otherwise - Not Compatible with Satellite/Mission
Objectives
                     0.000    1.000
   $Case  2
              54 Is the design capable of avoiding detection?
                   2   Av_Det  nAv_Det
                   2        1        2
                   2
                   2       22       23
                            1        1
                       Sm_Sig   Sm_Rad
                        1.000    0.000
   $Case  1
                  Otherwise - Not Capable of Avoiding Detection
                        0.000    1.000
   $Case  2
              55 Is the design capable of avoiding attack?
                   2  Av_Attk nAv_Attk
                   2        1        2
                   2
                   1       31
                            1
                     St_Intg
                        1.000    0.000
   $Case  1
                  Otherwise - Not Capable of Avoiding Attack
                        0.000    1.000
   $Case  2
              56 Is the reactor armor adequate?
                   2    Armor   nArmor
                   2        1        2
                   3
                   1        1
                            1
                     S-PRIME
                        1.000    0.000
   $Case  1
                   1        1
                            2
                     SPACE-R
```

```
                1.000     0.000
$Case  2
             Otherwise - Not Used
                0.000     1.000
$Case  3
         57 Is the design capable of surviving attack?
              2   Sur_Att nSur_Att
              2         1        2
              2
              3         6       31        56
                        1        1         1
                  h_redun  St_Intg     Armor
                    1.000    0.000
$Case  1
             Otherwise - Not Capable of Surviving Attack
                0.000     1.000
$Case  2
         58 Is the design capable of operating through an attack?
              2   Op_Attk nOp_Attk
              2         1        2
              2
              2         6       56
                        1        1
                  h_redun    Armor
                    1.000    0.000
$Case  1
             Otherwise - Not Capable of Operating Through an
Attack
                0.000     1.000
$Case  2
         59 What is the status of survivability?
              2      Surv    nSurv
              2         1        2
              2
              4        54       55        57        58
                        1        1         1         1
                   Av_Det  Av_Attk   Sur_Att   Op_Attk
                    1.000    0.000
$Case  1
             Otherwise - Not Survivable
                0.000     1.000
$Case  2
```

```
        60 Are there any credible mission-ending single point
failures?
                2   ME_SPFs nME_SPFs
                2         1        2
                3
                1         1
                          1
                    S-PRIME
                      0.010    0.990
   $Case  1
                1         1
                          2
                    SPACE-R
                      0.010    0.990
   $Case  2
                   Otherwise - Not Used
                      1.000    0.000
   $Case  3
        61 Is the overall system reliable?
                2       Rel      nRel
                2         1        2
                2
                2        13       60
                          1        2
                    Dem_Rel nME_SPFs
                      1.000    0.000
   $Case  1
                   Otherwise - Not Reliable
                      0.000    1.000
   $Case  2
        62 Can the reactor be shut down under all conditions
(physics calcs)?
                2   Phys_SD nPhys_SD
                2         1        2
                3
                1         1
                          1
                    S-PRIME
                      0.990    0.010
   $Case  1
                1         1
                          2
```

```
                 SPACE-R
                   0.990    0.010
   $Case  2
                Otherwise - Not Used
                   1.000    0.000
   $Case  3
           63 Does the design meet all preset safety requirements?
                2   Safety  nSafety
                2        1        2
                3
                1        1
                         1
                  S-PRIME
                   0.900    0.100
   $Case  1
                1        1
                         2
                  SPACE-R
                   0.900    0.100
   $Case  2
                Otherwise - Not Used
                   1.000    0.000
   $Case  3
           64 Is the radiological risk to the biosphere low?
                2  lRadRsk  hRadRsk
                2        1        2
                2
                5        4       31       34       62       63
                         1        1        1        1        1
                     P_TFE  St_Intg  l_FPRel  Phys_SD   Safety
                     1.000    0.000
   $Case  1
                Otherwise - Possible High Radiological Risk to
Biosphere
                     0.000    1.000
   $Case  2
           65 Is the design concept salable to the public (safety,
cost, benefit)
                2     Sale     nSale
                2        1        2
                2
                2       18       64
```

```
                      1         1
                At_Cost  1RadRsk
                  1.000    0.000
   $Case  1
               Otherwise - Not Salable to the Public
                  0.000    1.000
   $Case  2
               6 6    I s    t h e    d e s i g n    M a n - R a t e d ?
????????????????????????????????????
              2   ManRtd  nManRtd
              2        1        2
              3
              1        1
                       1
                S-PRIME
                  0.500    0.500
   $Case  1
              1        1
                       2
                SPACE-R
                  0.500    0.500
   $Case  2
               Otherwise - Not Used
                  1.000    0.000
   $Case  3
          67 What is the safety and public acceptance?
              2  Safe_PA nSafe_PA
              2        1        2
              2
              3       64       65       66
                       1        1        1
                1RadRsk     Sale   ManRtd
                  1.000    0.000
   $Case  1
               Otherwise - No Safety or Public Acceptance
                  0.000    1.000
   $Case  2
          68 Will key technologies be demonstrated by 10/94?
              2   D_Tech  nD_Tech
              2        1        2
              2
              2        4        5
```

```
                    1        1
                 P_TFE    P_Core
                 1.000     0.000
  $Case  1
               Otherwise - Key Technologies Not Demonstrated by
10/94
                 0.000     1.000
  $Case  2
           69 Will the reactor fly by 10/99?
                2       Fly      nFly
                2         1         2
                2
                3        18        67        68
                          1         1         1
                At_Cost  Safe_PA   D_Tech
                 1.000     0.000
  $Case  1
               Otherwise - Will Not Fly by 10/99
                 0.000     1.000
  $Case  2
           70 Will the design meet the schedule?
                2      Schd     nSchd
                2         1         2
                2
                2        68        69
                          1         1
                 D_Tech       Fly
                 1.000     0.000
  $Case  1
               Otherwise - Schedule Not  Met
                 0.000     1.000
  $Case  2
           71 Is the development risk acceptable (technical, cost,
schedule)?
                2    lDvRsk    hDvRsk
                2         1         2
                2
                5         4         5        13        18        70
                          1         1         1         1         1
                 P_TFE    P_Core   Dem_Rel   At_Cost      Schd
                 1.000     0.000
  $Case  1
```

```
                    Otherwise - High Development Risk
                       0.000    1.000
  $Case  2
              72 Is the performance assessable while the satellite is in
orbit?
                  2    AssPer  nAssPer
                  2         1        2
                  2
                  3        19       20       21
                            1        1        1
                        Telem     Cont  GrndCon
                        1.000    0.000
  $Case  1
                    Otherwise - Performance Not Assessable
                       0.000    1.000
  $Case  2
              73 Is the design testable - full system qualification and
acceptance?
                  2      Test    nTest
                  2         1        2
                  3
                  1         2
                            1
                        S_TFE
                        1.000    0.000
  $Case  1
                  1         2
                            2
                        M_TFE
                        0.500    0.500
  $Case  2
                    Otherwise - Not Used
                       0.000    1.000
  $Case  3
              74 Is the program risk acceptable?
                  2     AccPR   nAccPR
                  2         1        2
                  2
                  3        71       72       73
                            1        1        1
                       lDvRsk   AssPer     Test
```

```
                    1.000     0.000
$Case  1
                Otherwise - Program Risk Not Acceptable
                    0.000     1.000
$Case  2
          75 Is operational life long?
              2  lOpLife  sOpLife
              2        1        2
              2
              1       28
                       1
                Flx_Op
                 1.000     0.000
$Case  1
                Otherwise - Short Operational Lifetime
                    0.000     1.000
$Case  2
          76 Is the lifetime tailorable to the mission?
              2   TailLf  nTailLf
              2        1        2
              2
              2       28       44
                       1        1
                Flx_Op     Scale
                 1.000     0.000
$Case  1
                Otherwise - Lifetime Not Tailorable to Mission
                    0.000     1.000
$Case  2
          77 Is the design lifetime attractive?
              2     Life    nLife
              2        1        2
              2
              2       75       76
                       1        1
               lOpLife    TailLf
                 1.000     0.000
$Case  1
                Otherwise - Lifetime Not Attractive
                    0.000     1.000
$Case  2
```

Binners

```
          SNPS Scoring Binning Input
           12          Design     Costs  Operation    Maint  Scalable
Compat
                     Survive     Reliab     Safety  Schedule  ProgRisk
Lifetime
            2    2   S-PRIME   SPACE-R

            1    1         1
                           1
                     S-PRIME
            1    2         1
                           2
                     SPACE-R
            2    2   At_Cost nAt_Cost
            1    1        18
                           1
                     At_Cost
            1    2        18
                           2
                    nAt_Cost
            2    2    Flx_Op  nFlx_Op
            1    1        28
                           1
                      Flx_Op
            1    2        28
                           2
                     nFlx_Op
            2    2     E_BHM   nE_BHM
            1    1        37
                           1
                       E_BHM
            1    2        37
                           2
                      nE_BHM
            2    2     Scale   nScale
            1    1        44
                           1
                       Scale
            1    2        44
```

```
             2
        nScale
2   2     Comp     nComp
1   1       53
             1
          Comp
1   2       53
             2
         nComp
2   2     Surv     nSurv
1   1       59
             1
          Surv
1   2       59
             2
         nSurv
2   2      Rel      nRel
1   1       61
             1
           Rel
1   2       61
             2
          nRel
2   2  Safe_PA nSafe_PA
1   1       67
             1
       Safe_PA
1   2       67
             2
      nSafe_PA
2   2     Schd     nSchd
1   1       70
             1
          Schd
1   2       70
             2
         nSchd
2   2    AccPR    nAccPR
1   1       74
             1
         AccPR
1   2       74
```

```
                     2
                nAccPR
        2   2     Life    nLife
        1   1       77
                     1
                  Life
        1   2       77
                     2
                 nLife
        1
       12   1        2        3        4        5        6
  7     8
            9       10       11       12
      SORT FOR 12 SCORING TOP EVENTS

      SNPS Costs Binning Input
       10          Design  TFE_Tech  Core_Tech    Redun  TFE_Cost
Dev_Cost
              Dem_Cost  Dem_Rel Life_Cost    Costs
        2   2  S-PRIME   SPACE-R

        1   1        1
                     1
               S-PRIME
        1   2        1
                     2
               SPACE-R
        2   2    P_TFE   nP_TFE
        1   1        4
                     1
                 P_TFE
        1   2        4
                     2
                nP_TFE
        3   3   P_Core  nP_Core      Irr
        1   3        4
                     2
                nP_TFE
        1   1        5
                     1
                P_Core
        1   2        5
```

```
                 2
          nP_Core
3    3    h_redun  l_redun        Irr
2    3          4        5
                2    +   2
           nP_TFE  nP_Core
1    1          6
                1
          h_redun
1    2          6
                2
          l_redun
3    3    l_Tcost h_Tcost        Irr
3    3          4        5         6
                2    +   2    +    2
           nP_TFE  nP_Core   l_redun
1    1         14
                1
          l_Tcost
1    2         14
                2
          h_Tcost
2    2  l_dvcost h_dvcost
1    1         15
                1
         l_dvcost
1    2         15
                2
         h_dvcost
2    2  l_dmcost h_dmcost
1    1         16
                1
         l_dmcost
1    2         16
                2
         h_dmcost
3    3   Dem_Rel nDem_Rel        Irr
4    3          4        5         6        14
                2    +   2    +    2    +    2
           nP_TFE  nP_Core   l_redun   h_Tcost
1    1         13
                1
```

```
                    Dem_Rel
          1    2          13
                           2
                  nDem_Rel
          3    3   l_lcost  h_lcost         Irr
          2    3          15        16
                           2    +    2
                  h_dvcost h_dmcost
          1    1          17
                           1
                   l_lcost
          1    2          17
                           2
                   h_lcost
          2    2   At_Cost nAt_Cost
          1    1          18
                           1
                   At_Cost
          1    2          18
                           2
                  nAt_Cost
          1
         10    1           2         3         4         5         6
  7     8
               9          10
        SORT FOR 10 COST TOP EVENTS

        SNPS Flexible Operation Binning Input
         13           Design      Telem    Control   Grndcon      Redun
Dem_Rel
                       Signat     Radiat      SU_FG    MSU_SD     OD_Pwr
Var_Env
                      Flex_Op
          2    2      S-PRIME   SPACE-R
          1    1            1
                            1
                      S-PRIME
          1    2            1
                            2
                      SPACE-R
          2    2        Telem   nTelem
          1    1           19
```

		1		
		Telem		
1	2	19		
		2		
		nTelem		
3	3	Cont	nCont	Irr
1	3	19		
		2		
		nTelem		
1	1	20		
		1		
		Cont		
1	2	20		
		2		
		nCont		
2	2	GrndCon	nGrndCon	
1	1	21		
		1		
		GrndCon		
1	2	21		
		2		
		nGrndCon		
3	3	h_redun	l_redun	Irr
1	3	21		
		2		
		nGrndCon		
1	1	6		
		1		
		h_redun		
1	2	6		
		2		
		l_redun		
3	3	Dem_Rel	nDem_Rel	Irr
2	3	21	6	
		2	+ 2	
		nGrndCon	l_redun	
1	1	13		
		1		
		Dem_Rel		
1	2	13		
		2		
		nDem_Rel		

```
3    3    Sm_Sig  nSm_Sig       Irr
3    3        21        6        13
               2   +    2   +     2
        nGrndCon  l_redun  nDem_Rel
1    1        22
               1
          Sm_Sig
1    2        22
               2
         nSm_Sig
3    3    Sm_Rad  nSm_Rad       Irr
4    3        21        6        13        22
               2   +    2   +     2   +     2
        nGrndCon  l_redun  nDem_Rel   nSm_Sig
1    1        23
               1
          Sm_Rad
1    2        23
               2
         nSm_Rad
2    2     SU_FG   nSU_FG
1    1        24
               1
           SU_FG
1    2        24
               2
          nSU_FG
3    3    MSU_SD  nMSU_SD       Irr
1    3        24
               2
          nSU_FG
1    1        25
               1
          MSU_SD
1    2        25
               2
         nMSU_SD
3    3    OD_Pwr  nOD_Pwr       Irr
2    3        24       25
               2   +    2
          nSU_FG  nMSU_SD
1    1        26
```

```
                  1
              OD_Pwr
1    2           26
                  2
            nOD_Pwr
3    3      Var_Env  nVar_Env        Irr
3    3           24        25         26
                  2    +    2    +     2
             nSU_FG   nMSU_SD    nOD_Pwr
1    1           27
                  1
            Var_Env
1    2           27
                  2
           nVar_Env
2    2       Flx_Op   nFlx_Op
1    1           28
                  1
             Flx_Op
1    2           28
                  2
            nFlx_Op
1
13   1            2         3          4          5          6
     7            8         9         10         11         12
    13
SORT FOR 13 FLEXIBLE OPERATION TOP EVENTS

SNPS Easy to Build, Handle, and Maintain Binning Input
 13          Design    TFE_Rel    Cor_Rel   Rad_Size   Modular
Fabric
            Strc_In     Transp    Rep_Lau     FP_Rel     Shield
Rep_Orb
                BHM
2    2      S-PRIME   SPACE-R
1    1            1
                  1
            S-PRIME
1    2            1
                  2
            SPACE-R
2    2        P_TFE     nP_TFE
```

1	1	4		
		1		
		P_TFE		
1	2	4		
		2		
		nP_TFE		
3	3	P_Core	nP_Core	Irr
1	3	4		
		2		
		nP_TFE		
1	1	5		
		1		
		P_Core		
1	2	5		
		2		
		nP_Core		
3	3	Sm_Rad	nSm_Rad	Irr
2	3	4	5	
		2	+ 2	
		nP_TFE	nP_Core	
1	1	23		
		1		
		Sm_Rad		
1	2	23		
		2		
		nSm_Rad		
3	3	Mod	nMod	Irr
2	3	4	5	
		2	+ 2	
		nP_TFE	nP_Core	
1	1	29		
		1		
		Mod		
1	2	29		
		2		
		nMod		
2	2	E_Fab	nE_Fab	
1	1	30		
		1		
		E_Fab		
1	2	30		
		2		

```
            nE_Fab
3    3    St_Intg  nSt_Intg         Irr
2    3         30        23
                2    +    2
           nE_Fab   nSm_Rad
1    1         31
                1
          St_Intg
1    2         31
                2
         nSt_Intg
3    3      Trans    nTrans         Irr
1    3         30
                2
           nE_Fab
1    1         32
                1
            Trans
1    2         32
                2
           nTrans
3    3    Rep_Lau  nRep_Lau         Irr
2    3         30        32
                2    +    2
           nE_Fab    nTrans
1    1         33
                1
          Rep_Lau
1    2         33
                2
         nRep_Lau
3    3    l_FPRel   h_FPRel         Irr
3    3         30        32          33
                2    +    2    +      2
           nE_Fab    nTrans    nRep_Lau
1    1         34
                1
          l_FPRel
1    2         34
                2
          h_FPRel
3    3     Shield   nShield         Irr
```

```
          4    3        30        32        33        34
                         2    +    2    +    2    +    2
                    nE_Fab    nTrans nRep_Lau   h_FPRel
          1    1        35
                         1
                    Shield
          1    2        35
                         2
                   nShield
          3    3   Rep_Orb nRep_Orb        Irr
          3    3        30        32        33
                         2    +    2    +    2
                    nE_Fab    nTrans nRep_Lau
          1    1        36
                         1
                   Rep_Orb
          1    2        36
                         2
                  nRep_Orb
          2    2     E_BHM    nE_BHM
          1    1        37
                         1
                     E_BHM
          1    2        37
                         2
                    nE_BHM
          1
         13    1         2         3         4         5         6
               7         8         9        10        11        12
              13
         SORT FOR 13 EASY TO BUILD, HANDLE, AND MAINTAIN TOP EVENTS

         SNPS Flexible/Scalable Design Binning Input
          11            Design        TFEs  Spectrum  Scale_Sm  Scale_Md
Scale_Lg
                   Modular   Simp_CC   Simp_SP Tech_Adv Flx_Scal
          2    2   S-PRIME   SPACE-R
          1    1         1
                         1
                   S-PRIME
          1    2         1
                         2
```

```
              SPACE-R
2      2        S_TFE     M_TFE
1      1            2
                    1
                S_TFE
1      2            2
                    2
                M_TFE
3      3        fSpec     tSpec      eSpec
1      1            3
                    1
                fSpec
1      2            3
                    2
                tSpec
1      3            3
                    3
                eSpec
2      2       Scal_s   nScal_s
1      1           38
                    1
               Scal_s
1      2           38
                    2
              nScal_s
3      3       Scal_m   nScal_m        Irr
1      3           38
                    2
              nScal_s
1      1           39
                    1
               Scal_m
1      2           39
                    2
              nScal_m
3      3       Scal_l   nScal_l        Irr
2      3           38        39
                    2   +     2
              nScal_s   nScal_m
1      1           40
                    1
               Scal_l
```

```
1    2        40
               2
         nScal_l
3    3       Mod      nMod       Irr
3    3        38        39        40
               2   +     2   +     2
         nScal_s   nScal_m   nScal_l
1    1        29
               1
             Mod
1    2        29
               2
            nMod
3    3    SimpCC   nSimpCC       Irr
3    3        38        39        40
               2   +     2   +     2
         nScal_s   nScal_m   nScal_l
1    1        41
               1
          SimpCC
1    2        41
               2
         nSimpCC
3    3    SimpSP   nSimpSP       Irr
4    3        38        39        40        41
               2   +     2   +     2   +     2
         nScal_s   nScal_m   nScal_l   nSimpCC
1    1        42
               1
          SimpSP
1    2        42
               2
         nSimpSP
3    3    Tech_A   nTech_A       Irr
5    3        38        39        40        41        42
               2   +     2   +     2   +     2   +     2
         nScal_s   nScal_m   nScal_l   nSimpCC   nSimpSP
1    1        43
               1
          Tech_A
1    2        43
               2
```

```
                  nTech_A
    2     2         Scale    nScale
    1     1            44
                        1
                    Scale
    1     2            44
                        2
                   nScale
    1
   11     1             2         3         4         5         6
          7             8         9        10        11
   SORT FOR 11 FLEXIBLE/SCALABLE DESIGN TOP EVENTS

   SNPS Compatability With Satellite/Mission Objectives Binning
Input
   15              Design  Rad_Size     FP_Rel     Shield  Min_Impct
MonCon
                 Mul_SuSd        Scale  Imp_OpPer  SpecPwr    LaunchV
Std_Con
                 Sec_Func  Std_Int      Comp
    2     2       S-PRIME   SPACE-R
    1     1             1
                        1
                  S-PRIME
    1     2             1
                        2
                  SPACE-R
    2     2        Sm_Rad  nSm_Rad
    1     1            23
                        1
                   Sm_Rad
    1     2            23
                        2
                  nSm_Rad
    3     3       1_FPRel  h_FPRel        Irr
    1     3            23
                        2
                  nSm_Rad
    1     1            34
                        1
                  1_FPRel
    1     2            34
```

```
                   2
             h_FPRel
3    3        Shield   nShield        Irr
2    3            23        34
                   2   +     2
             nSm_Rad   h_FPRel
1    1            35
                   1
              Shield
1    2            35
                   2
             nShield
2    2       MIN_IMP  nMIN_IMP
1    1            45
                   1
             MIN_IMP
1    2            45
                   2
            nMIN_IMP
3    3        MonCon    nMonCon       Irr
1    3            45
                   2
            nMIN_IMP
1    1            46
                   1
              MonCon
1    2            46
                   2
             nMonCon
3    3        MSU_SD   nMSU_SD        Irr
2    3            45        46
                   2   +     2
            nMIN_IMP   nMonCon
1    1            25
                   1
              MSU_SD
1    2            25
                   2
             nMSU_SD
3    3         Scale    nScale        Irr
3    3            45        46         25
                   2   +     2    +     2
```

		nMIN_IMP	nMonCon	nMSU_SD
1	1	44		
		1		
		Scale		
1	2	44		
		2		
		nScale		
3	3	Imp_Per	nImp_Per	Irr
1	3	45		
		2		
		nMIN_IMP		
1	1	47		
		1		
		Imp_Per		
1	2	47		
		2		
		nImp_Per		
3	3	hSpPwr	lSpPwr	Irr
2	3	45	47	
		2	+ 2	
		nMIN_IMP	nImp_Per	
1	1	48		
		1		
		hSpPwr		
1	2	48		
		2		
		lSpPwr		
3	3	Sm_LV	nSm_LV	Irr
2	3	45	47	
		2	+ 2	
		nMIN_IMP	nImp_Per	
1	1	49		
		1		
		Sm_LV		
1	2	49		
		2		
		nSm_LV		
3	3	Std_Con	nStd_Con	Irr
3	3	45	47	49
		2	+ 2	+ 2
		nMIN_IMP	nImp_Per	nSm_LV
1	1	50		

```
                    1
              Std_Con
   1    2          50
                    2
             nStd_Con
   3    3     Sec_Fun nSec_Fun       Irr
   3    3          45       47        49
                    2    +   2    +    2
             nMIN_IMP nImp_Per    nSm_LV
   1    1          51
                    1
              Sec_Fun
   1    2          51
                    2
             nSec_Fun
   3    3     Std_Int nStd_Int       Irr
   4    3          45       47        49        51
                    2    +   2    +    2   +     2
             nMIN_IMP nImp_Per    nSm_LV  nSec_Fun
   1    1          52
                    1
              Std_Int
   1    2          52
                    2
             nStd_Int
   2    2        Comp    nComp
   1    1          53
                    1
                 Comp
   1    2          53
                    2
                nComp
   1
  15    1           2        3         4         5         6
7        8
        9          10       11        12        13        14
15
         SORT FOR 15 COMPATABILITY TOP EVENTS

         SNPS Survivability Binning Input
          11           Design  Signatur  Rad_Size  Detection  St_Intg
Attack
```

		Armor	Redund	Sur_Atck	Op_Atck	Surv
2	2	S-PRIME	SPACE-R			
1	1	1				
		1				
		S-PRIME				
1	2	1				
		2				
		SPACE-R				
2	2	Sm_Sig	nSm_Sig			
1	1	22				
		1				
		Sm_Sig				
1	2	22				
		2				
		nSm_Sig				
3	3	Sm_Rad	nSm_Rad	Irr		
1	3	22				
		2				
		nSm_Sig				
1	1	23				
		1				
		Sm_Rad				
1	2	23				
		2				
		nSm_Rad				
2	2	Av_Det	nAv_Det			
1	1	54				
		1				
		Av_Det				
1	2	54				
		2				
		nAv_Det				
3	3	St_Intg	nSt_Intg	Irr		
1	3	54				
		2				
		nAv_Det				
1	1	31				
		1				
		St_Intg				
1	2	31				
		2				
		nSt_Intg				

```
3    3   Av_Attk nAv_Attk        Irr
1    3        54
               2
         nAv_Det
1    1        55
               1
         Av_Attk
1    2        55
               2
        nAv_Attk
3    3     Armor   nArmor        Irr
2    3        54       55
               2   +    2
         nAv_Det nAv_Attk
1    1        56
               1
           Armor
1    2        56
               2
          nArmor
3    3   h_redun  l_redun        Irr
2    3        54       55
               2   +    2
         nAv_Det nAv_Attk
1    1         6
               1
         h_redun
1    2         6
               2
         l_redun
3    3   Sur_Att nSur_Att        Irr
2    3        54       55
               2   +    2
         nAv_Det nAv_Attk
1    1        57
               1
         Sur_Att
1    2        57
               2
        nSur_Att
3    3   Op_Attk nOp_Attk        Irr
3    3        54       55         57
```

```
                 2    +    2    +    2
          nAv_Det nAv_Attk nSur_Att
    1    1       58
                  1
          Op_Attk
    1    2       58
                  2
         nOp_Attk
    2    2     Surv     nSurv
    1    1       59
                  1
             Surv
    1    2       59
                  2
            nSurv
    1
   11    1        2         3         4         5         6
7      8
         9       10        11
   SORT FOR 11 SURVIVABILITY TOP EVENTS

   SNPS Overall Reliability Binning Input
    3       Dem_Rel  ME_SPFs   Reliab
    2    2  Dem_Rel nDem_Rel
    1    1       13
                  1
            Dem_Rel
    1    2       13
                  2
           nDem_Rel
    3    3 nME_SPFs  ME_SPFs Irr_SPFs
    1    3       13
                  2
           nDem_Rel
    1    2       60
                  1
            ME_SPFs
    1    1       60
                  2
           nME_SPFs
    2    2      Rel      nRel
    1    1       61
```

```
                    1
                  Rel
    1   2          61
                    2
                 nRel
    1
    3   1           2         3
    SORT FOR 3 RELIABILITY TOP EVENTS

    SNPS Demonstrable Reliability Binning Input
     7             Power    Coolant    Control Heat_Rem Shld/Str
Supp_Sys
              Dem_Rel
    2   2     Rel_Pwr nRel_Pwr

    1   1           7
                    1
              Rel_Pwr
    1   2           7
                    2
             nRel_Pwr
    3   3     Rel_NaK nRel_NaK       Irr
    1   3           7
                    2
             nRel_Pwr
    1   1           8
                    1
              Rel_NaK
    1   2           8
                    2
             nRel_NaK
    3   3      Rel_RC  nRel_RC       Irr
    2   3           7        8
                    2   +    2
             nRel_Pwr nRel_NaK
    1   1           9
                    1
               Rel_RC
    1   2           9
                    2
              nRel_RC
    3   3      Rel_HX  nRel_HX       Irr
```

```
3   3         7        8         9
              2   +    2    +    2
       nRel_Pwr nRel_NaK  nRel_RC
1   1        10
              1
         Rel_HX
1   2        10
              2
        nRel_HX
3   3    Rel_SS  nRel_SS       Irr
4   3         7        8         9        10
              2   +    2    +    2    +    2
       nRel_Pwr nRel_NaK  nRel_RC  nRel_HX
1   1        11
              1
         Rel_SS
1   2        11
              2
        nRel_SS
3   3   Rel_Sup nRel_Sup       Irr
5   3         7        8         9        10        11
              2   +    2    +    2    +    2    +    2
       nRel_Pwr nRel_NaK  nRel_RC  nRel_HX   nRel_SS
1   1        12
              1
        Rel_Sup
1   2        12
              2
       nRel_Sup
2   2   Dem_Rel nDem_Rel
1   1        13
              1
        Dem_Rel
1   2        13
              2
       nDem_Rel
1
7   1         2        3         4         5         6
7
SORT FOR 7 DEMONSTRABLE RELIABILITY TOP EVENTS

SNPS Safety and Public Acceptance Binning Input
```

```
          11         Design   TFE_Rel   St_Intg    FP_Rel   Physics
Safety
                   Rad_Risk     Costs  Salable  Man_Rtd  Safe_PA
           2    2   S-PRIME   SPACE-R
           1    1         1
                          1
                    S-PRIME
           1    2         1
                          2
                    SPACE-R
           2    2     P_TFE    nP_TFE
           1    1         4
                          1
                      P_TFE
           1    2         4
                          2
                     nP_TFE
           3    3   St_Intg nSt_Intg        Irr
           1    3         4
                          2
                     nP_TFE
           1    1        31
                          1
                    St_Intg
           1    2        31
                          2
                   nSt_Intg
           3    3   l_FPRel   h_FPRel       Irr
           2    3         4        31
                          2    +    2
                     nP_TFE nSt_Intg
           1    1        34
                          1
                    l_FPRel
           1    2        34
                          2
                    h_FPRel
           3    3   Phys_SD nPhys_SD        Irr
           3    3         4        31        34
                          2    +    2   +     2
                     nP_TFE nSt_Intg   h_FPRel
           1    1        62
```

```
                1
          Phys_SD
 1   2         62
                2
         nPhys_SD
 3   3     Safety  nSafety        Irr
 4   3          4       31         34        62
                2  +     2   +      2  +      2
           nP_TFE nSt_Intg    h_FPRel  nPhys_SD
 1   1         63
                1
           Safety
 1   2         63
                2
          nSafety
 2   2    lRadRsk  hRadRsk
 1   1         64
                1
          lRadRsk
 1   2         64
                2
          hRadRsk
 3   3    At_Cost nAt_Cost        Irr
 1   3         64
                2
          hRadRsk
 1   1         18
                1
          At_Cost
 1   2         18
                2
         nAt_Cost
 3   3       Sale    nSale        Irr
 1   3         64
                2
          hRadRsk
 1   1         65
                1
             Sale
 1   2         65
                2
            nSale
```

```
          3    3   ManRtd  nManRtd       Irr
          2    3       64       65
                        2   +    2
                  hRadRsk    nSale
          1    1       66
                        1
                   ManRtd
          1    2       66
                        2
                  nManRtd
          2    2  Safe_PA nSafe_PA
          1    1       67
                        1
                  Safe_PA
          1    2       67
                        2
                 nSafe_PA
          1
         11    1        2        3        4        5        6
 7
               8        9       10       11
        SORT FOR 11 SAFETY AND PUBLIC ACCEPTANCE TOP EVENTS

        SNPS Schedule Binning Input
          8           Design   TFE_Rel  Core_Rel    D_Tech      Costs
Safe_PA
                        Fly Schedule
          2    2  S-PRIME   SPACE-R
          1    1        1
                        1
                  S-PRIME
          1    2        1
                        2
                  SPACE-R
          2    2    P_TFE   nP_TFE
          1    1        4
                        1
                    P_TFE
          1    2        4
                        2
                   nP_TFE
          3    3   P_Core  nP_Core       Irr
```

```
1   3      4
           2
      nP_TFE
1   1      5
           1
      P_Core
1   2      5
           2
     nP_Core
2   2   D_Tech  nD_Tech
1   1     68
           1
      D_Tech
1   2     68
           2
     nD_Tech
3   3  At_Cost nAt_Cost      Irr
1   3     68
           2
     nD_Tech
1   1     18
           1
     At_Cost
1   2     18
           2
    nAt_Cost
3   3  Safe_PA nSafe_PA      Irr
1   3     68
           2
     nD_Tech
1   1     67
           1
     Safe_PA
1   2     67
           2
    nSafe_PA
3   3      Fly     nFly      Irr
1   3     68
           2
     nD_Tech
1   1     69
           1
```

```
                    Fly
    1    2          69
                     2
                   nFly
    2    2         Schd      nSchd
    1    1          70
                     1
                   Schd
    1    2          70
                     2
                 nSchd
    1
    8    1           2         3         4         5         6
7
         8
  SORT FOR 8 SCHEDULE TOP EVENTS

  SNPS Program Risk Binning Input
   14           Design    TFE_Rel  Core_Rel    Dem_Rel      Costs
Schedule
            Dev_Risk     Telem   Control Grnd_Con Ass_Perf
TFE
            Testable Prog_Risk
    2    2   S-PRIME    SPACE-R
    1    1         1
                   1
             S-PRIME
    1    2         1
                   2
             SPACE-R
    2    2     P_TFE    nP_TFE
    1    1         4
                   1
               P_TFE
    1    2         4
                   2
              nP_TFE
    3    3    P_Core   nP_Core       Irr
    1    3         4
                   2
              nP_TFE
    1    1         5
```

```
                 1
            P_Core
1   2            5
                 2
           nP_Core
3   3      Dem_Rel  nDem_Rel         Irr
2   3            4         5
                 2    +    2
            nP_TFE   nP_Core
1   1           13
                 1
           Dem_Rel
1   2           13
                 2
          nDem_Rel
3   3      At_Cost  nAt_Cost         Irr
3   3            4         5          13
                 2    +    2     +     2
            nP_TFE   nP_Core  nDem_Rel
1   1           18
                 1
           At_Cost
1   2           18
                 2
          nAt_Cost
3   3         Schd     nSchd         Irr
4   3            4         5          13         18
                 2    +    2     +     2    +     2
            nP_TFE   nP_Core  nDem_Rel  nAt_Cost
1   1           70
                 1
              Schd
1   2           70
                 2
             nSchd
2   2       lDvRsk    hDvRsk
1   1           71
                 1
            lDvRsk
1   2           71
                 2
            hDvRsk
```

3	3	Telem	nTelem	Irr
1	3	71		
		2		
		hDvRsk		
1	1	19		
		1		
		Telem		
1	2	19		
		2		
		nTelem		
3	3	Cont	nCont	Irr
2	3	71	19	
		2	+ 2	
		hDvRsk	nTelem	
1	1	20		
		1		
		Cont		
1	2	20		
		2		
		nCont		
3	3	GrndCon	nGrndCon	Irr
3	3	71	19	20
		2	+ 2	+ 2
		hDvRsk	nTelem	nCont
1	1	21		
		1		
		GrndCon		
1	2	21		
		2		
		nGrndCon		
3	3	AssPer	nAssPer	Irr
1	3	71		
		2		
		hDvRsk		
1	1	72		
		1		
		AssPer		
1	2	72		
		2		
		nAssPer		
3	3	S_TFE	M_TFE	Irr
2	3	71	72	

```
                         2     +    2
                    hDvRsk   nAssPer
          1    1         2
                         1
                     S_TFE
          1    2         2
                         2
                     M_TFE
          3    3      Test     nTest        Irr
          2    3        71        72
                         2     +    2
                    hDvRsk   nAssPer
          1    1        73
                         1
                      Test
          1    2        73
                         2
                     nTest
          2    2     AccPR    nAccPR
          1    1        74
                         1
                     AccPR
          1    2        74
                         2
                    nAccPR
          1
         14    1         2         3         4         5         6
  7
               8         9        10        11        12        13
 14
        SORT FOR 14 PROGRAM RISK TOP EVENTS

        SNPS Attractive Lifetime Binning Input
          6            Design   Flex_Op   Op_Life      Scale  Tail_Lif
Lifetime
          2    2   S-PRIME   SPACE-R
          1    1         1
                         1
                   S-PRIME
          1    2         1
                         2
                   SPACE-R
```

```
2    2    Flx_Op  nFlx_Op
1    1        28
               1
          Flx_Op
1    2        28
               2
         nFlx_Op
2    2   lOpLife  sOpLife
1    1        75
               1
         lOpLife
1    2        75
               2
         sOpLife
3    3     Scale   nScale      Irr
1    3        75
               2
         sOpLife
1    1        44
               1
           Scale
1    2        44
               2
          nScale
3    3    TailLf  nTailLf      Irr
1    3        75
               2
         sOpLife
1    1        76
               1
          TailLf
1    2        76
               2
         nTailLf
2    2      Life    nLife
1    1        77
               1
            Life
1    2        77
               2
           nLife
1
```

6 1 2 3 4 5 6

SORT FOR 6 ATTRACTIVE LIFETIME TOP EVENTS

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