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Spaceborne Power Systems Preference Analyses

Volume I: Summary

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Prepared for
Defense Advanced Research Projects Agency
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ABSTRACT

Sixteen alternative spaceborne nuclear power system concepts were ranked using multiattribute decision analysis. The purpose of the ranking was to identify promising concepts for further technology development and the issues associated with such development.

Eleven individuals representing four groups were successfully interviewed to obtain their preferences. The four groups were: safety, systems definition and design, technology assessment, and mission analysis.

The ranking results were consistent from group to group and for different utility function models for individuals. The highest ranked systems were the heat-pipe thermoelectric systems, heat-pipe Stirling, in-core thermionic, and liquid-metal thermoelectric systems. The next group contained the liquid-metal Stirling, heat-pipe AMTEC (Alkali Metal Thermoelectric Converter), heat-pipe Brayton, liquid-metal out-of-core thermionic, and heat-pipe Rankine systems. The least preferred systems were the liquid-metal AMTEC, heat-pipe thermophotovoltaic, liquid-metal Brayton and Rankine, and gas-cooled Brayton. Although the R&D community subsequently discounted the heat-pipe reactor systems, the three non-heat-pipe technologies selected matched the top three non-heat-pipe systems ranked by this study (liquid-metal thermoelectric, in-core thermionic, and liquid-metal Stirling).

The multiattribute decision analysis process was viewed as a useful exercise for identifying options which needed further development. The analysis highlighted the need for additional and higher quality technical data as well as a need to provide an on-line capability to display source calculations interactively. An approach was suggested for displaying such traceability.

FOREWORD

The Defense Advanced Projects Research Agency, together with the U.S. Department of Energy and NASA, established the Space Power-100 Development Project to assess the potential and demonstrate the feasibility of developing a nuclear power system for operation in space. The SP-100 R&D Project Office was given the responsibility to assess the state of the required technologies and make recommendations for research in support of such a development from a systems perspective. Therefore, the objectives of the assessment were to characterize and give priority to the various subsystem technologies and system concepts through the use of simulation, based on projections of the subsystem capabilities.

This report describes the multiattribute decision analysis that ranked 16 power system concepts using the preferences of 11 individuals, all knowledgeable in advanced nuclear reactor and power-conversion technologies. The advanced system concepts were designed to meet a 100-kW power requirement, 3000-kg mass requirement, and 7-year lifetime.

The report is divided into two volumes. Volume I is a summary of the multiattribute decision analysis. Volume II describes the multiattribute decision analysis and provides detailed technical information on the methodology and system concepts.

ACKNOWLEDGMENTS

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Organization	Location
Air Force Weapons Laboratory	Albuquerque, New Mexico
Jet Propulsion Laboratory	Pasadena, California
Los Alamos National Laboratories	Albuquerque, New Mexico
NASA Lewis Research Center	Cleveland, Ohio

A very special thanks is owed to Fran Mulvehill who patiently and cheerfully typed this manuscript with its many difficult tables. Notwithstanding the help of these individuals above, the responsibility for this report rests with the authors.

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CONTENTS

SECTION I

INTRODUCTION AND PURPOSE

The initial phase of the SP-100 Project effort was faced with a formidable task--to define, examine, and categorize a broad matrix of spaceborne nuclear power system concepts. Each system could be composed of a reactor subsystem, shield subsystem, cooling subsystem, and power conversion subsystem. The objective was to screen the infeasible from the feasible subsystem combinations and then rank order the most promising candidate systems. After a preliminary study to determine a list of candidate systems, 16 alternative spaceborne nuclear power systems were studied and ranked using a multiattribute decision analysis. The systems were all designed to meet a 100-kW power level and 3000-kg mass limit and to operate in the space environment for a 7-year lifetime. The systems included seven heat-pipe cooled and seven liquid-metal cooled systems with a variety of dynamic and static power-conversion systems. One gas-cooled system and an in-core system were also examined. The conversion systems included Brayton, Stirling, Rankine, thermoelectric, thermophotovoltaic, thermionic, and AMTEC (Alkali-Metal Thermoelectric Conversion) technologies.

The purpose of the study was to develop a methodology for ranking the 16 systems and to rank the systems as an aid to the decision-making process. The results of the study were used to identify critical research-and-development issues and to support a plan for proving the viability of the SP-100 system concept.

The method used to rank the systems was a multiattribute decision analysis. The method combines an individual's preferences with analytical estimates of the attribute states to produce a ranking for that individual. A flow diagram for the method is shown in Figure 1-1.

Ten attributes were initially intended to be used in the ranking, but two were not included because it was believed that their inclusion would not have affected the ranking results significantly. The two attributes dropped were estimated development cost and production cost in 1983 dollars so that only eight attributes impacted the rankings: safety, radiator area, design reliability, technical maturity, estimated cost to reach technical feasibility, survivability, dormancy capability, and producibility.

Because several individuals are involved in a major decision such as ranking technical concepts, the rankings had to be determined for groups as well as for individuals. Thus, the Methodology Section (in Volume II) includes discussion of group-decision rules. Three group-decision rules were used to aggregate individual rankings because there is no single definitive rule for groups: rank sum rule, additive utility rule, and Nash bargaining rule.

This report is divided into two volumes. Volume I is a summary consisting of six sections: An introduction (Section I); rankings (Section II); the effects of rankings on the decision-making process (Section III); the implications of the analysis on future decisions (Section IV); the usefulness of the approach (Section V); and the conclusions (Section VI). Volume II presents the multiattribute decision analysis and consists of seven sections: An introduction (Section I); the methodology (Section II); a description of the attributes (Section III); a listing of the alternatives and state data (Section IV); a summary of the interviews and preference data (Section V); a presentation and analysis of the rankings and results (Section VI); and a summary of the concordance of rankings (Section VII).

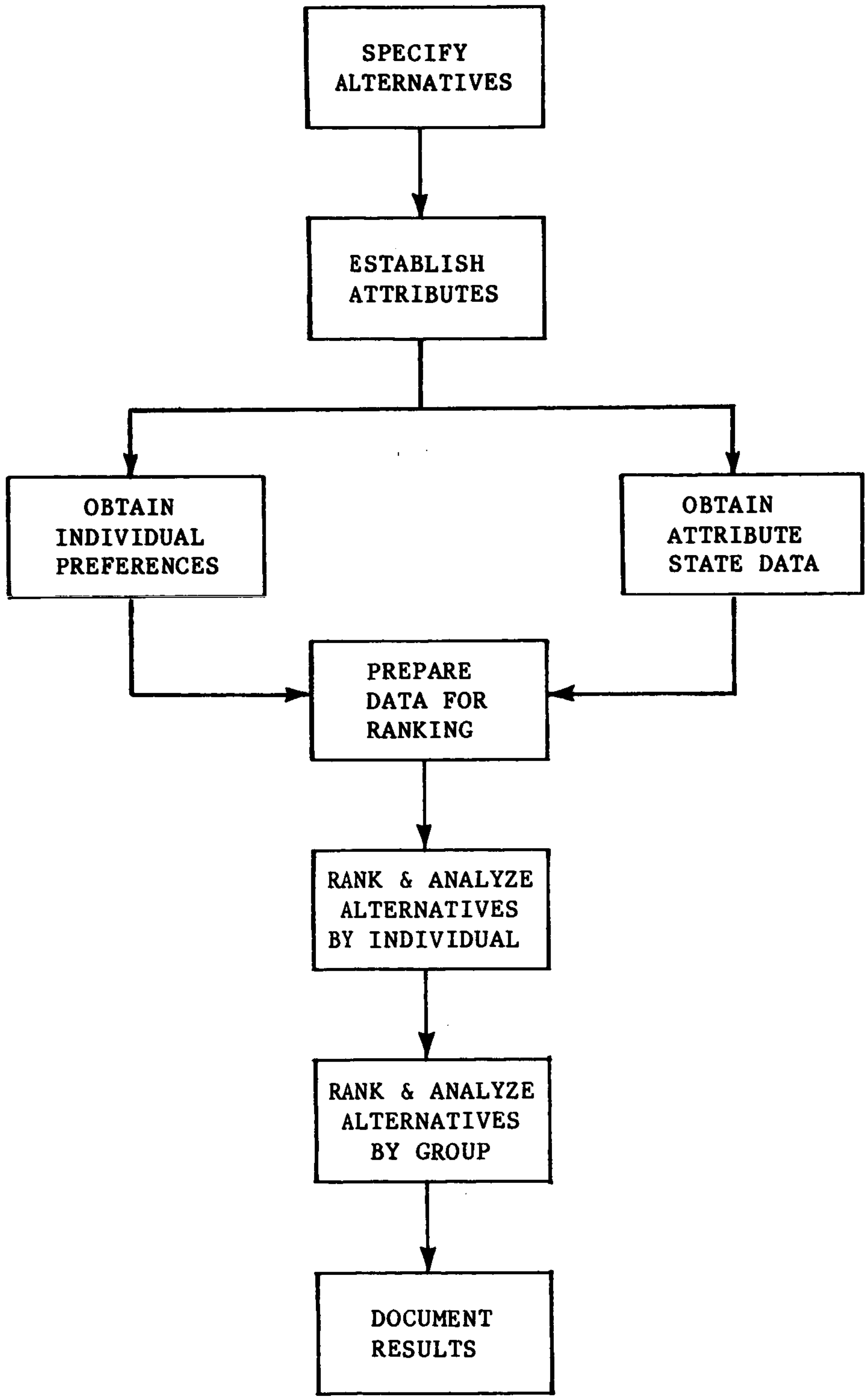


Figure 1-1. Ranking Methodology Flow Diagram

SECTION II

RANKINGS

The multiattribute decision-analysis method combines the technical specifications of the systems (a system database) with the preferences or values of the interested parties (a value database) to produce an overall value associated with each system.

The system database for the 16 systems was constructed by examining the subsystems and components of each system for each attribute. Explicit attributes, such as radiator area, were determined using models to design a system that met requirements. The output of these models yielded the required radiator area. A number of attributes could not be defined explicitly and were characterized by subjective scales. In these cases, the system concept was examined down to the subsystem or component level, and aggregated weightings were performed to determine the system level quantities. This effort resulted in an extensive system database, which is summarized in Table 2-1.

The value database used to prioritize the 16 concepts was constructed by identifying and interviewing, in a structured fashion, individuals with an interest in the ranking process. Eleven individuals, knowledgeable in spaceborne power technologies, were successfully interviewed to obtain their preferences with regard to the states of the eight attributes selected. These individuals were selected from organizations with the following characteristics:

(1) Ongoing research and development programs in advanced power conversion systems.

(2) A proven record of achievement in the research and development of nuclear power systems.

Table 2-1. System Database For Sixteen System Concepts

Alternative System Concept [a]	Safety	Radiator Area	Design Reliab.	Technical Maturity	Est. Cost/ Tech. Feas. $M	Survivability	Dormancy	Producibility
	Attribute							
LOCTP	7	42	8	6.0	193	7	4	6
LBO	7	100	6	7.0	198	6	4	4
LSH	7	31	7	7.8	124	7	4	5
LRL	7	27	4	6.9	140	5	2	3
LAP	7	60	4	6.9	114	6	2	5
LTEP	7	80	9	7.2	143	8	5	8
GBH	3	50	2	3.8	213	5	9	4
HOCTP	8	42	8	6.0	200	8	8	6
HBO	8	107	7	7.0	190	7	8	4
HSH	8	31	8	7.8	124	8	8	5
HRL	8	27	5	6.9	160	6	4	3
HAP	8	60	5	6.7	114	7	4	5
HTPVP	8	108	5	3.9	240	5	9	7
HTEP	8	67	10	6.3	135	10	10	8
HTEPa	8	80	10	7.4	135	10	10	8
ICT	6	38	7	7.6	170	9	10	7

[a]LOCTP = Liquid-metal cooled/out-of-core thermionic
LBO = Liquid-metal cooled/Brayton
LSH = Liquid-metal cooled/Stirling
LRL = Liquid-metal cooled/Rankine
LAP = Liquid-metal cooled/AMTEC
LTEP = Liquid-metal cooled/thermoelectric
GBH = Gas-cooled/Brayton
HOCTP = Heat-pipe cooled/out-of-core thermionic
HBO = Heat-pipe cooled/Brayton
HSH = Heat-pipe cooled/Stirling
HRL = Heat-pipe cooled/Rankine
HAP = Heat-pipe cooled/AMTEC
HTPVP = Heat-pipe cooled/thermophotovoltaic
HTEP = Heat-pipe cooled/thermoelectric (1380K)
HTEPa = Heat-pipe cooled/thermoelectric (1250K)
ICT = In-core thermionic

(3) An understanding of space environment issues that have direct impact on developing nuclear power technologies for space applications.

These individuals represented four distinct groups:

(1) Safety Group. This group was concerned with a range of safety issues from ground development through launch, on-orbit operation, and re-entry.

(2) Systems Definition and Design Group. This group was concerned with the design issues and options involved in the development and deployment of the technology.

(3) Technology Assessment Working Group. This group was involved in assessing the technical issues facing the demonstration of technical feasibility for such power systems.

(4) Mission Analysis Group. This area involved the concerns of possible mission users who would use the system concepts.

Rankings were calculated for the 11 individuals successfully interviewed and the four groups that they represented. Rankings for the individuals were calculated using several different multiattribute utility models and with each of the attributes individually removed. Rankings for the groups were also calculated according to three different group-decision rules. Figure 2-1 displays the baseline rankings and their variation across groups using one such rule (including all attributes).

The ranking results were quite consistent from group to group and for different utility function models for individuals. Generally, the rankings fell into four areas: most preferred systems (those high-ranking systems that were insensitive to different model assumptions), preferred (those

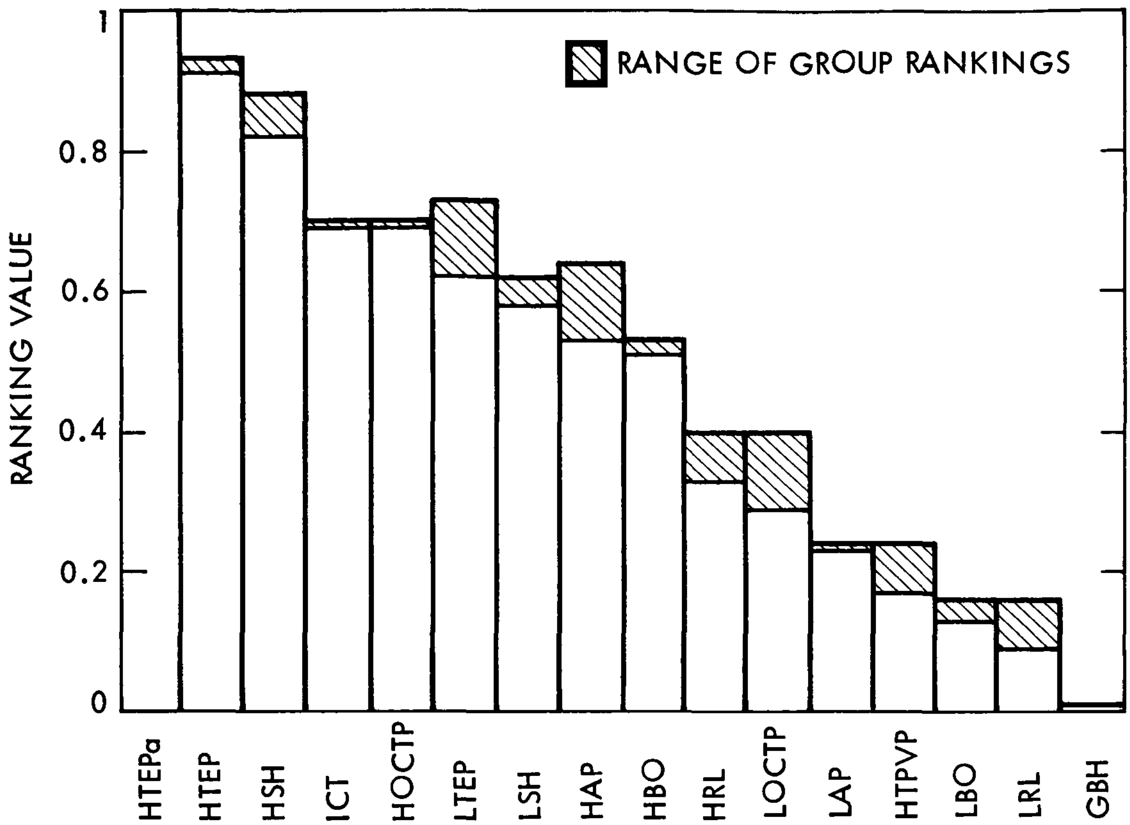


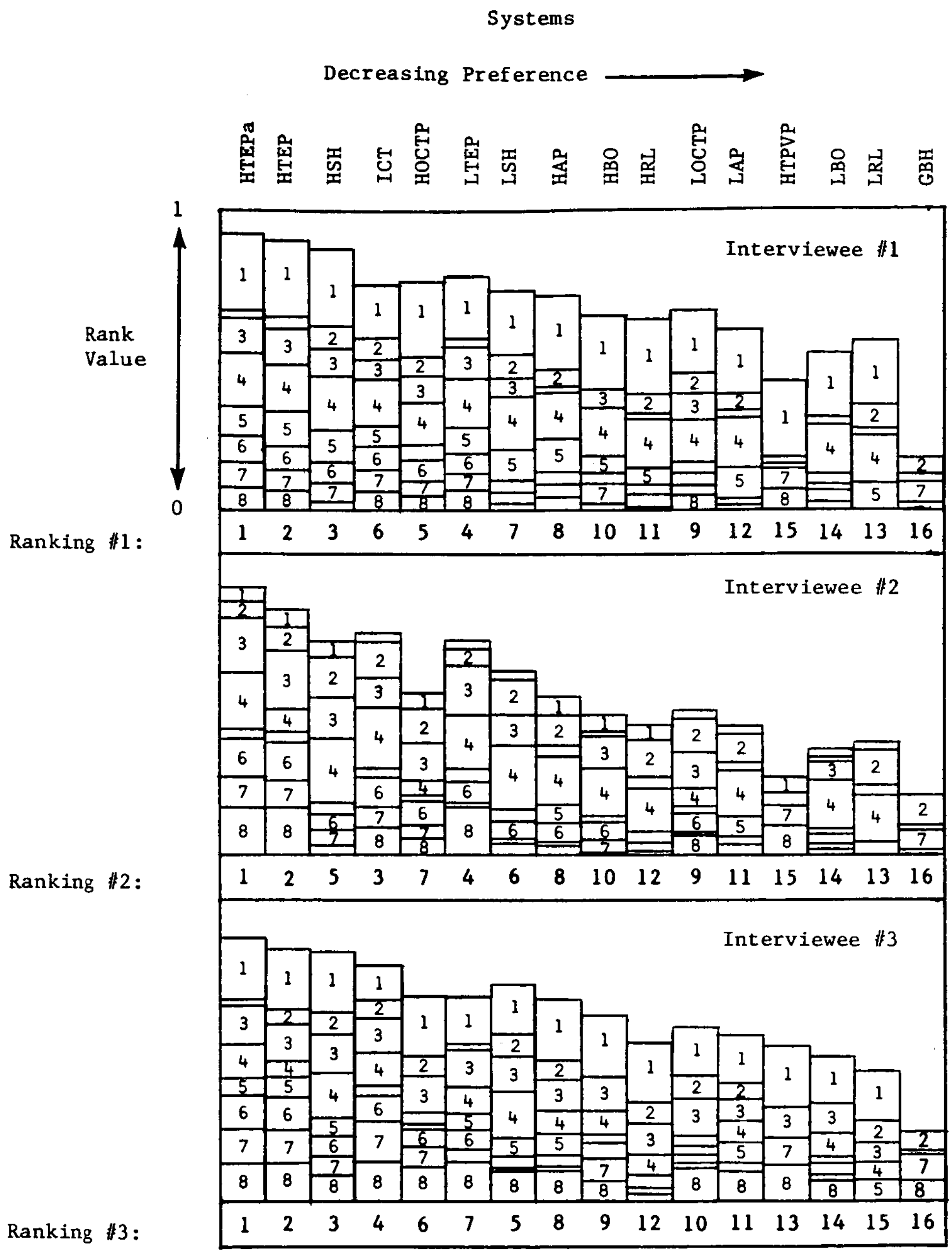
Figure 2-1. Overall System Rankings Showing Ranges Across Groups (System Acronyms defined in Table 2-1)

systems that were somewhat affected by different model assumptions but still remained clustered together at the high end of the rankings), intermediate (those systems that were somewhat affected by different model assumptions but still remained clustered together at the low end of the rankings), and least preferred (those low-ranking systems that were insensitive to different model assumptions). The most preferred systems were the heat-pipe thermoelectrics (HTEP, HTEPa). The preferred systems were the heat-pipe Stirling (HSH), in-core thermionic (ICT), and liquid-metal thermoelectric (LTEP). The intermediate systems were the liquid-metal Stirling (LSH), heat-pipe AMTEC (HAP), heat-pipe Brayton (HBO), liquid-metal, out-of-core thermionic (LOCTP), and heat-pipe Rankine (HRL). The least preferred concepts were the liquid-metal AMTEC (LAP), heat-pipe thermophotovoltaic (HTPVP), liquid-metal Brayton (LBO), liquid-metal Rankine (LRL), and gas-cooled Brayton (GBH).

These rankings were used to initiate planning for the technical development of the promising concepts. Specifically, the rankings were used to identify technology areas for more comprehensive research. A subsequent technology "downscoping" evaluation to select the most promising concepts eliminated almost all of the heat-pipe concepts as being riskier than previously thought, with insufficient operational data for their pursuit. The results of the present analysis had a direct impact on the list of systems that were candidates for this downscoping effort. It should be noted that the rank ordering of the remaining system concepts (after removing the heat-pipe systems) was substantially the same with the preliminary results obtained herein.

The concordance or agreement among the rankings was calculated for individuals within groups, different group-decision rules, and different multiattribute utility models. The concordance calculations were carried out to ascertain how robust the rankings were. In general, the rankings were highly concordant across individuals, different group-decision rules, and different multiattribute utility models, implying that the rankings were indeed robust.

The strong concordance of rankings was due to two contributing factors. These factors are illustrated with an example using interview data from the Technology Assessment Working Group. Figure 2-2 displays the individual rankings (assuming a linear model) for three interviewees, showing the proportional contribution of each attribute and the group rankings.



	HTEPa	HTEP	HSH	ICT	HOCTP	LTEP	LSH	HAP	HBO	HRL	LOCTP	LAP	HTPVP	LBO	LRL	GBH
Sum of Ranks:	3	6	11	13	18	15	18	24	29	35	28	34	43	42	41	48
Scaled Ranks:	1.0	.93	.84	.78	.67	.73	.67	.53	.42	.29	.44	.31	.11	.13	.16	0.0
Group Ranking:	1	2	3	4	6	5	6	8	10	12	9	11	15	14	13	16

Figure 2-2. Sample of Individual and Group Rankings Showing Contributions from each Attribute; (1=Safety, 2=Radiator Area, 3=Reliability, 4=Technical Maturity, 5=Cost, 6=Survivability, 7=Dormancy, 8=Producibility; numbers shown are for contributions ≥0.05 only). (System Acronyms defined in Table 2-1)

The first factor was a general consensus regarding the importance of the safety and technical maturity attributes (attributes 1 and 4)--the multipliers used to weight the utility values of each system resulted in consistently large contributions from these attributes. The proportional contribution from safety and technical maturity is apparent (usually one-third to one-half of the total score). In those cases in which the contribution is small from one, it is large from the other (interviewee #2). Figure 2-2 shows that the cost, survivability, dormancy, and producibility attributes (attributes 5, 6, 7, and 8) did not dominate significantly as individual attributes but, taken as a group, accounted for approximately one-third to one-half of the total scores. Thus, any changes in safety and technical maturity had a greater impact than changes in the remaining attributes.

The second factor was the inherent ranking implied by the system (attribute) data associated with each system concept, irrespective of the preference data obtained from the interviews. The most preferred systems were always the same because they performed well across a number of attributes (see Table 2-1). If a system performs well on numerous important attributes (like the HTEP systems, which had four of eight attributes at the "best" possible values), the resulting ranking tends to be insensistive to individual preferences because such systems dominate the other alternatives. Figure 2-2 shows this in two ways. The first case can be seen by examining interviewee #2's allocation for safety (attribute 1) versus interviewees' #1 and #3 allocation for safety (attribute 1). Interviewee #2 did not believe that safety was the predominant issue in ranking system concepts because the technical feasibility of such systems was yet to be proven ("If it can't be built, safety is irrelevant"). As a result, technical maturity was most important. The important observation to make is that the general trend of the rankings is the same even with completely different assumptions about the importance of safety and technical maturity. In particular, the most preferred systems are still the most preferred systems because the contributions from other high-scoring attributes make up the difference (attributes 3, 6, and 7).

The second case can be visualized by imagining that any one attribute box (for example, safety--attribute 1) is removed from all of the vertical bars. Note how the ranking order, beginning with attribute 2 at the top, follows the same general pattern from most-preferred to least-preferred concept. Specifically, note how the most-preferred systems are still the most preferred even with safety (usually the most important attribute) removed entirely. The analysis performed in this study found the rankings to be preserved in virtually all cases, regardless of which attribute was removed. This was due to the dominance inherent in the system data and general consensus about the importance of the attributes. As would be expected, these effects carried over into the group rankings used to condense the results of each group.

SECTION III

EFFECTS OF RANKINGS ON THE DECISION-MAKING PROCESS

The results of the ranking process had a number of effects on the decision-making process. The first effect was on the R&D planning process. Common problems among intermediate- and low-ranking systems were reviewed to identify common technology problems or barriers. Where such commonalities were identified, R&D tasks were proposed to resolve the issues or obtain additional information to improve the understanding of the issues.

A second effect was reduction and focusing on a more manageable set of alternatives than had been previously available. The identification of alternatives aided the process of screening technically incompatible or unlikely subsystem combinations. Nonetheless, the sixteen remaining systems constituted a diverse set of possible R&D programs.

A third effect was an evolving awareness that there were weaknesses in the databases used to rank the systems. Many of the data values assumed certain requirements could be met. Those systems that did not meet the assumed requirements during the analysis phase were eliminated from consideration. The effect of this action was to eliminate possibly high performing systems that fell marginally short of the requirements. This problem, coupled with the tendency to give more value to systems with large databases versus those with little data, eroded the credibility of the system database to some extent. Although the information used was probably the best available, an outcome of the process was the generally accepted need for more technical information.

It should be noted that an additional evaluation was performed by the SP-100 Project Office as a check using the same system database but with a somewhat different model of preferences. The results of that analysis concurred substantially with this study.

A fourth impact provided by the rankings was the general consensus that the process itself yielded benefits in learning and communication of the characteristics of the alternatives. It should be noted that the limitations of the ranking process (specifically, the credibility of the system data and complexity of the calculations) lead to a discounting of the rankings as an absolute representation of value. Nonetheless, the general trend of the rankings was valuable for pointing to technology development problems.

SECTION IV

IMPLICATIONS OF THE ANALYSIS ON FUTURE DECISIONS

The first implication on future decisions of the analysis conducted in this study is a need for clarity in the accounting trail from the system and value databases through to the calculated scores used to rank the systems. Although such accounting trails are accessible and available, it is difficult to display such information in real time. It was clear from this study that such transparency would be useful--forays into computer listings to produce requested backup information at a later time are insufficient. Some of these problems could be ameliorated with creative display graphics (such as Figure 2-2), but this kind of information display provides summary information rather than the source of the calculations.

A second implication of the analysis is the usefulness of the process for providing a strawman list for the decision makers to focus on. Whether or not there is consensus, the decision-analysis process provides a useful starting point for discussion. The rankings developed in this study were modified after a number of discussions on the heat-pipe reactors. The conclusions were drawn by the R&D community that there were risk and technical problems, less experience, and a less proven database for the heat-pipe options than had been anticipated at the outset of the analysis. As a result, the heat-pipe reactors were subsequently discounted. It is interesting to note that even after removing the heat-pipe reactor systems, the three concepts ultimately selected were the top three in the list of rankings produced by this analysis and supported by a subsequent backup study performed to check the analysis.

The changes that were ultimately made grew out of the initial work performed in this study. It is anticipated that the selection of the primary technology (in July 1985) will use some form of interactive decision support tool. Such methods are believed to be useful by management as a starting point for arbitration toward final decisions. The degree of use will be determined by the simplicity and interactive display capability of the methods.

SECTION V

USEFULNESS OF THE APPROACH

The multiattribute decision analysis used in this study had a number of strengths and weaknesses. On the positive side, the methods used helped to organize and direct the identification and collection of data. The approach quantified the system concepts in terms of a number of attributes and then prioritized the concepts on a uniform and consistent basis by individual and group.

On the negative side, the methodology needs to provide faster audit trails to substantiate final ranking values. Interactive display graphics similar to Figure 2-2 to summarize the results would be a useful addition.

Although not a methodological problem, the process also highlighted the issue of insufficient and marginal data. The question of uncertainties in different data points should be addressed so that the resulting rankings reflect the data uncertainties.

An additional problem that has been raised regarding the usefulness of the approach is the time frame allocated for the decision analysis. The entire procedure from definition of the attributes to analysis and presentation was approximately six weeks. Given the multi-organizational nature of the task and the limited amount of time, there is no question that more time would have alleviated some of the problems encountered.

To summarize, the overall conclusion of this study is that the decision analysis was useful as a starting point, providing insights about the technologies and decision parameters, and pointing to deficiencies and needs that could be supported in the planning process to prove technical feasibility.

SECTION VI

CONCLUSIONS

During this study, a number of conclusions were drawn:

1. Based on available information, Figure 2-1 summarizes the ranking of system concepts.
2. Eleven individuals with expertise in each of four categories (nuclear safety, systems definition and design, technology assessment, and mission analysis) were successfuly interviewed to obtain their preferences regarding eight specific attributes.
3. Attributes were ranked (most preferred to least preferred) over the attribute state ranges as follows for all groups: safety, technical maturity, design reliability, producability, survivability, dormancy, estimated cost to reach technical feasibility, and radiator area.
4. Rankings at the individual and group levels were generally in agreement. (Disagreement within groups was due mainly to differences in attribute weights; the main effect was the perception of safety versus technical maturity--most individuals rated safety as the highest-weighted attribute--except those who said that safety was not a key issue until technical feasibility could be demonstrated.)
5. Overall agreement among individuals and groups was supported statistically using the concept of concordance among rankings.
6. Rankings were robust under a variety of assumptions regarding the form of the multiattribute decision analysis model. This was

due to a clear dominance of the attributes by some systems with high rankings and consistently poor performance on many attributes by those systems with low rankings. The majority of cases that were (minimally) affected were in the middle of the list where trade-offs between similarly weighted attributes took place. After the R&D community later discounted the heat-pipe reactor systems, the top three systems selected matched the top three non-heat-pipe systems ranked by this study.

7. The attribute-by-attribute dominance of some systems, visible by examining the system database (Table 2-1), shows how even large variations in preferences across individuals could have only a small effect on ranking outcomes.

8. The use of multiattribute decision analysis had a generally positive impact on the decision process. The method provided organization, focused the list of numerous technical combinations, provided insights on system database needs and data quality, and supported the subsequent planning process for R&D tasks to prove technical feasibility.

9. A need exists to modify the existing software to provide a user-interactive tool that can be used to conduct on-line sensitivity analyses and display source calculations on request.

10. The methodology and the process in this study were perceived as a useful starting point for focusing on the technologies and identifying the major problems between high-ranking and lower-ranking concepts.