



# Reliability Assessment Approach for Stirling Convertors and Generators

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Prepared for the  
Space Technology and Applications International Forum (STAIF-2003)  
cosponsored by the United States Department of Energy  
and the National Aeronautics and Space Administration  
Albuquerque, New Mexico, February 2-5, 2003

National Aeronautics and  
Space Administration

Glenn Research Center

## Acknowledgments

The work described in this paper was performed for the Office of Space Science (Code S) and the Office of Aeospace Technology (Code R) at NASA Headquarters, both of which provided funding for these efforts.

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## **Summary**

Stirling power conversion is being considered for use in a radioisotope power system for deep-space science missions because it offers a multifold increase in the conversion efficiency of heat to electric power. Quantifying the reliability of a radioisotope power system that utilizes Stirling power conversion technology is important in developing and demonstrating the capability for long-term success. A description of the Stirling power convertor is provided, along with a discussion about some of the key components. Ongoing efforts to understand component life, design variables at the component and system levels, related sources, and the nature of uncertainties is discussed. The requirement for reliability also is discussed, and some of the critical areas of concern are identified. A section on the objectives of the performance model development and a computation of reliability is included to highlight the goals of this effort. Also, a viable physics-based reliability plan to model the design-level variable uncertainties at the component and system levels is outlined, and potential benefits are elucidated. The plan involves the interaction of different disciplines, maintaining the physical and probabilistic correlations at all the levels, and a verification process based on rational short-term tests. In addition, both top-down and bottom-up coherency were maintained to follow the physics-based design process and mission requirements. The outlined reliability assessment approach provides guidelines to improve the design and identifies governing variables to achieve high reliability in the Stirling Radioisotope Generator design.

## **Introduction**

The NASA Glenn Research Center and the Department of Energy (DOE) are developing a free-piston Stirling power convertor to be used in an advanced radioisotope power system for future NASA deep-space science missions. The Stirling Radioisotope Generator (SRG) is being evaluated as an alternative to replace the Radioisotope Thermoelectric Generators with a power system having a multifold increase in efficiency. For an equivalent level of power, the SRG will reduce the inventory of the radioisotope fuel by a factor of 4 in comparison to the Radioisotope Thermoelectric Generators. Stirling radioisotope power systems similar to those being developed today were initially studied at Glenn in the late 1980s (ref. 1). The current free-piston Stirling effort is the result of two efforts: (1) a 1997 DOE-sponsored study that found the Stirling concept to be the most mature option of the advanced power convertor concepts under consideration (refs. 2 and 3) and (2) the joint industry/Government Stirling Technology Readiness Assessment team of 1999 (ref. 4). DOE, which is responsible for providing radioisotope power systems for NASA missions, managed the recent development of the free-piston Stirling power convertor for this application. Glenn has been involved in the development of Stirling power conversion technology for over 25 yr and is currently providing technical support to DOE.

It is important to assess the reliability of the Stirling convertor and the SRG because this is new technology, with an operation unlike that of the Radioisotope Thermoelectric Generators used in the past. Prior to quantifying the reliability of the SRG, it is important for one to understand that reliability is the probability that parts, components, subsystems, or systems will perform their designed-for functions without failure in specified environments for a desired period of time (ref. 5). No matter what analytical technique is used, the result will be an estimate of the probability of success that is called the reliability. Reliability assurance for planetary missions is a challenging task.

The new radioisotope power system to be developed for NASA deep-space missions will be required to perform efficiently and reliably without maintenance. These missions are typically long lived, lasting for up to 14 yr. The reliability of the SRG should be assessed over the life of the mission, including prelaunch handling, ascent, space flight, possible descent to a planetary surface, and the mission itself. The SRG consists of five major components and subsystems—the heat source, the Stirling power convertor, the structure, the radiator, and the control electronics—and other associated hardware. In order to achieve the desired performance objective and assured success of the power system, it is necessary to perform feasible component-, subsystem-, and system-level tests to validate the design. However, because of technical limitations, in addition to time and cost constraints, it may not be possible to run long-term tests that simulate the actual operating conditions. Because many of the wear-out failure mechanisms that might normally be encountered by moving and contacting parts have been designed out of the Stirling convertor, it may not be possible to precipitate enough failures through life testing or accelerated life testing to estimate the operational life of the Stirling convertor. System-level interactions and variations in processing will likely become the dominant contributors to the total system reliability. The SRG design must achieve a level of reliability that promotes minimal risk to the success of the mission.

The design variables governing the performance and life of the SRG will have uncertainties from different sources. The reliability of individual components is one necessary input to evaluate system reliability. The key to obtaining the best estimate of system reliability is to obtain the best estimate of component reliabilities. The concept is that the reliability of the SRG be derived from the uncertainties of the design variables or physical parameters. If data on the design variables are lacking, the uncertainties can be inferred from data on similar equipment or from expert advice.

Developing a mission-ready generator requires knowledge of (1) the interaction of components with one another, and (2) of the effect of design variables on the performance of the components, the subsystem, and the system. Because of the highly integrated, multidisciplinary nature of the SRG, it is difficult to establish the functional, physics-based relations to determine system-level reliability. Typical engineering design practice makes use of factors of safety and margins to guide the design. It is worth noting that there have been great advances over the past decade in reliability-based designs and that the industry has moved toward developing products and systems based on reliability-based designs (ref. 6). These innovative concepts have resulted in cost-effective, efficient, safe, and reliable products. Although reliability-based design approaches are gaining acceptance by the industry, they have not become a part of design standards (such as the ASME Boiler Code, the MIL design handbook, etc.), certification processes, or mandatory legal requirements. Thus, the current use of reliability quantification has become a complementary tool to the well-established deterministic methods of design for deriving a greater confidence in the design. Under this philosophy, the Stirling project at Glenn has developed an initial reliability quantification plan. Knowing the probability of success for the intended mission is thought to be more valuable in assessing power system options than knowing about factors of safety and design margins.

Designers often use computer simulations or virtual experiments to understand the behavior of components and/or systems under different design and operating conditions and to estimate reliability. Simulations can often be performed at lower cost and within a shorter time period than system-level tests. They also enable engineers to quantify the impact of variations in critical design variables on system-level performance. In addition, computer simulations can be validated with available test data, and system performance models can be enhanced to consider the interactions between components and the applicable design variables.

## Stirling Radioisotope Generator

The Stirling convertor is a free-piston Stirling engine that has been integrated with a linear alternator in a common pressure vessel. This device converts thermal energy from the decay of a radioisotope heat source into electric power at a fixed frequency. As part of the Stirling technology development at Glenn, efforts have focused on minimizing and/or eliminating life-limiting mechanisms. The Stirling convertors currently being considered for flights do not have rubbing piston seals, oil lubrication systems, or other wear mechanisms, but rather they achieve noncontacting operation of the moving components through the use of flexures. Thus, the Stirling convertor was developed for long life and high reliability through a design process that eliminated wear-out failure mechanisms. The specific Stirling convertor being transitioned to flight is the Technology Demonstration Convertor (TDC) that was developed by the Stirling Technology Company of Kennewick, Washington (ref. 7). The TDC was sized to use the nominal 250 W of heat provided by a DOE general-purpose heat source module. A total of 16 TDCs have been built, four of which have been used in a wide range of tests at Glenn and are shown on test stands in figure 1. Critical components governing the performance and reliability of the convertor are the heater head, regenerator, displacer, flexures, clearance seals, cooler, linear alternator (magnets, stators, and coils), and the controller. The controller acts as a load for the convertor by processing the electrical power generated at the desired voltage to maintain the desired piston amplitude. The controller also corrects the power factor, rectifies the alternating-current power, and filters the output. Key components in the Stirling convertor and a description of their functions are shown in figure 2.

Two Stirling convertors and general-purpose heat source modules will be integrated into a generator referred to as the SRG. Following a competitive procurement by DOE, Lockheed Martin Astronautics of Valley Forge, Pennsylvania, was selected as the system integration contractor (ref. 8). A cutaway of the generator design developed by Lockheed Martin is shown in figure 3. The power system for a mission would consist of one or more generators to achieve the required power level. Each generator has two Stirling convertors operating in a synchronous mode to produce a dynamically balanced unit. The power system architecture chosen for a mission may incorporate a redundant generator to be used as a backup in the unlikely event of a single generator failure. A reliability assessment of the power system must consider the operational presence of all the units. Although the concepts are simple, the design for long life with the required performance and assured reliability is a challenging task.

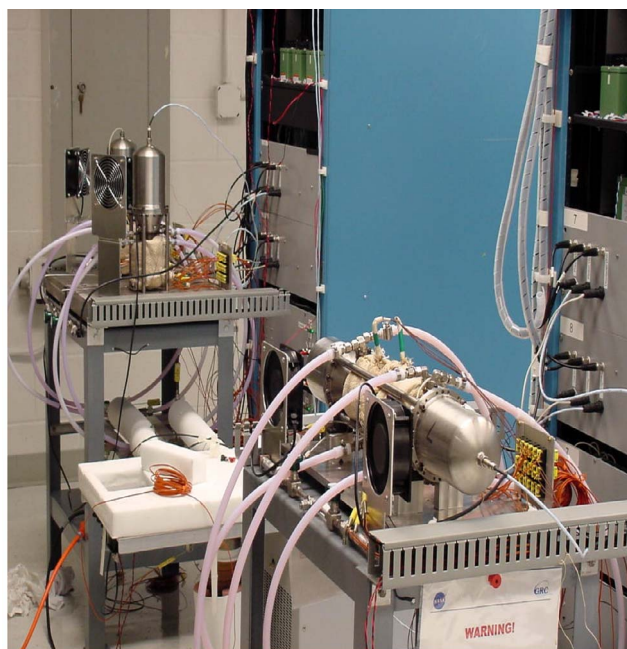


Figure 1.—Free-piston Stirling Technology Demonstration Convertors on test stands at Glenn Research Center.

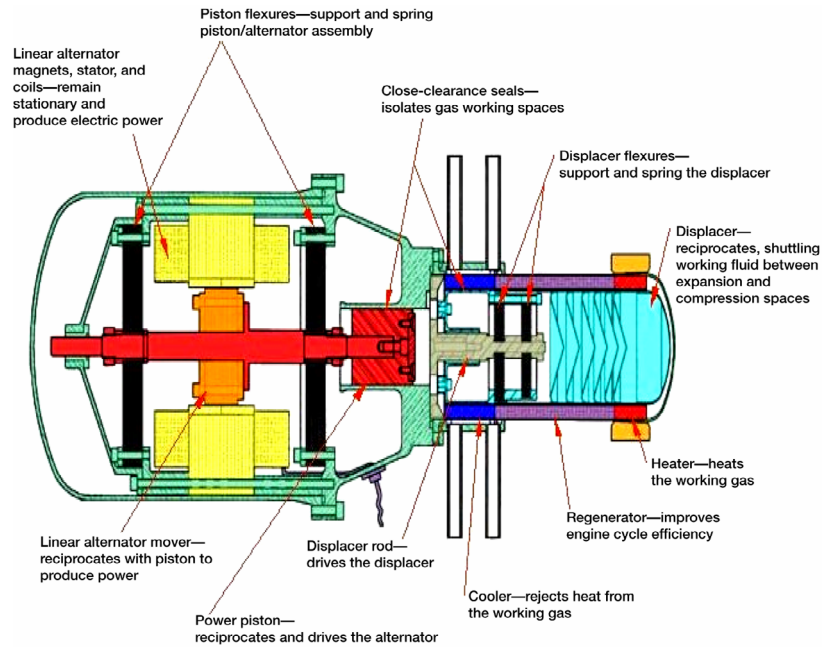


Figure 2.—Technology Demonstration Converter cross section with major components labeled.

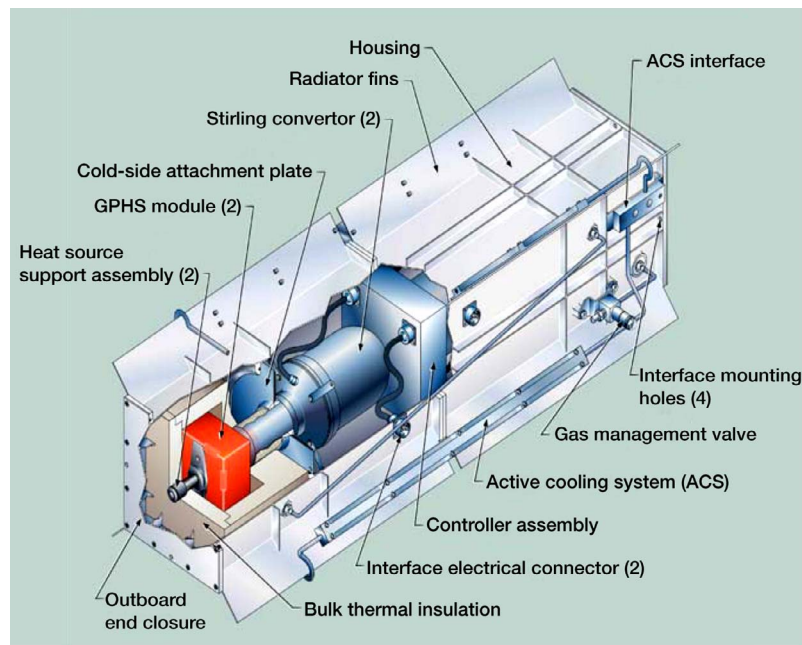


Figure 3.—Cutaway of the Stirling Radioisotope Generator with one Stirling converter and one general-purpose heat source (GPHS) module shown.



## Objectives

Deep-space missions are expected to have lives up to 14 yr or more. A reliable supply of uninterrupted power that meets all the mission power-quality requirements is necessary to achieve mission success. Radioisotope power systems of the past have been able to achieve this objective; however, they have done so with an efficiency that is substantially lower than that of the proposed SRG. In the SRG, the reliability of the Stirling convertor is a key to meeting the generator and power system reliability requirements. The state-of-the-art in Stirling convertor development is the culmination of more than 25 yr of technology development efforts at Glenn and of approximately 35 yr in the free-piston Stirling industry. Over this period, many changes in the development process occurred to establish the viability of this energy-conversion technology. As a result, the engineering design calculations and test results appear to indicate that the Stirling convertor of today has the potential for being a reliable machine. Glenn's Stirling project office has led a technology development effort that involves several engineering areas, including materials; mechanical, electrical, structural, and thermal components; controllers; and sensors. Similar to the development of many components, the Stirling convertor faces manifold reliability issues because of uncertainties in the design variables, manufacturing processes, integration process, and human interaction. However, it should be noted that many components of the system have been successfully tested individually, as well as at the subsystem level, over a long period of time under various environmental and operational conditions. Nonetheless, it is important to establish (quantify) the reliability of the convertor and the generator (SRG) to develop reliability and instill confidence.

Reliability of the Stirling convertor has been a key element in the development of the TDC and SRG. Focused efforts have been underway on some of the key components, such as the heater head and the linear alternator permanent magnets (ref. 9). These components were highlighted in a failure mode and effect analysis of the convertor (ref. 4). An effort is currently being planned to quantify the reliability of the Stirling convertor, with future expansion to encompass the generator.

As previously mentioned, reliability of the SRG should be assessed over the life and for all phases of the mission. The design must achieve a level of reliability that promotes minimal risk to the mission. Since the convertor and generator have multidisciplinary components, and their interactions are involved in the operation, it is essential to not only consider individual component failure but also its role at the system level. Over and above assuring reliability from a design point, it is important to verify the assessment process through comparison with existing test data, when available. Considering the practical cost and time limitations of obtaining long-life (3 yr for Mars and up to 14 yr for deep-space missions) test data, one must develop and use testing procedures that are relevant to assessing the reliability and verifying the analysis.

## Uncertainty in Design

Experience has enabled scientists and engineers to learn about uncertainties from various disciplines involved in the Stirling convertor. The most important uncertainties are those related to the mechanical (structural), electrical, electromagnetic, electronics, and thermal management disciplines. Uncertainties related to structural aspects of the convertor are mostly related to the heater head and the flexures. The heater head is the only structural part of the convertor that is subject to high-temperature loads resulting in creep that could affect the operational life. Efforts over the last 2 yr have led to a reliability-based long-life heater head design (ref. 10). Other structural parts, such as the flexures and housing, have been designed far beyond their endurance limits with little impact on the mass and overall performance of the convertor. The proposed reliability effort will focus on the nonstructural areas of the Stirling convertor and the generator.

One important aspect of performing a system reliability assessment relates to the definition of the system. This is true in the case of the Stirling convertor and the SRG. As described earlier, a power

system for a deep-space mission involves at least one and, very often, up to three SRGs. Each SRG contains two synchronously operating, balanced Stirling convertors and can be considered a standalone unit. The number of SRGs may or may not include one generator for redundancy, to supply power in the event of one failed SRG. Although all the Stirling convertors and SRGs will be manufactured from the same design and manufacturing procedures, and from nominally identical materials, there is a basis for believing that all units would not fail from the same failure mechanism. Failures are not anticipated to be design related, rather they would be dominated by process-related events and/or human-interaction-related issues. Therefore, a redundant SRG would, in fact, act as a risk-mitigation measure at the power-system level. We acknowledge that the application of redundancy in the power system assumes that care was taken in the SRG design to prevent common-cause failure mechanisms. Thus, redundancy is expected to enhance the reliability of the entire power system, and in turn, of the mission.

## Reliability Prediction Approach

Quantification of the Stirling convertor and generator reliability requires the knowledge of analytical approaches and the physics involved. A variety of approaches have been developed and applied to general reliability analysis over the past few decades. Several of the techniques have been applied to engineering solutions and have been proven to be meaningful by leading to successful designs. The reliability of individual components is a necessary input to the system reliability analysis. Development of a system reliability model that represents the SRG requires a synthesis of various reliability analysis methods. Component reliabilities may be determined by different failure distributions such as exponential (electronics) or Weibull (mechanical), or they may be determined by using another approach that does not involve time-to-failure data from life testing. The technical approach to be adopted in the reliability plan development and analysis relies largely upon the nature and the source of uncertainties, the disciplines involved, the behavior of the components and/or systems, and the governing physics. Another logical approach would be to perform accelerated life testing at elevated environmental conditions that exceed levels for a typical planetary or deep-space mission. The idea would be to induce SRG failures resulting from design weaknesses over a reasonably short period of time. However, given the elimination of wear-out failure mechanisms, accelerated tests may not reduce the test time necessary to accrue failures to a reasonable duration. The critical components for achieving long life in a Stirling convertor do not have a common acceleration mechanism, and therefore, accelerated life tests of the convertor and/or system are not possible. Considering the highly integrated, multidisciplinary nature of the SRG, it is not clear that traditional accelerated life tests could accurately predict the reliability of life.

A radioisotope power system would consist of one or more SRGs, as shown in figure 4. Each SRG includes two Stirling convertors and a controller. Since Stirling convertors and controllers are composed of many components, each can be considered as a subsystem. The reliability-based design and system reliability quantification of the power system involves (1) analytical quantification of component and system reliability and (2) verification of analytical results with the test data. The analytical and computational process involves the following general steps:

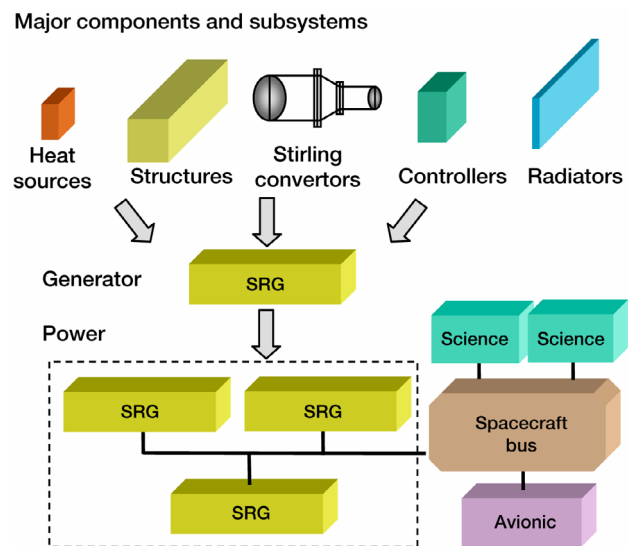


Figure 4.—Some components and subsystems in the power system. SRG, Stirling Radioisotope Generator.

- (1) Determine and describe the intended operating environment, mission reliability requirements, scenarios, timeline, and mission success as they relate to the power system.
- (2) Identify the components, subsystems, interfaces, and system boundary.
- (3) Identify the disciplines for each component and subsystem and for the system in general.
- (4) Identify the component- and system-level design variables that are critical from an uncertainty and reliability viewpoint.
- (5) Understand the physics behind the performance of individual components, and determine the interaction among components at the system level. Develop mathematical or phenomenological component and system performance models.
- (6) Determine uncertainties at both the component and system level on the basis of the components and system, physics, phenomena, component behavior, and objectives of the analysis.
- (7) Collect data and quantify uncertainties related to the design variables at the component and system level.
- (8) Quantify and predict the reliability at the component and system level. Identify the variables governing the reliability, and quantify their level of sensitivity.
- (9) Validate and verify the quantification through comparison with test data at the component, subsystem, and system level.
- (10) Develop guidelines to perform component- and/or system-level tests to verify the simulated results and develop confidence in the design methodology.
- (11) Develop guidelines to improve the reliability and/or mitigate the risk.
- (12) Perform final evaluations of the improved designs, if there are any, and develop procedures and plans for the certification and flight-readiness process.

It is evident from these steps that component reliability needs to be evaluated first and that the computed component failure distributions should be used as input for system reliability quantification. Components such as the linear alternator, heater head, regenerator, displacer, clearance seals, controllers, and many other accessories are generally designed on the basis of fabrication technology, experience, and tests supported by computational simulations in related fields. Looking at several disciplines along with discussions with experts involved in Stirling convertor development has revealed that the important areas that need to be considered in the reliability quantifications include mechanical and electrical, thermal management, and controls. Structural components, other than the heater head, are not expected to be critical. The reliability-based design of the heater head is being finalized. Accelerated tests are being planned to verify the design, and testing should begin soon (refs. 9 and 10).

Owing to the multidisciplinary nature of the Stirling convertor, developing the performance models describing the physics and interaction among different components and subsystems is a difficult task. Existing models are empirical and have very limited mathematics behind them. Therefore, a sound knowledge of and experience with the deterministic approaches that are being used in the current development and design process of the Stirling convertor are of extreme importance in order to understand the sources of uncertainties as well as simulate their effects on the component and/or system performance. Mere knowledge of reliability, probability, and statistical theories would not be sufficient for this reliability assessment. The behavior of many of these components and their interactions at the component and/or system levels are not well defined mathematically, and they are considered to have discontinuous and discrete functions. Insufficient data related to the design variable uncertainties can be accounted for by computing the confidence bounds on the reliability estimates. On the basis of the previously outlined steps, figure 5 describes the component reliability procedure in general, which may vary depending upon the nature of the component.

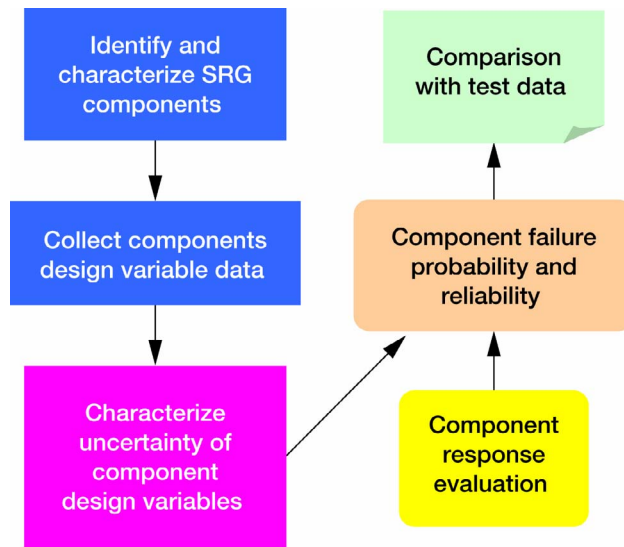


Figure 5.—Component reliability evaluation process.  
SRG, Stirling Radioisotope Generator.

Traditional probabilistic approaches—such as first-order second moment, second-order second moment, and fast probability integration—may not be suitable for a reliability assessment because of the high nonlinearity of component behavior, interactions among components, discreteness of some of the variables, and the nature of uncertainties (refs. 11 and 12). However, in order to make a reliability prediction of the Stirling convertor, it is imperative that one have knowledge of reliability modeling and that reliability be expressed as the probability of success in the final answer. Techniques such as Monte-Carlo simulations and failure rate analysis methods for accessories may be more appropriate for Stirling convertors.

As mentioned earlier, the reliability analysis must address the probability over the desired life. A system reliability model requires a definition of the conceptual behavioral diagram (tree) of the components and the system, uncertainties in the component-level design variables, failure probability distributions of the components and the system, and failure definitions of the components and the system. The approach to system reliability prediction requires a coherent top-down and bottom-up analysis of an SRG. Either a fault tree or a success tree approach could be used to include component failure probabilities. A system success tree defines the logical and causal relationship between the events that bring about the top-level success event. The intermediate events on the second level or subsequent levels of the success tree define events that may occur independently or in combination to bring about the top-level success event. Appropriate logic gates are used to further analyze each of these intermediate events at lower levels of the success tree. The success tree is developed as far as necessary, or to the level of basic events. Likewise, the complement of this same process, the fault tree, may be carried out.

The fault tree's bottom-up approach enables quantification of the effect of design variables at the component level as well as at the subsystem level, in a qualitative as well as quantitative manner, whereas the success tree's top-down approach ensures that overall mission requirements are met at all levels of the system. To simulate the effect of uncertainties in the variables at different levels on the overall system reliability, both physical and probabilistic correlations must be retained throughout the entire analysis. System reliability approaches such as fault tree analysis and success tree analysis (ref. 13) can be used, or reliability block diagrams can be applied. These methods use either Monte-Carlo or adaptive Monte-Carlo simulation methods to perform the system reliability computation. Fault tree and success tree approaches are complements of each other and can be used to encompass basic fault tree or failure events that may be caused by system command faults or human error. A fault tree tool can be used to find the cut sets: the combination of basic success events that can cause a top-level failure event. The minimal cut set can also

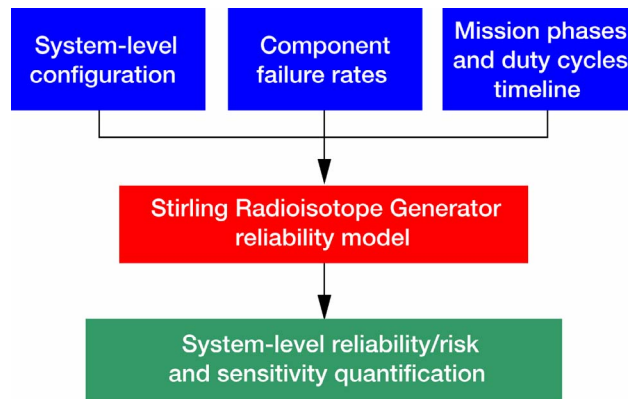


Figure 6.—System reliability quantification process.

be found: the smallest combination of basic fault events that result in a top-level failure event. The quantitative evaluations of a fault tree consist of the determination of the top-level event probability, the importance measures for the basic fault events, sensitivity studies, and uncertainty analysis. Uncertainty analysis calculates the variability in the fault tree top-level event probability resulting from uncertainties in the basic event probabilities. A typical flow diagram of the system reliability assessment for an SRG is given in figure 6.

Other aspects of the reliability quantification plan are the quantification of uncertainties in the design variables and verification of the quantified component/system reliability with the test data. Design variable uncertainties have to be based on the available data, expert opinions, and judgment. Design variable uncertainties may not exist in the form of probability distributions, since many variables may not be continuous in nature as required by the probability distributions. Other forms of uncertainty modeling may need to be used in the process. Appropriate statistical methods will be required to quantify the design variable uncertainties. Another aspect of quantified component and system verification requires the availability of test data. Since tests cannot be performed for the design life, approaches to design accelerated tests, similar to those for the heater head, need to be developed. In addition to expertise in reliability analysis, a strong background and experience in related areas is needed to design such tests. The accelerated testing must be performed at the component as well as the system level. Since reliability assessment normally precedes testing, we suggest that the test data be used to support the verification process. Bayesian methods of reliability analysis (ref. 14) may prove to be appropriate for the verification process.

Life testing a manufacturing lot of maybe six or seven Stirling convertors under simulated mission conditions may not precipitate any failures over a period of years. The next logical approach would be accelerated life testing of components. Conducting accelerated life testing at environmental and stress conditions that exceed the expected levels for a typical deep-space mission, and extrapolating or interpolating the results is one way to verify the design reliability. The idea would be to induce failures resulting from design weaknesses over a short (and reasonable) period of test time in order to quantify the reliable life of the component or the system. The computational evaluation of the component or system using the methodology for long-term design can be performed with the variables used in the tests, and comparisons could be made to validate the accelerated tests. Accelerated test models can be used to interpolate or extrapolate the results to the expected mission variable levels to predict operating life.

## Concluding Remarks

Reliability quantification of the SRG provides confidence in continuous performance and enables designers, fabricators, manufacturers, and system integrators to augment the certification process required for launch and success. Also, reliability-based design facilitates the development of cost and performance effectiveness, and it allows tradeoff studies to be performed between alternative designs. It is important to assess the reliability of the SRG because it is a candidate power-generation technology for long-duration space missions. Due to the fact that the Stirling convertor has been designed to eliminate wear-out failure mechanisms common with contacting parts and friction, it will be challenging to develop life tests. As a first step in the approach to reliability assessment, a methodology for reliability quantification has been proposed that combines system reliability modeling tools with the detailed and comprehensive evaluation of uncertainties in the design variables. In particular, the approach has been presented to derive component and system reliability from the uncertainties in the basic physical design variables. In addition, the approach presented will provide sensitivity to the physical variables governing the component and/or system reliability. Sensitivity information helps develop guidelines to improve the design reliability. It can also be used to develop quality control, inspection criteria, and procedures.

## References

1. Bents, David J.: Preliminary Assessment of Rover Power Systems for the Mars Rover Sample Return Mission. NASA TM-102003, 1989.
2. Frazier, T.A.: Advanced Conversion Technology Review Panel Report. Proceedings of the 33rd Intersociety Energy Conversion Engineering Conference, IECEC-98-398, 1998.
3. Mondt, J.F.; Underwood, M.; and Nesmith, B.J.: Advanced Converter Technology Evaluation and Selection for ARPS (Advanced Radioisotope Power Source). AIP Conference Proceedings 420, pt. 3, 1998, pp. 1098-1105.
4. Furlong, Richard; and Shaltens, Richard: Technology Assessment of DoE's 55-We Stirling Technology Demonstrator Convertor (TDC). AIAA Paper 2000-3018, 2000.
5. Kececioglu, Dimitri: Reliability Engineering Handbook. Prentice-Hall, Englewood Cliffs, NJ, 1991.
6. Shah, A.R., et al.: Probabilistic Evaluation of Uncertainties and Risks in Aerospace Components. Chapter 10, AIAA, Washington, DC, 1992, pp. 365-415.
7. Qui, Songgang, et al.: Developing a Free-Piston Stirling Convertor for Advanced Radioisotope Space Power Systems. AIP Conference Proceedings, vol. 608, 2002, pp. 912-917.
8. Cockfield, Robert D.; and Chan, Tak S.: Stirling Radioisotope Generator for Mars Surface and Deep Space Missions. Proceedings of the 37th Annual IEEE Intersociety Energy Conversion Engineering Conference, IECEC 2002 Paper 20188, 2002.
9. Thieme, L.G.; Schreiber, J.G.; and Mason, L.S.: Stirling Technology Development at NASA GRC. American Institute of Physics Conference Proceedings, no. 608, 2002, pp. 872-879.
10. Halford, Gary R., et al.: Structural Analyses of Stirling Power-Convertor Heater Head for Long-Term Reliability, Durability, and Performance. AIP Conference Proceedings, vol. 608, no. 1, 2002, pp. 880-887.
11. Melchers, Robert E.: Structural Reliability Analysis and Prediction. John Wiley & Sons, New York, NY, 1999.
12. Wu, Y.T.; and Wirsching, P.H.: New Algorithm for Structural Reliability Estimation. J. Eng. Mech., vol. 113, no. 9, 1987, pp. 1319-1336.
13. Stamatiatos, Michael, et al.: Fault Tree Handbook With Aerospace Applications. Version 1.1, Prepared for NASA Office of Safety and Mission Assurance, NASA Headquarters, 2002.
14. Ang, Alfredo H-S.; and Tang, Wilson H.: Probability Concepts in Engineering Planning and Design. John Wiley & Sons, New York, NY, 1975.



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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2004		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE  Reliability Assessment Approach for Stirling Convertors and Generators			5. FUNDING NUMBERS  WBS-22-972-20-01	
6. AUTHOR(S)  Ashwin R. Shah, Jeffrey G. Schreiber, Edward Zampino, and Timothy Best				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER  E-14554	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA TM-2004-213078	
11. SUPPLEMENTARY NOTES Prepared for the Space Technology and Applications International Forum (STAIF-2003) cosponsored by the United States Department of Energy and the National Aeronautics and Space Administration, Albuquerque, New Mexico, February 2-5, 2003. Ashwin R. Shah, Sest, Inc., 18000 Jefferson Park, Suite 104, Middleburg Heights, Ohio 44130; and Jeffrey G. Schreiber, Edward Zampino, and Timothy Best, NASA Glenn Research Center. Responsible person, Jeffrey G. Schreiber, organization code 5490, 216-433-6144.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Categories: 20, 38, and 44 Distribution: Nonstandard  Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Stirling power conversion is being considered for use in a Radioisotope Power System for deep-space science missions because it offers a multifold increase in the conversion efficiency of heat to electric power. Quantifying the reliability of a Radioisotope Power System that utilizes Stirling power conversion technology is important in developing and demonstrating the capability for long-term success. A description of the Stirling power convertor is provided, along with a discussion about some of the key components. Ongoing efforts to understand component life, design variables at the component and system levels, related sources, and the nature of uncertainties is discussed. The requirement for reliability also is discussed, and some of the critical areas of concern are identified. A section on the objectives of the performance model development and a computation of reliability is included to highlight the goals of this effort. Also, a viable physics-based reliability plan to model the design-level variable uncertainties at the component and system levels is outlined, and potential benefits are elucidated. The plan involves the interaction of different disciplines, maintaining the physical and probabilistic correlations at all the levels, and a verification process based on rational short-term tests. In addition, both top-down and bottom-up coherency were maintained to follow the physics-based design process and mission requirements. The outlined reliability assessment approach provides guidelines to improve the design and identifies governing variables to achieve high reliability in the Stirling Radioisotope Generator design.				
14. SUBJECT TERMS  Stirling convertors			15. NUMBER OF PAGES 16	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE  Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT  Unclassified	20. LIMITATION OF ABSTRACT	





