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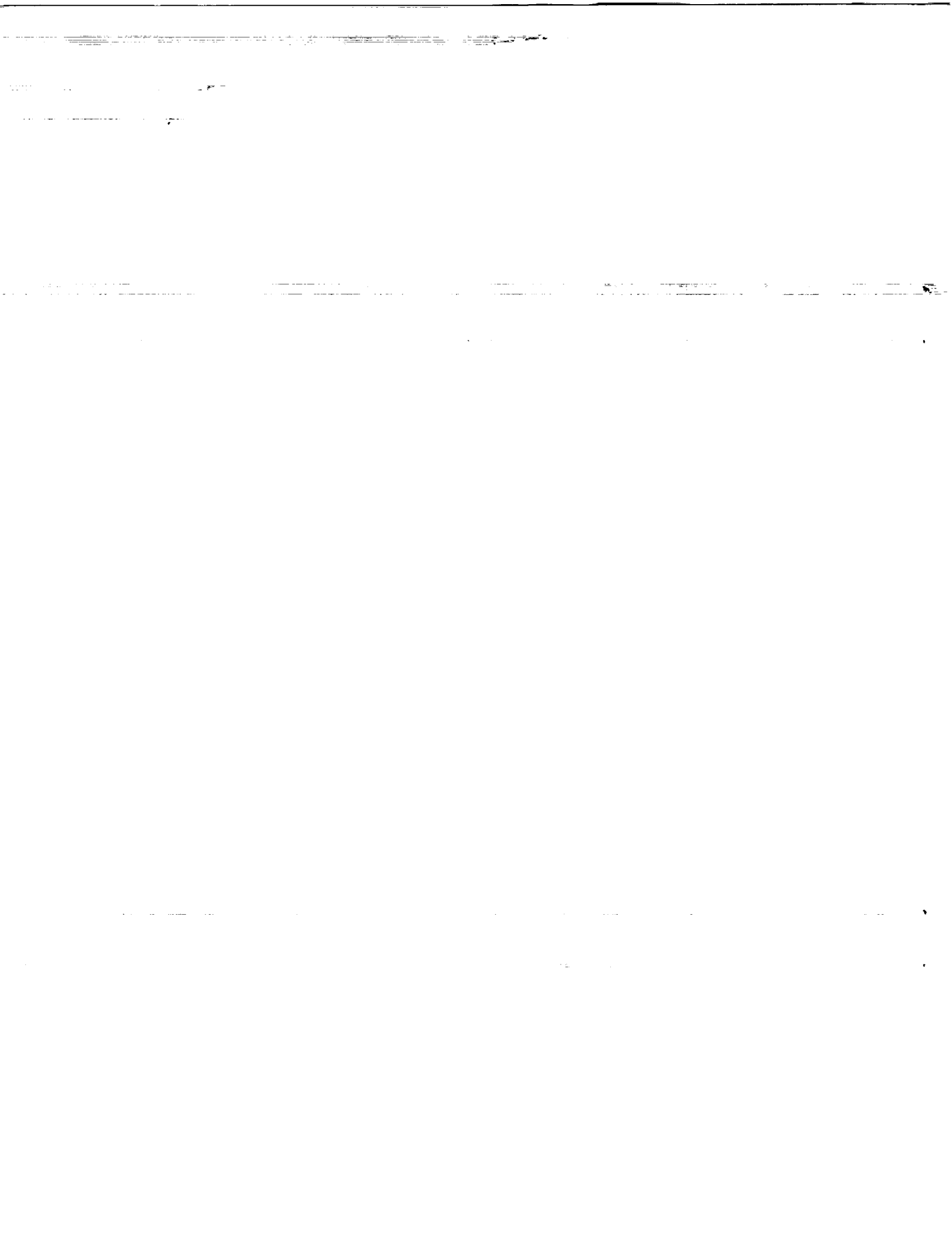
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A Reliability and Mass Perspective of SP-100 Stirling Cycle Lunar-Base Powerplant Designs

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A RELIABILITY AND MASS PERSPECTIVE OF SP-100 STIRLING CYCLE

LUNAR-BASE POWERPLANT DESIGNS

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SUMMARY

This report presents an approach to identifying high-reliability and low-mass space powerplant conceptual designs that are based on emerging or advanced technologies which have little or no reliability data base. The approach consists of estimating a range of expected unit reliabilities, or failure rates, for these emerging technology elements to determine the impact of varying the unit failure rates and of applying redundancy at various system levels on the overall reliability of powerplant designs. When combined with powerplant mass estimates, the resulting matrix can be used to characterize and select attractive powerplant design options as a function of the expected reliability of the emerging technologies.

The study applied this methodology to a lunar-base powerplant concept based on emerging SP-100 reactor heat source technology and Stirling cycle power-generation technology. A range of reactor and power-generation unit reliability estimates was arbitrarily selected to allow for the uncertainty inherent in these emerging technologies, but only the boundaries of this range were used in the analysis. Reliability estimates of reactor and power-generation subsystem units ranged from low, or pessimistic, values of 0.90 and 0.80, respectively; to high, or optimistic, values of 0.98 and 0.95.

A total of 80 lunar-base powerplant designs were investigated. These powerplants incorporated redundancy at two different levels, and each powerplant was required to produce at least 800 kWe to meet an assumed mission success criterion. Design redundancy options at the highest system level included four different powerplant configurations:

(1) A nonredundant single system producing 800 kWe
(2) Two nonredundant 400-kWe systems operating in series to deliver 800 kWe
(3) Two fully redundant 800-kWe systems operating in parallel
(4) Three partially redundant 400-kWe systems operating in a two-out-of-three mode

At the lowest system level (the reactor and power-generation subsystem units), the powerplants had one of twenty different design redundancy options. Reactor subsystems were either single (nonredundant) or dual (fully redundant) parallel reactor units. Power-generation subsystems were composed of one to nine partially redundant (k-out-of-n) parallel power-generation units including up to two spare units.

As a result of this study some interesting perspectives on the characteristics and selection criteria of high-reliability and low-mass lunar-base powerplant design configurations have emerged. For example, as expected, the wide range of emerging-technology reliability estimates used had a significant

effect on the selection of high-reliability and low-mass design configurations. Powerplant designs that provided high reliability with low mass when optimistic emerging technology reliability estimates were assumed were generally unacceptable when pessimistic reliability estimates were substituted. Therefore, to ensure acceptable powerplant reliability, one should select minimum mass configurations on the basis of pessimistic reliability estimates.

Another interesting result of the study was that for either low or high unit reliability estimates, the best combination of high powerplant reliability and low mass occurred when redundancy was applied at the lowest level of system hierarchy. Thus, the most attractive powerplant design concepts were nonredundant single-system powerplants with subsystem-unit redundancy options. Selection of the best redundancy option for the subsystem units, however, depended on the definition of an acceptable overall powerplant reliability criterion.

The issue of defining an acceptable overall powerplant reliability criterion was addressed, and the definition of this criterion significantly affected the selection of the best subsystem unit redundancy configuration. Since the calculated overall reliability of any powerplant configuration is highly dependent on the emerging technology reliability estimates, powerplant reliability is a relative value. Therefore, an acceptable reliability criterion must be defined on the basis of emerging technology reliability estimates. The reasonable choice appeared to be an acceptable reliability criterion that required the overall powerplant reliability to be equal to, or better than, any emerging technology subsystem unit reliability estimate. However, that selection required every acceptable powerplant configuration to have two fully redundant, parallel reactor units. Although dual reactors do not impose a significant mass penalty, they may require integration and operational considerations that were not fully explored in this study. Therefore, selecting an attractive powerplant design on the basis of an arbitrary reliability criterion may involve a tradeoff with design or operational complexity as well as with mass.

Additional perspectives into selecting the best redundancy options for the subsystem units were gained by analyzing the effect of varying the overall powerplant reliability criterion with estimates of emerging technology reliabilities. For example, with pessimistic emerging technology reliability estimates and a corresponding reliability criterion of approximately 0.90 or better, the lowest mass 800-kWe powerplant configuration consisted of a single 800-kWe system composed of two fully redundant, parallel reactor units coupled to a total of six parallel, partially redundant 200-kWe power-generation subsystem units, of which two are spares. This configuration provided a powerplant reliability of 0.8921 at a mass of 26 660 kg. If higher overall powerplant reliabilities are desired, and additional mass is acceptable, fewer power-generation units are needed. For example, a decrease to five 267-kWe power-generation units, including two spares, provides a powerplant reliability of 0.9327 at a mass of 28 320 kg, and a further decrease to four 400-kWe power-generation units, including two spares, provides the highest single-system powerplant reliability of 0.9631 at a mass of 32 340 kg.

For optimistic emerging technology reliability estimates and a corresponding reliability criterion of 0.98 or better, the lowest mass powerplant, again, consisted of a single-system 800-kWe configuration. However, this

configuration had two fully redundant reactor units coupled to nine 167-kWe power-generation units, including two spares. This configuration provided a powerplant reliability of 0.9898 at a mass of 25 060 kg. Decreasing the number of power-generation units again provides higher powerplant reliability at the expense of mass, up to a maximum of 0.9991 at a mass of 32 340 kg for a four-unit power-generation subsystem, including two spares, with each unit rated at 400 kWe.

Reducing the acceptable reliability criterion to, say, the reliability of the lowest emerging technology subsystem unit allows single-unit reactor subsystems to be selected with a resultant powerplant mass decrease. For example, with pessimistic emerging-technology reliability estimates and a corresponding reliability criterion of approximately 0.80 or better, the lowest mass configuration was a single-system powerplant composed of only one reactor unit coupled to six parallel, partially redundant 200-kWe power-generation subsystem units including two spares. This configuration provided a powerplant reliability of 0.8110 at a mass of 23 360 kg. If higher power-plant reliabilities are desired, a wide range of single unit reactor subsystem options are viable up to a reliability criterion of about 0.84.

For optimistic emerging technology reliability estimates and a corresponding reliability criterion of 0.95 or better, the lowest mass conceptual design was a single-system powerplant composed of one reactor unit coupled to five 200-kWe partially redundant power-generation units with one spare. This configuration provided a powerplant reliability of 0.9578 at a mass of 21 390 kg. If higher powerplant reliabilities are desired, a wide range of single-unit reactor subsystem options are viable up to a reliability criterion of about 0.98.

The perspectives developed in this study provided valuable insight into the considerations required to identify and characterize high-reliability and low-mass lunar-base powerplant designs. In general, this methodology can provide similar reliability perspectives for any space power mission designs based on emerging technologies with unknown reliabilities.

INTRODUCTION

As part of NASA's efforts to provide viable options for carrying out a focused program of human exploration of the solar system, its Office of Exploration (now absorbed into the NASA Office of Aeronautics and Exploration Technology) desired to establish a knowledge-based understanding for a selection rationale. A series of illustrative cases and tradeoffs were studied to develop conceptual point designs and technical requirements and to understand the driving technology factors and operational considerations in choosing options. One pathway of human exploration was encompassed in a hypothetical lunar evolution case study. A permanent facility, with significant capabilities for operations, research, and self-support, would be established on the lunar surface. Then, lunar resources, including propellants, would be developed and exploited to reduce support requirements from Earth. Ultimately, these permanent facilities would be developed for expanded lunar operations and scientific activities to support expansion of the human presence into the solar system.

In its role assigned by the NASA Office of Exploration as the Special Assessment Agent for power and propulsion, the NASA Lewis Research Center developed a conceptual design to assess integration and operational issues for a proposed lunar-base powerplant that could provide about 800 kWe (ref. 1). The powerplant concept was based on the SP-100 reactor heat source and Stirling cycle dynamic power generation: emerging technologies that are currently being developed in government-sponsored programs and are projected for system technology validation by the late 1990's. The powerplant design has features that are highly compatible with a human-rated lunar base from the standpoints of nuclear safety and of potential for repair or replacement of nonnuclear subsystems.

From a reliability design configuration perspective, the reference powerplant consisted of a single power system composed of two serially connected subsystems: a reactor subsystem and a power-generation subsystem. The reactor subsystem consisted of a single (nonredundant) reactor unit, and the partially redundant power-generation subsystem contained eight parallel units, of which six were required to operate and two were spares (redundant). The reliability path diagram for this configuration (fig. 1) illustrates the nonredundant reactor subsystem and the partial (k-out-of n) redundancy employed in the power-generation subsystem.

In order to achieve mission success over an unspecified time period, the single reactor unit must be operating, and at least six out of eight power-generation units must be operating concurrently. This design was selected to provide a reasonable combination of good reliability and low mass on the basis of previous analyses of reactor space power systems using dynamic power conversion subsystems (ref. 2). However, the configuration may not provide an acceptable overall powerplant reliability especially for potentially low, or pessimistic, estimates of reactor and power-generation subsystem unit reliabilities.

A key issue involved in assessing the reliability of this design - and, in general, for any power system using emerging technologies - is the estimation of unit reliabilities, or failure rates, for the emerging technologies. The lack of a substantial or relevant reliability data base for these technologies is a serious concern for powerplant designers attempting to meet a mission reliability requirement. A potential solution to this problem, however, is available at the early conceptual design stage. By selecting a range of anticipated reliabilities for the emerging technologies, the designer can, through the application of combinatorial reliability theory, predict the sensitivity of overall powerplant reliability to variation in powerplant design configuration. The results can then be used to select redundancy options to achieve high overall reliability.

This methodology yielded the following results for the reference lunar-base powerplant. For optimistic, upper-bound reliability estimates of 0.98 for the reactor unit and 0.95 for each power-generation unit, the resulting overall power system reliability was 0.9743 - about as high as the highest subsystem-unit reliability estimate. For pessimistic, lower-bound reactor and power-generation unit reliabilities of 0.90 and 0.80, the resulting overall power system reliability was 0.7172 - significantly less than the highest subsystem-unit reliability estimate, and even lower than the lowest subsystem-unit reliability estimate. This result clearly illustrates the deleterious

effect of potentially low values of emerging-technology unit reliabilities on the overall reliability of the reference powerplant design.

Because of concern for overall powerplant reliability, especially for human-rated space missions, this study was undertaken to characterize powerplant configurations that could improve overall reliability, particularly for low estimates of emerging-technology reliability. The conflict between quality, as represented by reliability, and the outlay of resources, as represented by mass, is particularly prominent in space systems and has been the subject of numerous studies. This conflict cannot be circumvented, but it can be minimized through selective design. The mathematical techniques available to optimize redundancy and increase system reliability are well known. These techniques rely on varying disciplines ranging from reliability to optimization procedures. (For example, see ref. 3.) Since improvements in overall reliability through redundancy always come at the expense of additional mass, it is especially important to identify and characterize a wide variety of alternative low-mass powerplant configurations based on varying redundancy at different system hierarchy levels.

An important aspect of this study was the development of mass models incorporating all the design features of the original lunar-base powerplant concept. These models were used to estimate powerplant mass for all alternative powerplant conceptual designs considered, and the combined powerplant reliability and mass results defined a matrix from which attractive configuration options could be selected and evaluated. In addition, a simple reliability-improvement criterion was developed to focus on appropriate powerplant design selections at any level of desired powerplant reliability over the range of expected reactor and power-generation unit reliabilities. Thus, a method was formulated to select specific space power design configurations that provide high overall reliability in combination with low mass as a function of the unit reliabilities of the emerging technologies used.

DESIGN RELIABILITY IMPROVEMENT

The reliability of any system can generally be improved by using more reliable components and/or applying distributed redundancy at one or more levels of the system. For the conceptual designs under consideration, all subsystem units were assumed to have given, fixed levels of reliability. Distributed redundancy options were explored as the sole means to improve overall reliability. Redundancy can generally be categorized according to two criteria: the level(s) at which redundancy is applied, and the state of the redundant elements while the system is in operation. These criteria, and their application to alternative lunar-base design configurations, formed the basis for reliability improvement techniques evaluated in this study. In addition, all redundant elements were assumed to be independent, and their operation was described as either a "success" or a "failure" over a specified time interval.

The reference powerplant (ref. 1) design was analyzed to understand the reliability improvements that could be realized by applying redundancy at different levels of the system hierarchy. The reference powerplant had redundancy solely at the subsystem unit level, and then only partially (in the power-generation subsystem). Figure 2 depicts the reactor and power-generation subsystem of the reference powerplant and shows the key components

of each subsystem. For simplicity, only one of the eight identical power-generation units is shown. The reference powerplant design configuration is described in detail next as a basis to characterize alternative design configurations.

The reference reactor subsystem consisted of (1) a single 2.5-MWt SP-100 reactor which included a fueled core, vessel structure, control rods and reflectors, instrumentation, controls, an instrument-rated conical radiation shadow shield, and a cylindrical neutron shield/bulkhead and (2) a primary heat-transport loop which included a pump, an accumulator, and inlet and outlet piping and manifolds. These components, with the exception of the manifolds, were located in a manmade surface excavation lined with the cylindrical bulkhead. The bulkhead was made of boron/aluminum which provided excavation support and shielding to limit soil activation and radiation from scattered thermal neutrons. The lunar soil beyond the bulkhead provided ample shielding protection for radiation-sensitive components and human activities on the adjacent lunar surface.

The power-generation subsystem was located entirely on the lunar surface and consisted of eight identical and independent units with two spares. Each unit was composed of

(1) A platform to support the manifold and engines
(2) A secondary heat-transport loop including a heat exchanger built into the Stirling engine heater head, a pump, and an accumulator
(3) A 133-kWe-rated free-piston Stirling cycle engine with a linear alternator
(4) A waste-heat transport loop including a heat exchanger built into the Stirling engine's cold end, a pump, an accumulator, and a heat-pipe radiator
(5) Power management and distribution components including an ac-to-dc convertor, a parasitic load resistor radiator, and an electrical transmission cable

As previously noted, this powerplant only provided a reliability of 0.7172 when low estimates of reactor and power-generation unit reliabilities of 0.9 and 0.8, respectively, were assumed. Reliability was improved herein by applying a variety of redundancy options to the basic design concept. The following hierarchical definitions were used to clarify the redundancy options at various levels.

Powerplant   The powerplant consisted of either one, two, or three power systems connected in either series or parallel to provide various forms of system level redundancy. A powerplant output power level of 800 kWe indicated "successful" operation.

System   Each power system was composed of two series-connected subsystems: a reactor subsystem and a power-generation subsystem. Power system output was fixed at either 400 or 800 kWe to accommodate the various forms of system-level redundancy used to meet the 800-kWe powerplant requirement.

Subsystem   The reactor and power-generation subsystems were both composed of one or more units. All units within a given subsystem were identical and of equal reliability, and the reliability, or success probability, of any

unit was assumed to be independent of both the number and the operational state of the other like units.

Reactor Subsystem   The reactor subsystem was composed of either one or two parallel reactor units. Maximum unit output was limited to 2.5 MWt, and operation down to 25 percent partial-output was assumed to be acceptable.

Power-Generation Subsystem   The power-generation subsystem consisted of multiple parallel units to provide various levels of k-out-of-n, or partial, redundancy. Each of the n units was sized such that the required operating power level was achieved from k units. Maximum unit power output was limited to 400 kWe and no limit was set on minimum unit power output.

On the basis of these definitions, an option matrix of powerplant redundancy levels was established. The matrix contained 80 different design configurations that employed redundancy options at the system and subsystem unit level - 4 system-level options, 2 reactor subsystem options, and 10 power-generation subsystem options.

The four 800-kWe powerplant system level configuration options were

(1) A single, nonredundant, 800-kWe power system operating at full power
(2) Two parallel, redundant, 800-kWe power systems, each assumed to be operating at half power
(3) Three 400-kWe power systems, each assumed to be operating at two-thirds power in a partially redundant (two-out-of-three) mode
(4) Two nonredundant, 400-kWe, series-connected power systems

These system-level redundancy options are illustrated in figure 3. System-level redundancy options were not considered for power systems with smaller outputs because of the significant anticipated powerplant mass increases.

At the subsystem level, the two reactor subsystem options included a nonredundant, single 2.5-MWt unit operating at either full or 50-percent power, and two fully redundant 2.5-MWt units, each operating at either 50- or 25-percent power. Power-generation subsystem options were based on partial-to-full redundancy (k-out-of-n) configurations and ranged from two-to-ten power-generation units including either zero, one, or two spare units. Total subsystem power output varied with specified system power level (i.e., 400 or 800 kWe), and unit power levels also depended on the number of operating and spare units used. For example, the smallest power-generation unit size of 58 kWe was used in a 400-kWe subsystem (seven-out-of-eight) configuration. The largest power-generation unit size of 400 kWe (based on current design limits for Stirling engines) was used with either a 400-kWe subsystem (one-out-of-two) fully redundant configuration, or an 800-kWe subsystem (two-out-of-three) configuration. Figure 4 shows a power-system-level reliability path diagram of a fully redundant two-unit reactor subsystem serially connected to a generic, k-out-of-n, partially redundant power-generation subsystem.

The second redundancy criterion to be defined is the operational state of the redundant elements while the powerplant is in operation. There are three possible operational redundancy states: active, standby, or combined active-standby. The active redundancy operational state was previously assumed for the reference powerplant design, and it is also assumed for all

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other designs considered in this study. In this state all redundant subsystem units are always "on" and operational at some fraction of rated capacity. Active redundancy is quite common in complex remote systems, such as space applications, where components are subjected to a hazardous environment. It eliminates the need for potentially unreliable decision, startup, and switching devices that would be required for parallel elements in a state of standby redundancy. It also eliminates the need for a controlled startup of a "cold" unit to full capacity in the event of a failure.

Active redundancy is also justified by the present design philosophy for most complex systems. Since redundancy is usually costly, many systems are designed, when possible, to begin a mission by using all available system capability. As failures occur, the performance of the system is degraded, but vital functions can still be performed. System "failure" occurs when the performance of the system falls below acceptable, or minimum, levels. This philosophy is particularly applicable to a human-rated application where active redundancy provides available system capability, and partial-power output from a degraded system can provide power for vital life-support functions.

For this study, however, a partial-power output requirement was not considered, and system "failure" was assumed to occur when powerplant power output fell below the rated capacity value of 800 kWe. In addition, there are some unaddressed operational questions associated with active redundancy that apply to partial-power operation. For example, in the purely active redundancy mode assumed in this study, all parallel units operating at partial-power are not only subject to the operational environment, they may also be operating far from their design points. Although it is generally expected that partial-power operation would lead to lower unit failure rates for the reactor, this may not be the case for power-generation units. Because of the limited knowledge base of the emerging technologies used in this study, these operational questions cannot be addressed until after further analytical and experimental evaluation.

It should also be noted that combined active-standby redundancy was not extensively evaluated herein. However, in certain situations this type of redundancy may increase overall reliability for systems and subsystems operating in k-out-of-n configurations. For example, reliability tradeoff studies based on varying the relationships between operating failure rate, standby failure rate, and the reliability of switching and startup can be more reliable for some combined active-standby configurations (ref. 4). However, these analyses require additional estimates of partial-power, standby, switching, and startup reliabilities for the various units. Given the extremely limited reliability data base associated with the emerging technologies considered for space nuclear power systems, evaluation of the combined active-standby redundancy mode was deemed to be beyond the scope of this study and was not pursued further. For the interested reader, the reliability characteristics and calculation techniques applicable to active-standby redundancy are discussed comprehensively in reference 4.

RELIABILITY ANALYSIS

The objective of the reliability analysis was to determine the overall powerplant reliability of the various system and subsystem configurations investigated. Powerplant reliability was conservatively defined as the

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probability of providing a specified power output (800 kWe) for a fixed
mission duration; no partial-power output states were specified.

The analysis dealt with active redundancy only, and it was assumed that
the reliability of any active element was independent of the state of the
other elements and that all elements within a given subsystem were identical.
Since the concern is with end-of-mission success, and it was presumed that a
required mission time was specified (although not explicitly stated), the unit
success probability could be treated as an assigned constant. That is, time
dependency would likely play a part in the determination of a unit's success
probability, but for this analysis the reliability of a given unit was just a
specified constant.

Generalized equations for active and fully redundant parallel design con-
figurations are well documented in standard reliability texts (e.g., ref. 5).
However, the specific reliability summation expansion equations used for the
partially redundant (k-out-of-n) power-generation configurations investigated
are not commonly documented and are included in appendix A along with a com-
plete tabulation of all powerplant, system, and subsystem reliability equa-
tions and analysis results.

The reliability analysis included twenty-six 400-kWe subsystem configu-
rations and twenty-four 800-kWe subsystem configurations. These fifty con-
figurations provided the reliability data base and system level building
blocks for the four powerplant configuration options. In addition, a set of
high and low estimates of subsystem unit reliabilities was analyzed for each
subsystem configuration to evaluate overall powerplant reliability sensitivity
to emerging technology reliability.

                                MASS ANALYSIS

Mass estimates were developed for the 50 subsystem design configurations.
These estimates were based on a "from-the-ground-up" mass estimation for all
components and are consistent with the mass estimates developed for the
reference powerplant (ref. 1). A tabulation of subsystem mass values is
included in appendix A in conjunction with the reliability analysis results.
Detailed mass breakdowns for reactor and power-generation subsystems and units
are presented in appendix B. Reactor subsystem unit mass estimates were based
on the use of a modified 2.5-MWt SP-100 reactor for both single- and dual-
reactor subsystem design options. A description of specific reactor unit mod-
ifications required for integration with Stirling engines and operation in a
lunar surface excavation is given in reference 1. Also, additional design
modifications to specific reactor subsystem elements were made to reflect the
mass savings due to partial-power operation. This was reflected in reduced
masses for radiation shields, bulkhead/shields, heat-transport loops, and man-
ifolds. Mass estimates for dual-reactor subsystem design concepts were based
on individual excavations for each reactor subsystem and included 100-percent
component redundancy (i.e., linear scaling of component mass) with the excep-
tion of the inlet and outlet manifolds. A larger shared inlet and outlet man-
ifold was assumed for dual installations with a 33-percent mass increase above
the single-reactor manifold estimate.

Power-generation subsystem mass estimates were based on linear scaling of
component masses based on variations in number of units and electrical output

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per unit with the exception of the waste heat radiator and the power management and distribution elements, which were based on fixed specific mass values of 7.8 kg/m^2 and 2.1 kg/kWe, respectively. Stirling engine/linear alternator unit mass estimates were taken from a recent scaling study (ref. 6) that provided engine/alternator specific mass as a function of electrical power. All single-cylinder Stirling engine/alternator unit masses were conservatively based on a larger 113-percent rated power output engine to account for uncertainty, and actual engine operating power levels were conservatively assumed to be about 90 percent of the electrical output of the larger engine. For example, if four engines were required to supply 800 kWe, each engine must provide 200 kWe. However, the mass estimate for each engine was based on a 225-kWe engine operating at 200 kWe. In addition, a maximum rated output of 450 kWe (400 kWe actual) was assumed because of increased uncertainty in engine design at larger sizes.

DISCUSSION OF RESULTS

On the basis of analyses carried out in this study, specific conclusions were reached regarding selection of preferable powerplant, power system, and subsystem configurations of lunar surface powerplants required to meet an assigned 800-kWe electrical load at high reliability and low mass. The major conclusion derived from this effort was that a powerplant consisting of a single (nonredundant) power system composed of two reactor subsystem units and at least four power-generation subsystem units, including two spares, will provide low powerplant mass over a wide range of acceptable reliability criteria and subsystem unit reliability estimates.

Of the four powerplant system design configurations investigated, the single 800-kWe system configuration was the most attractive from a reliability and mass perspective. This is clearly shown in figures 5 and 6, which graphically display the study results in terms of reliability versus mass for all powerplant configurations. The four system configurations are denoted by different symbols, and the subsystem design configurations are defined by three numbers. The first number denotes the number of reactor units, the second denotes the total number of power-generation units, and the third number denotes the number of spare power-generation units. The connecting lines between the subsystem configuration design points are shown for clarity only; they indicate a design commonality of similar type redundancy for both reactor units and spare power-generation units. Actual connecting lines between similar configuration types are truly represented by horizontal lines of constant reliability. This type of graphic depiction will be shown in a discussion of mass-reliability envelopes.

Figure 5 displays results for estimated optimistic reactor and power-generation unit reliability estimates of 0.98 and 0.95, respectively, with a minimum acceptable powerplant reliability criterion cutoff value of 0.95, equivalent to the lower power-generation unit reliability estimate. Figure 6 displays results for pessimistic unit reliability estimates of 0.90 and 0.80 with a minimum acceptable powerplant reliability criterion cutoff value of 0.80, again, equivalent to the lower power-generation unit reliability estimate.

It is important to note that arbitrary selection of the lowest mass acceptable reliability system configuration at either one of the (high or low)

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subsystem reliability estimates will not guarantee minimum mass at an acceptable reliability for the other subsystem reliability estimate. For example, if an arbitrary acceptable overall powerplant reliability criterion is established as approximately equal to or greater than the highest subsystem unit reliability estimate, then the lowest mass powerplant configuration for the optimistic subsystem unit reliability estimates of 0.98 and 0.95 is a single nonredundant powerplant with either a (292) or a (241) subsystem configuration. As shown in figure 5 the (292) configuration has a total powerplant mass of 25 060 kg and provides an overall reliability of 0.9898, and the (241) configuration has powerplant mass and reliability values of 25 260 kg and 0.9856. However, when pessimistic reactor and power-generation unit reliability estimates of 0.90 and 0.80 are selected, the powerplant reliability drops to an unacceptable value of 0.7303 for the (292) configuration (not shown in fig. 6 because it is less than the overall reliability cutoff value) and 0.8110 for the (241) configuration.

Therefore, minimum-mass powerplant configurations should be selected for pessimistic estimates of emerging technology unit reliability in order to ensure acceptable values of overall powerplant reliability. On this basis, the lowest mass powerplant that can provide an overall reliability of approximately 0.90 (equivalent to the highest unit reliability estimate) is a single system with a (262) configuration. This configuration provides a powerplant reliability of 0.8921 for pessimistic subsystem reliability estimates. If additional mass is acceptable and higher reliability is desired, the (252) subsystem configuration increases powerplant reliability to 0.9327. This configuration exhibits a total mass of 28 320 kg, which is only 6 percent higher than the (262) configuration. If maximum powerplant reliability is desired and mass is not overly constrained, the (242) configuration provides significant reliability improvement to 0.9631 at a powerplant mass of 32 340 kg.

The study conclusions and results discussed to this point have been based on an acceptable powerplant reliability criterion keyed to the highest subsystem unit reliability estimate - either 0.98 or 0.90. It is of interest, however, to illustrate the effect of varying the acceptable reliability criterion on the selection of minimum mass configurations for powerplant configurations based on single 800-kWe power systems. This is qualitatively illustrated in table I, which ranks the system configurations according to mass as a function of acceptable system reliability criterion for the high and low subsystem reliability estimates. These results illustrate the wide variation in minimum mass system design configurations that occur for different assumptions of acceptable reliability criteria. In general, as the acceptable reliability criterion is relaxed, the number of acceptable system configurations increases and the mass ranking changes. When the acceptable reliability criterion drops below the lowest unit reliability estimates, single-reactor-unit configurations emerge as acceptable single-system powerplants. For example, for optimistic unit reliability estimates, the (151) configuration with an overall powerplant reliability of 0.9578 yields the lowest mass for a 0.95 reliability criterion. For pessimistic unit reliability estimates, the (162) configuration with an overall powerplant reliability of 0.8110 yields the lowest mass for a 0.80 reliability criterion.

To facilitate the process of defining a reasonable compromise of mass and reliability, English developed an approach based on the delineation of a reliability versus minimum mass envelope (R.E. English, 1990, NASA Lewis Research Center, Cleveland, OH, personal communication). This graphical

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technique is illustrated in figure 7, which depicts the minimum mass power-plant configurations as a function of desired overall powerplant reliability for both pessimistic and optimistic subsystem unit reliabilities. The figure displays the actual reliability step function change associated with each powerplant configuration and provides a more realistic description of the results for use as a design tool.

CONCLUDING REMARKS

As a result of this study some interesting perspectives on the characteristics and selection criteria of high-reliability and low-mass lunar-base powerplant design configurations have emerged. For example, as expected, the wide range of emerging-technology reliability estimates used had a significant effect on the selection of high-reliability and low-mass design configurations. Powerplant designs that provided high reliability with low mass when optimistic emerging technology reliability estimates were assumed were generally unacceptable when pessimistic reliability estimates were substituted. Therefore, to ensure acceptable values of reliability, one should select minimum mass configurations on the basis of pessimistic reliability estimates.

Another interesting result of the study was that for either low or high reliability estimates, the best combination of high powerplant reliability and low mass occurred when redundancy was applied at the lowest level of system hierarchy. Thus, the most attractive powerplant design concepts were non-redundant, single-system powerplants with subsystem-unit redundancy options. Selection of the best redundancy option for the subsystems, however, depended on the definition of an acceptable overall powerplant reliability criterion.

The issue of defining an acceptable overall powerplant reliability criterion was addressed, and the definition of this criterion significantly affected the selection of the best redundancy configuration for the subsystem units. Since the calculated overall reliability of any powerplant configuration is highly dependent on the emerging technology reliability estimates, powerplant reliability is a relative value. Therefore, an acceptable reliability criterion must be defined on the basis of emerging technology reliability estimates. The reasonable choice appeared to be an acceptable reliability criterion that required the overall powerplant reliability to be equal to, or better than, any emerging technology subsystem unit reliability estimate. However, that selection required every acceptable powerplant configuration to have two fully redundant, parallel reactor units. Although dual-unit reactors do not impose a significant mass penalty, they may have integration and operational problems that were not fully explored in this study. Therefore, selecting an attractive powerplant design on the basis of an arbitrary reliability criterion may involve tradeoffs with design or operational complexity as well as with mass.

Additional perspectives into selecting the best redundancy options for the subsystem units were gained by analyzing the effect of varying the overall powerplant reliability criterion with estimates of emerging technology reliabilities. For example, with pessimistic emerging technology reliability estimates and a corresponding reliability criterion of approximately 0.90 or better, the lowest mass powerplant configuration consisted of a single system composed of two fully redundant, parallel reactor units coupled to six parallel, partially redundant power-generation subsystem units including two

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spares. This configuration provided a powerplant reliability of 0.8921 at a mass of 26 660 kg. If higher overall powerplant reliabilities are desired, and additional mass is acceptable, fewer power-generation units are needed. For example, a decrease to five power-generation units, including two spares, provides a powerplant reliability of 0.9327 at a mass of 28 320 kg, and a further decrease to four power-generation units, including two spares, provides the highest single-system powerplant reliability of 0.9631 at a mass of 32 340 kg.

For optimistic emerging technology reliability estimates and a corresponding reliability criterion of 0.98 or better, the lowest mass powerplant, again, consisted of a single-system configuration. However, this configuration was composed of two fully redundant reactor units coupled to nine partially redundant power-generation units with two spares. This configuration provided a powerplant reliability of 0.9898 at a mass of 25 060 kg. Decreasing the number of power-generation units, again, provides higher powerplant reliability at the expense of mass, up to a maximum of 0.9991 at a mass of 32 340 kg for a four-unit power-generation subsystem with two spares.

Reducing the acceptable reliability criterion to, say, the reliability of the lowest emerging technology subsystem unit allows single-unit reactor subsystem configurations to be selected, with a resultant powerplant mass decrease. For example, with pessimistic emerging-technology reliability estimates and a corresponding reliability criterion of approximately 0.80 or better, the lowest mass configuration was a single-system powerplant composed of only one reactor unit coupled to six parallel, partially-redundant power-generation subsystem units including two spares. This configuration provided a powerplant reliability of 0.8110 at a mass of 23 360 kg. If higher powerplant reliabilities are desired, a wide range of single-unit reactor subsystem options are viable up to a reliability criterion of about 0.84.

For optimistic emerging technology reliability estimates and a corresponding reliability criterion of 0.95 or better, the lowest mass conceptual design was a single-system powerplant composed of one reactor unit coupled to five partially redundant power-generation units, including one spare. This configuration provided a powerplant reliability of 0.9578 at a mass of 21 390 kg. If higher powerplant reliabilities are desired, a wide range of single-unit reactor subsystem options are viable up to a reliability criterion of about 0.98.

Another useful product of this study was the delineation of the minimum mass envelope in a plot of reliability versus powerplant mass. This approach provides easy visualization of the best mass and reliability designs and should be useful for future powerplant design studies.

Partial-power powerplant operation is an important area of consideration that has only been lightly touched on in this study. A mission-planning strategy that requires highly reliable "survival" level power will be essential for any manned planet-surface expedition. Any of the powerplant configurations studied herein for an 800-kWe mission success power level will provide significantly higher reliabilities at a lower survival power level. For example, using pessimistic reactor and power-generation unit reliability estimates, a single-system (162) configuration which provides an overall powerplant reliability of 0.8110 at a mass of 23 360 kg for 800 kWe, will provide a reliability of 0.8999 at an assumed survival partial-power level of

400 kWe. The use of dual-reactor configurations can provide even more dramatic increases in survival power reliability. A single-system (262) configuration at 26 660 kg, which provided an overall powerplant reliability of 0.8921 at 800 kWe, will achieve a reliability of 0.9899 at 400 kWe. These results illustrate that reducing survival power level increases reliability in a very comforting way; an important factor for manned missions in a hostile environment. However, optimal powerplant configuration selection may change if mission "success" is redefined to emphasize a "survival" power level.

The methodology developed in this study provided valuable insight into the considerations required to identify and characterize high-reliability and low-mass lunar-base powerplant designs. In general, this methodology can provide similar reliability perspectives for any space power conceptual designs based on emerging technologies with unknown reliabilities.

APPENDIX A - RELIABILITY ANALYSIS

This appendix defines the symbols and provides the equations used in the reliability analysis.

Symbols

k	number of successes
n	total number of parallel power-generation units
p	power-generation subsystem unit reliability
RG	power-generation subsystem reliability
RP	powerplant reliability
RR	reactor subsystem reliability
RS	system reliability
r	reactor subsystem unit reliability
s	number of spare power-generation units

Powerplant Reliability Equations

The following equations were used to calculate overall powerplant reliability for the various levels of redundancy represented by the four powerplant types:

Powerplant type	Powerplant reliability
Single system (nonredundant)	$RP = RS$
Two parallel fully redundant systems	$RP = RS(2 - RS)$
Two series systems (nonredundant)	$RP = (RS)^2$
Three partially redundant (two-out-of-three) systems	$RP = 3RS^2 - 2RS^3$

System Reliability Equations

The following equations were used to calculate system reliability RS for the various levels of redundancy employed in the subsystem configurations:

$$RS = (RR)(RG)$$

where $RR = r$, for a single-reactor subsystem unit, or
$RR = r(2 - r)$, for two parallel, fully redundant reactor subsystem units, and

$$RG = \sum_{k=(n-s)}^{n} \frac{n!}{(n - k)!k!} p^k (1 - p)^{n-k}$$

for n partially redundant, parallel power-generation subsystem units including s spare units.

The general summation expansion for RG reduces to simplified polynomials for the two-spares (s = 2) case.

The following table presents the polynomial expressions derived from the summation expansion for RG for power-generation subsystems employing from three-to-nine units (3 < n < 9) with two spares (s = 2):

Total number of parallel power-generation units, n	Power-generation subsystem reliability, RG
3	$3p - 3p^2 + p^3$
4	$6p^2 - 8p^3 + 3p^4$
5	$10p^3 - 15p^4 + 6p^5$
6	$15p^4 - 24p^5 + 10p^6$
7	$21p^5 - 35p^6 + 15p^7$
8	$28p^6 - 48p^7 + 21p^8$
9	$36p^7 - 63p^8 + 28p^9$

For n partially-redundant power-generation subsystems using only one spare unit (s = 1), the summation expansion reduces to

$$RG = np^{n-1} - (n - 1)p^n$$

System Reliability and Mass Tabulation

Table II presents the matrix of reliability and mass results for single, nonredundant system configurations at two power levels, 400 and 800 kWe, and two levels of subsystem unit reliability.

APPENDIX B - MASS ANALYSIS

This appendix provides the detailed mass breakdown data used to generate total powerplant mass for 400- and 800-kWe system power outputs. It includes separate tabulations of reactor subsystem mass, power-generation subsystem mass, and total system mass.

Reactor Subsystem Mass

Table III presents the component breakdown of reactor subsystem mass elements for 400- and 800-kWe systems using one or two reactor subsystem units. Reactor mass values were conservatively based on a fixed thermal output of 2.5 MWt for all cases. Dual-reactor configurations are assumed to operate in parallel at 50 percent of required power and to share a single set of inlet and outlet manifolds with a 33-percent manifold mass penalty for additional primary-loop piping connections.

Power-Generation Subsystem Mass

For the power-generation subsystem mass, separate estimates were made for the Stirling engine/alternator units and the balance of the subsystem, which included four items: heat transport loop, surface platform, radiator, and power management and distribution (PMAD). Total subsystem mass varied directly with the total number of power-generation units used to generate system power levels of 400 and 800 kWe. The number of power-generation units required to meet each system power level varied with the rated power output of each unit and the number of spares. Stirling engine/alternator unit mass estimates were based on the specific mass and power level relationships obtained from reference 6.

Table IV presents the Stirling engine/alternator mass estimates as a function of the number of required units. Mass values are shown only for the number of required parallel units that can provide power outputs over the 400- to 800-kWe range. Table V presents the balance-of-subsystem mass breakdown for an 800-kWe subsystem output as a function of the number of required units. Table VI presents the balance-of-subsystem mass breakdown for a 400-kWe subsystem power output as a function of the number of required units. Tables VII and VIII present the system mass breakdown for 400- and 800-kWe system power outputs. Mass values are given for reactor and power-generation subsystems as a function of the total number, number of spares, and the power level (kWe) of power-generation units required to produce 400- and 800-kWe system power outputs.

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TABLE I. - EFFECT OF ACCEPTABLE SYSTEM RELIABILITY CRITERION ON
SUBSYSTEM CONFIGURATION SELECTION

Acceptable system reliability criterion	Subsystem configurations of minimum-mass powerplants[a]	
	Reactor unit reliability, 0.98; power-generation unit reliability, 0.95	Reactor unit reliability, 0.90; power-generation unit reliability, 0.80
0.98	(292),(282),(241),(272), (262),(231),(252),(242)	None meet reliability criterion
.95	(151),(192),(182),(141), (172),(162),(271),(261), (131),(251),(152),(292)	(242)
.90	(b)	(262),(252),(242)
.85	(b)	(262),(231),(252),(142),(242)
.80	(b)	(162),(131),(152),(241),(272)

[a]Numbers define the subsystem configuration. The first number is the num-
ber of parallel reactor units, the second number is the total number of
power-generation units, and the third number is the number of spare
power-generation units.
[b]All single- and dual-reactor configurations.

TABLE II. – MATRIX OF RELIABILITY AND MASS RESULTS

(a) System power level, 400 kWe

System configuration[a]	Power output of power-generation unit, kWe	System mass, kg	Low-end system relia-bility,[b] RS	High-end system relia-bility,[c] RS
110	400	11 490	0.7200	0.9310
121	400	15 820	.8640	.9775
131	200	12 930	.8064	.9729
132	400	20 150	.8928	.9799
141	133	12 180	.7373	.9663
142	200	14 850	.8755	.9795
151	100	11 960	.6635	.9578
152	133	13 440	.8479	.9789
161	80	11 780	.5898	.9479
162	100	12 920	.8110	.9778
171	67	11 850	.5190	.9365
172	80	12 550	.7668	.9763
182	67	12 520	.7172	.9743
210	400	14 490	.7920	.9496
221	400	18 770	.9504	.9971
231	200	15 880	.8870	.9924
232	400	23 100	.9821	.9995
241	133	15 130	.8110	.9856
242	200	17 800	.9631	.9991
251	100	14 910	.7299	.9769
252	133	16 390	.9327	.9985
261	80	14 730	.6488	.9668
262	100	15 870	.8921	.9974
271	67	14 800	.5709	.9553
272	80	15 500	.8435	.9958
282	67	15 470	.7966	.9938

[a]Numbers define the subsystem configuration. The first number is the number of parallel reactor units, the second number is the total number of power-generation units, and the third number is the number of spare power-generation units.
[b]For low estimates of reactor and power-generation unit reliability: $r = 0.90$; $p = 0.80$.
[c]For high estimates of reactor and power-generation unit reliability: $r = 0.98$; $p = 0.95$.

TABLE II. - Concluded.

(b) System power level, 800 kWe

System configuration[a]	Power output of power-generation unit, kWe	System mass, kg	Low-end system relia-bility,[b] RS	High-end system relia-bility,[c] RS
131	400	24 660	0.8064	0.9729
141	270	22 320	.7373	.9663
142	400	29 040	.8755	.9795
151	200	21 390	.6635	.9578
152	270	25 020	.8479	.9789
161	160	20 850	.5898	.9479
162	200	23 360	.8110	.9778
171	133	20 660	.5190	.9365
172	160	22 400	.7668	.9763
181	114	20 720	.4531	.9238
182	133	21 960	.7172	.9743
191	100	20 610	.3926	.9104
192	114	21 760	.6639	.9718
231	400	27 960	.8870	.9924
241	270	25 620	.8110	.9856
242	400	32 340	.9631	.9991
251	200	24 690	.7299	.9769
252	270	28 320	.9327	.9985
261	160	24 150	.6488	.9668
262	200	26 660	.8921	.9974
271	133	23 960	.5709	.9553
272	160	25 700	.8435	.9958
282	133	25 260	.7966	.9930
292	114	25 060	.7303	.9898

[a]Numbers define the subsystem configuration. The first number is the number of parallel reactor units, the second number is the total number of power-generation units, and the third number is the number of spare power-generation units.
[b]For low estimates of reactor and power-generation unit reliability: r = 0.90; p = 0.80.
[c]For high estimates of reactor and power-generation unit reliability: r = 0.98; p = 0.95.

TABLE III. - REACTOR SUBSYSTEM MASS BREAKDOWN

Element	System power output, kWe			
	800		400	
	Number of reactors			
	1	2	1	2
Reactor	760	1520	760	1520
Instrumentation and control	360	720	360	720
Radiation shield	940	1880	740	1480
Bulkhead/shield	770	1540	670	1340
Heat transport loop	350	700	300	600
Manifolds	420	550	370	490
Total	3600	6900	3200	6150

TABLE IV. - STIRLING ENGINE/ALTERNATOR UNIT MASS

Rated power per unit, kWe	Output power per unit, kWe	Specific mass at rated power, kg/kWe	Unit mass, kg
65	58	6.3	410
75	67	6.4	480
90	80	6.4	580
113	100	6.8	770
130	114	6.9	897
150	133	7.1	1065
180	160	7.3	1314
225	200	7.7	1733
300	267	8.2	2460
450	400	9.2	4140

Rated power per unit, kWe	Mass, kg									
	Number of units									
	1	2	3	4	5	6	7	8	9	10
65							2870	3280	3690	4100
75						2 880	3360	3840	4320	4800
90					2 900	3 480	4060	4240	5220	5800
113				3 080	3 850	4 620	5390	6160	6930	7700
130				3 588	4 485	5 382	6279	7176	8073	
150			3 195	4 260	5 325	6 390	7455	8520		
180			3 942	5 256	6 570	7 884	9198			
225		3466	5 199	6 932	8 665	10 298				
300		4920	7 380	9 840	12 300					
450	4140	8280	12 420	16 560						

TABLE V. – BALANCE OF POWER-GENERATION SUBSYSTEM MASS FOR 800-kWe OUTPUT

Element	Mass, kg								
	Total number of power-generation units								
	1	2	3	4	5	6	7	8	9
Heat transport	110	220	330	440	550	660	770	880	990
Surface platform	130	260	390	520	650	780	910	1040	1 170
Radiator	6240	6240	6240	6240	6240	6240	6240	6240	6 240
PMAD	1680	1680	1680	1680	1680	1680	1680	1680	1 680
Total, kg	8160	8400	8640	8880	9120	9360	9600	9840	10 080

TABLE VI. – BALANCE OF POWER-GENERATION SUBSYSTEM MASS FOR 400-kWe OUTPUT

Element	Mass, kg								
	Total number of power-generation units								
	1	2	3	4	5	6	7	8	9
Heat transport	90	180	270	360	450	540	630	720	810
Surface platform	100	200	300	400	500	600	700	800	900
Radiator	3120	3120	3120	3120	3120	3120	3120	3120	3120
PMAD	840	840	840	840	840	840	840	840	840
Total, kg	4150	4340	4530	4720	4910	5100	5290	5480	5670

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TABLE VII. - MASS BREAKDOWN OF 800-kWe SYSTEMS

(a) One spare power-generation unit

System or subsystem	Mass, kg							
	Total number of power-generation units							
	3	4	5	6	7	8	9	10
	Power output per unit, kWe							
	400	270	200	160	133	114	100	90
Power-generation subsystem								
Stirling engine/alternator units	12 420	9 840	8 670	7 890	7 460	7 280	6 930	5 800
Balance of subsystem	8 640	8 880	9 120	9 360	9 600	9 840	10 080	10 320
Total	21 060	18 720	17 790	17 250	17 060	17 120	17 010	16 120
System total[a]								
With single reactor unit	24 660	22 320	21 390	20 850	20 660	20 720	20 610	19 720
With two reactor units	27 960	25 620	24 690	24 150	23 960	24 020	23 910	23 020

(b) Two spare power-generation units

System or subsystem	Mass, kg					
	Total number of power-generation units					
	4	5	6	7	8	9
	Power output per unit, kWe					
	400	267	200	160	133	114
Power-generation subsystem						
Stirling engine/alternator units	16 560	12 300	10 400	9 200	8 520	8 080
Balance of subsystem	8 800	9 120	9 360	9 600	9 840	10 080
Total	25 440	21 420	19 760	18 800	18 360	18 160
System total[a]						
With single reactor unit	29 040	25 020	23 360	22 400	21 960	21 760
With two reactor units	32 340	28 320	26 660	25 700	25 260	25 060

[a]Mass of reactor subsystem is 3600 kg with one reactor unit and 6900 kg with two reactor units.

TABLE VIII. - MASS BREAKDOWN OF 400-kWe SYSTEMS

(a) One spare power-generation unit

System or subsystem	Mass, kg						
	Total number of power-generation units						
	2	3	4	5	6	7	8
	Power output per unit, kWe						
	400	200	133	100	80	67	58
Power-generation subsystem							
Stirling engine/alternator units	8 280	5 200	4 260	3 850	3 480	3 360	3 280
Balance of subsystem	4 340	4 530	4 720	4 910	5 100	5 290	5 480
Total	12 620	9 730	8 980	8 760	8 580	8 650	8 760
System total[a]							
With single reactor unit	15 820	12 930	12 180	11 960	11 780	11 850	11 960
With two reactor units	18 770	15 880	15 130	14 910	14 730	14 800	14 910

(b) Two spare power-generaton units

System or subsystem	Mass, kg					
	Total number of power-generation units					
	3	4	5	6	7	8
	Power output per unit, kWe					
	400	200	133	100	80	133
Power-generation subsystem						
Stirling engine/alternator units	12 420	6 930	5 330	4 620	4 060	3 840
Balance of subsystem	4 530	4 720	4 910	5 100	5 290	5 480
Total	16 950	11 650	10 240	9 720	9 350	9 320
System total[a]						
With single reactor unit	20 150	14 850	13 440	12 920	12 550	12 520
With two reactor units	23 100	17 800	16 390	15 870	15 500	15 470

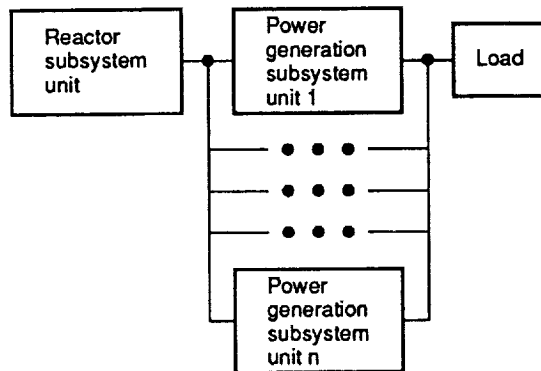[a]Mass of reactor subsystem is 3200 kg with one reactor unit and 6150 kg with two reactor units.

Figure 1.—Subsystem-level configuration for a single
reactor unit and multiple power-generation units.
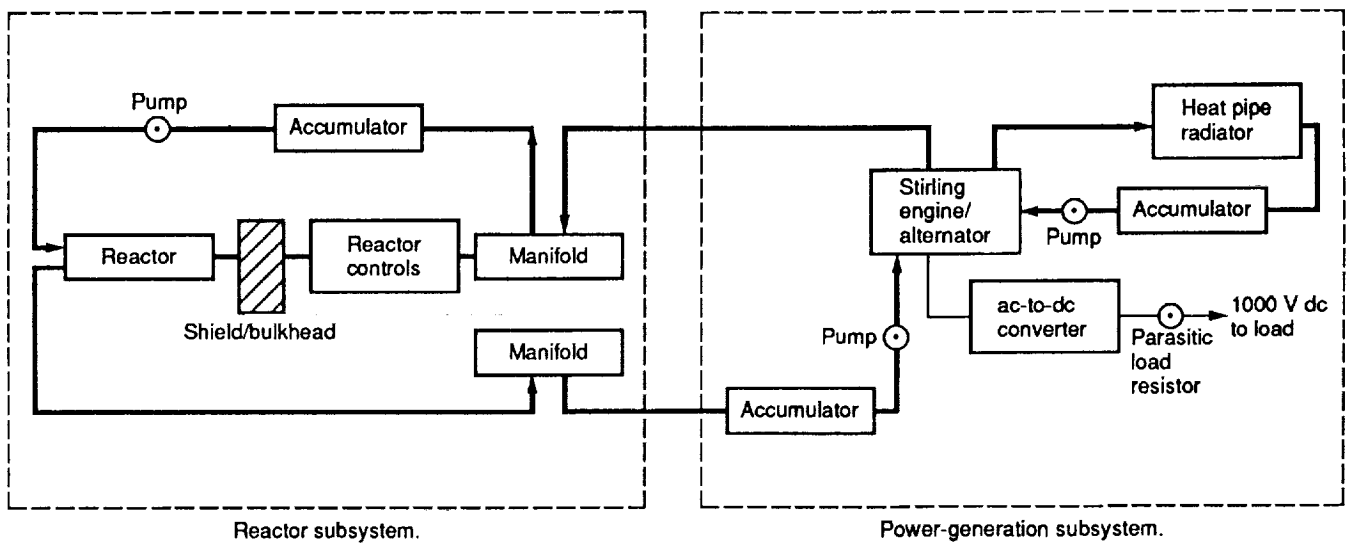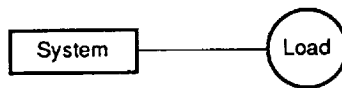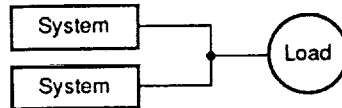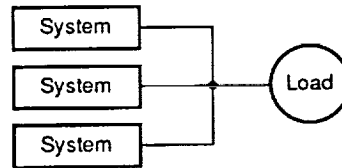

Reactor subsystem.

Power-generation subsystem.

Figure 2.—Simplified schematic of lunar-base powerplant.
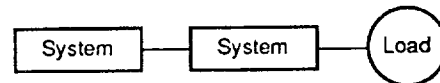
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Single, nonredundant 800-kWe system - no spare

Two parallel, redundant 800-kWe systems - one spare

Three partially redundant 400-kWe systems - one spare

Two series, nonredundant 400-kWe systems - no spare

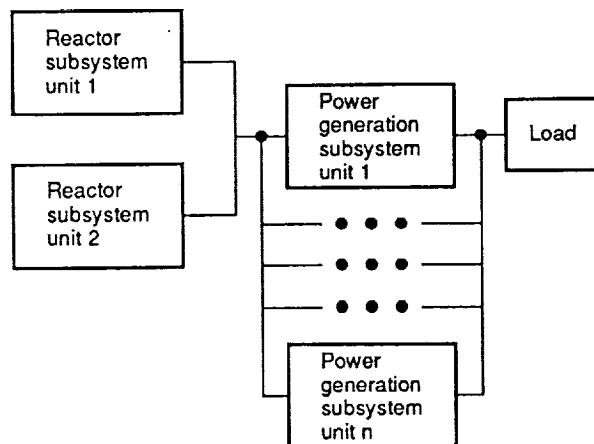Figure 3.—800-kWe lunar-base powerplant system redundancy options.

Figure 4.—Subsystem-level configuration for parallel dual reactor units and multiple power-generation units.
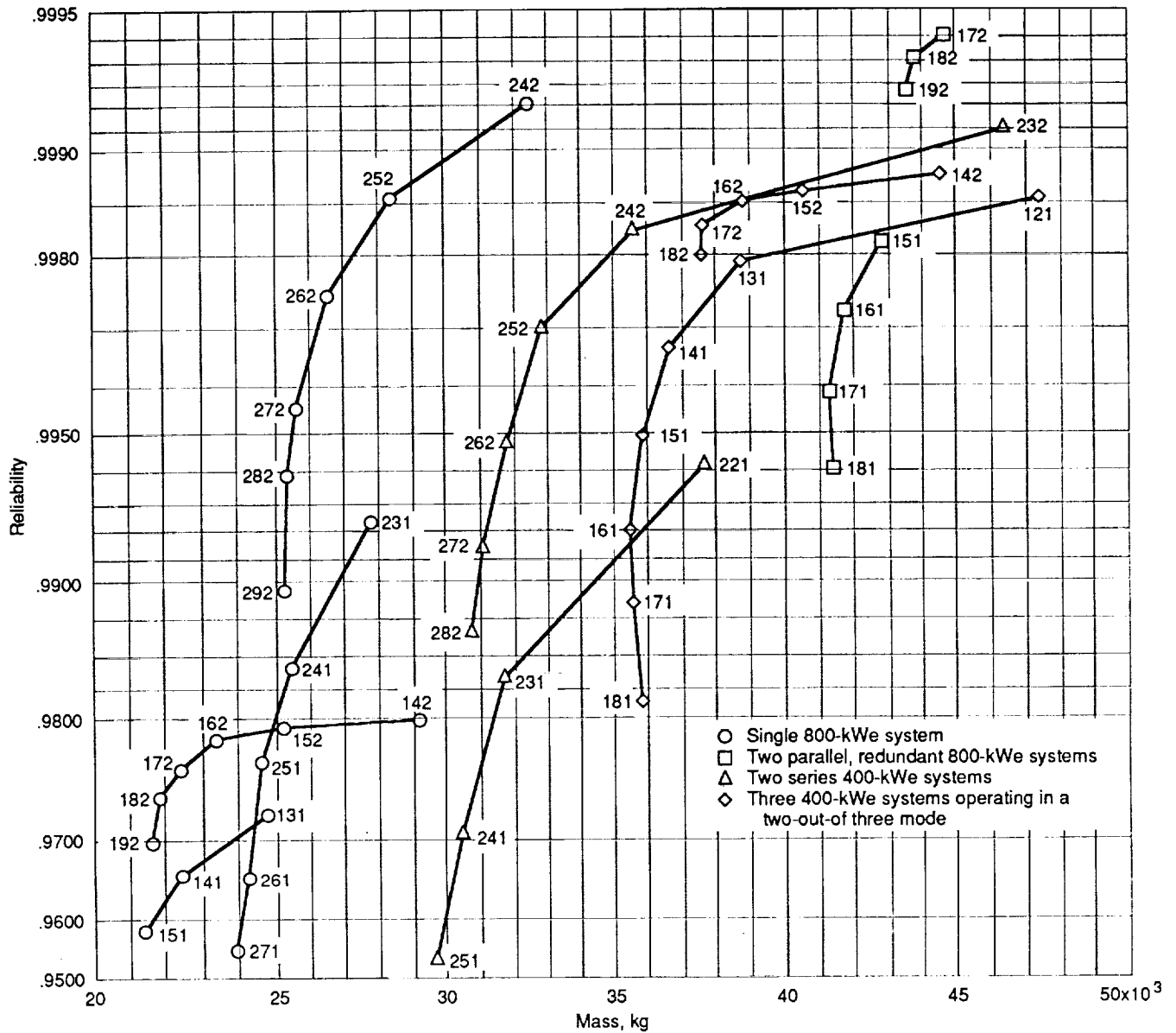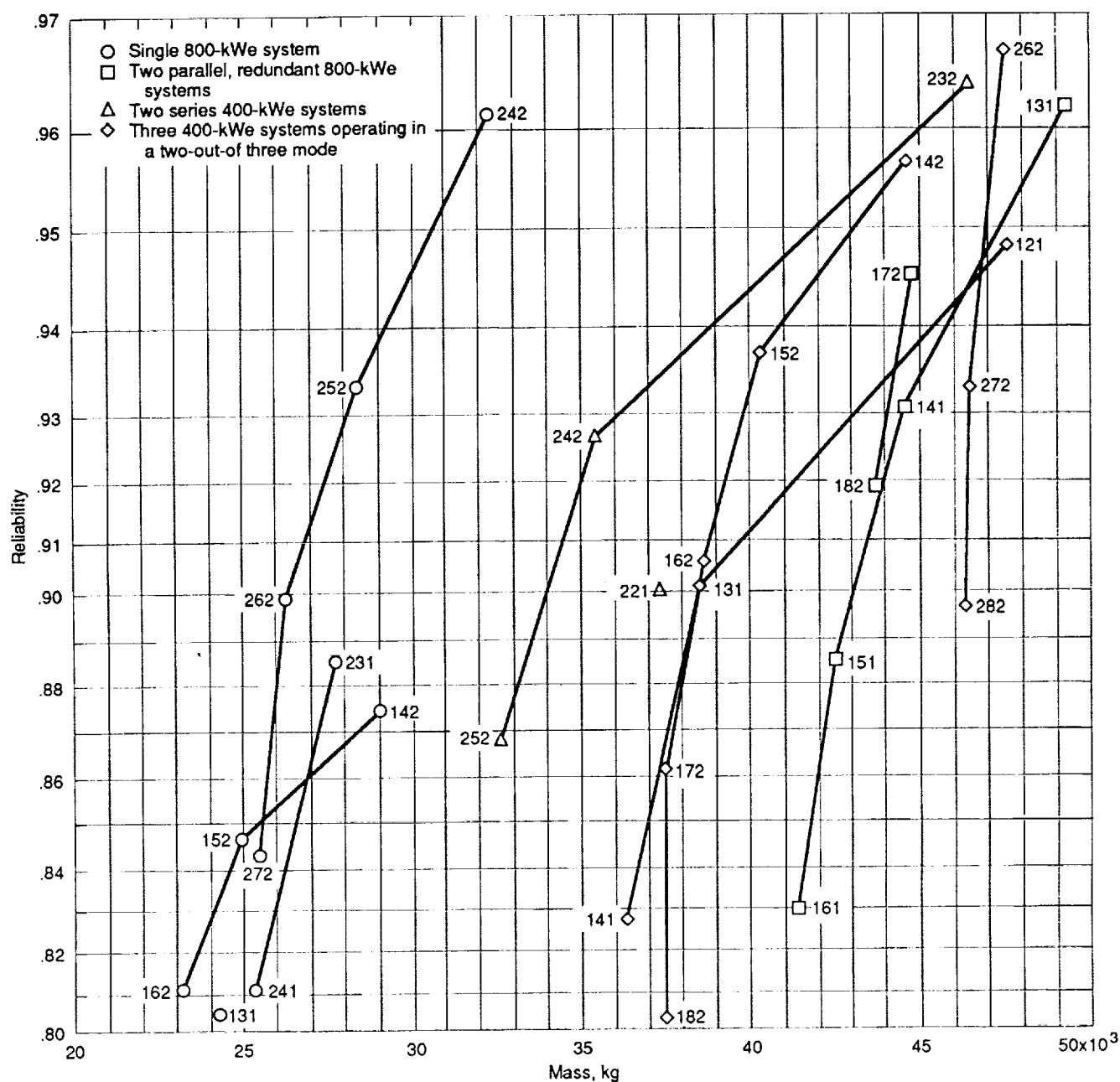
Figure 5.—Reliability and mass of 800-kWe lunar-base powerplant options for a reactor subsystem unit reliability of 0.98 and a power-generation unit reliability of 0.95. Numbers corresponding to points define the system configuration. The first number is the number of parallel reactor subsystems, the second number is the total number of power-generation units, and the third number is the number of spare power-generation units.

Figure 6.—Reliability and mass of 800-kWe lunar-base powerplant options for a reactor subsystem unit reliability of 0.90 and a power-generation unit reliability of 0.80. Numbers corresponding to points define the system configuration. The first number is the number of parallel reactor subsystems, the second number is the total number of power-generation units, and the third number is the number of spare power-generation units.
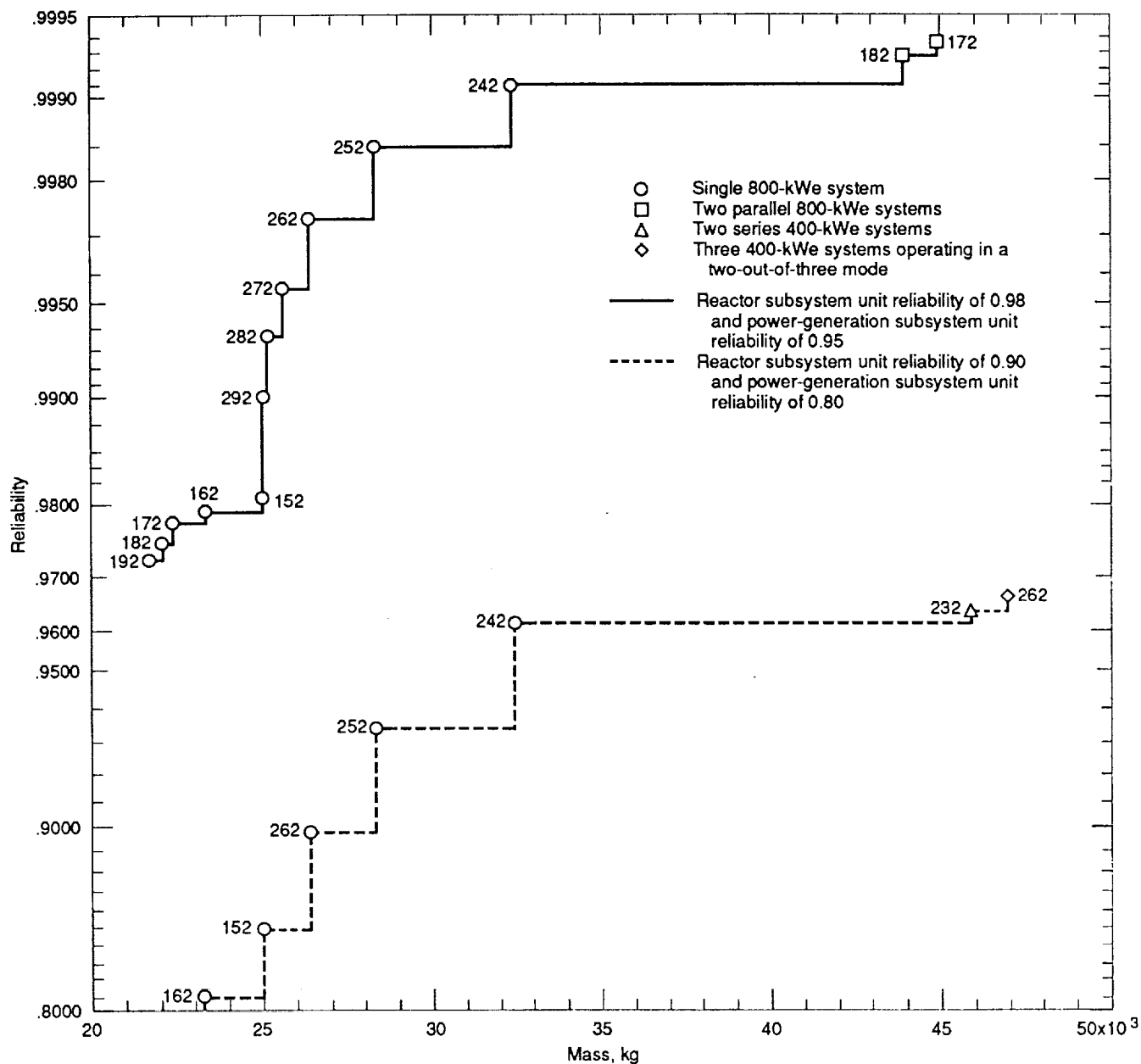
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Figure 7.—Reliability and mass envelopes for 800-kWe lunar base powerplants. Numbers corresponding to points define the system configuration. The first number is the number of parallel reactor subsystems, the second number is the total number of power-generation units, and the third number is the number of spare power-generation units.

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16. Abstract

The purpose of this study was to obtain reliability and mass perspectives on selection of space power system conceptual designs based on SP-100 reactor and Stirling cycle power-generation subsystems. These subsystems employ advanced and/or emerging technologies that have an unknown reliability data base. Therefore, any predictions of overall system reliability will lack validity in a quantitative sense or, at best, engender a low level of confidence. However, it is clear that, at least in a qualitative sense, certain conceptual design configurations can provide higher overall reliabilities than others. This can be achieved through what is referred to as optimal allocation of redundancy. Significant improvement in the reliability of any multielement system can be realized with alternative design configurations that use redundancy at an appropriate level of the system hierarchy. However, improvements in system reliability will always come at the expense of system mass. The approach taken in this study was to (1) develop a criterion for an acceptable overall reliability risk as a function of the expected range of emerging technology subsystem unit reliabilities, (2) conduct reliability and mass analyses for a diverse matrix of 800-kWe lunar-base design configurations employing single and multiple powerplants with both full and partial subsystem redundancy combinations, and (3) derive reliability and mass perspectives on selection of conceptual design configurations that meet an acceptable reliability criterion with the minimum system mass increase relative to reference powerplant design. The perspectives developed in this study provided valuable insight into the considerations required to identify and characterize high-reliability and low-mass lunar-base powerplant conceptual designs. In general, the methodology developed can provide similar perspectives for any space power system conceptual designs that are based on emerging technologies with unknown reliabilities.

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