Reliability Issues in Stirling Radioisotope Power Systems

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Stirling power conversion is a potential candidate for use in a Radioisotope Power System (RPS) for space science missions because it offers a multifold increase in the conversion efficiency of heat to electric power and reduced requirement of radioactive material. Reliability of an RPS that utilizes Stirling power conversion technology is important in order to ascertain long term successful performance. Owing to long life time requirement (14 years), it is difficult to perform long-term tests that encompass all the uncertainties involved in the design variables of components and subsystems comprising the RPS. The requirement for uninterrupted performance reliability and related issues are discussed, and some of the critical areas of concern are identified. An overview of the current on-going efforts to understand component life, design variables at the component and system levels, and related sources and nature of uncertainties are also discussed. Current status of the 110 watt Stirling Radioisotope Generator (SRG110) reliability efforts is described. Additionally, an approach showing the use of past experience on other successfully used power systems to develop a reliability plan for the SRG110 design is outlined.

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Presentation outline:

- Background
- Stirling radioisotope generator (SRG) power system description
- Stirling convertor assembly (SCA) components
- Objectives
- Identification of uncertainties
- Reliability issues in SCA components
- Summary/concluding remarks
- Acknowledgment

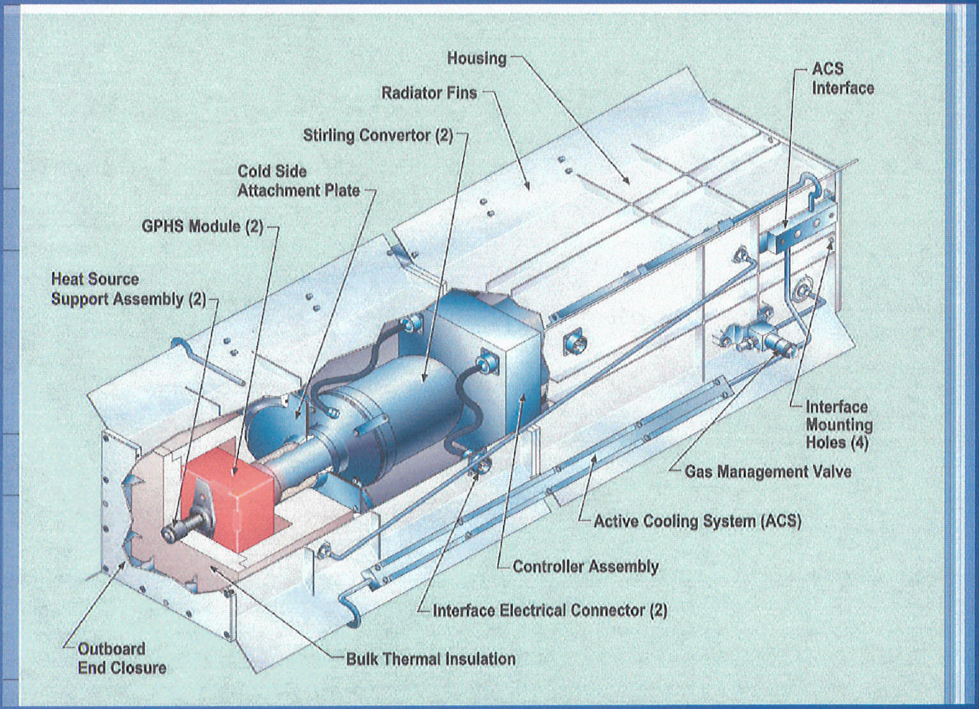
Background:

- Stirling power conversion is a potential candidate for use in Radioisotope Power System RPS for NASA deep space science missions.
- RPS is required to supply uninterrupted power, perform efficiently, reliably and without maintenance for at least 14 years
- Long life includes pre-launch handling, assent, space flight and possible descent to a planetary surface
- Reliability of Stirling Radioisotope Generator (SRG) and Stirling convertor are key elements of the SRG power system

Objectives:

- Identify critical components of the Stirling Convertor Assembly (SCA)
- Identify uncertainties associated with components
- Describe possible failures affecting the performance of SCA and mission success
- Reliability Issues
- Status of current work

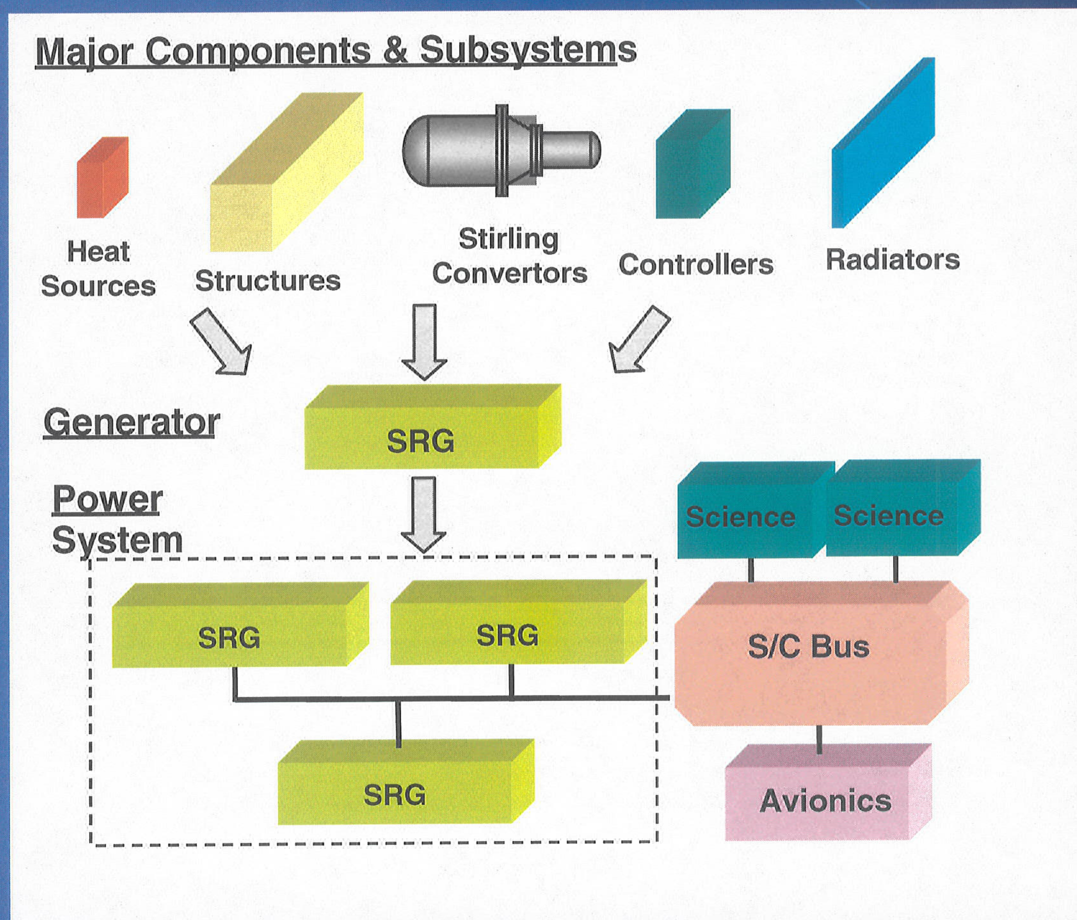
SRG Power system:



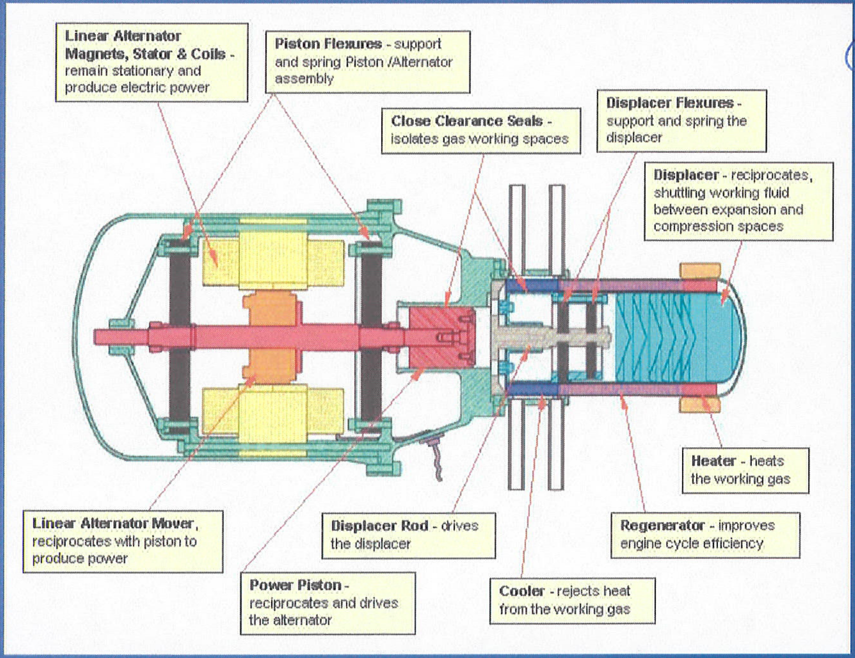
- Major SRG components:
  - Heat source (GPHS) (DOE)
  - Stirling power convertor (GRC)
  - Structure (LMA)
  - Radiator (LMA)
  - Control electronics and other associated hardware (LMA)
- SRG has two GPHS and at least two Stirling convertors
- Mission power system has more than one SRG

Courtsey of Lockheed Martin

SRG Power system diagram:



Stirling convertor assembly:



- GRC Stirling Convertor is a culmination of 25 years of research
- Minimizes and/or eliminates life limiting mechanisms
- Devoid of rubbing seals, oil lubricating system and wear out failure mechanisms
- Uses non-contacting moving components such as flexures
- Components governing the performance and reliability are: Heater head, regenerator, linear alternator, controller, displacer and flexures

Uncertainties:

- SCA is composed of multi-disciplinary components e.g. mechanical, structural, electrical, electromagnetic, electronics, thermal management, etc.
- Uncertainties arise from materials manufacturing, fabrication, environmental conditions, loads, boundary conditions, interaction among components, integration process, human aspects, etc.
- Variable uncertainties can be quantified in the form of probability distribution functions, stochastic process, power spectral density functions, fuzzy sets, grey systems theory, expert opinions/judgment etc.

SCA Critical components:

- Heater head: Conducts heat from the General Purpose Heat Source to the thermodynamic cycle of SCA
- Displacer flexures assembly: Transfers working fluid from hot end to cold end to covert thermal energy to electrical energy
- Alternator flexure assembly: Helps convert mechanical energy in to electrical energy
- Linear alternator: Converts mechanical energy into electrical energy
- Regenerator: Transfers heat into and out of the working fluid during each cycle
- Fasteners: Joins different components together to provide integrity of the convertor and prevent leakage
- Electronics, miscellaneous parts and items: Sensors, controls, electronics, etc.

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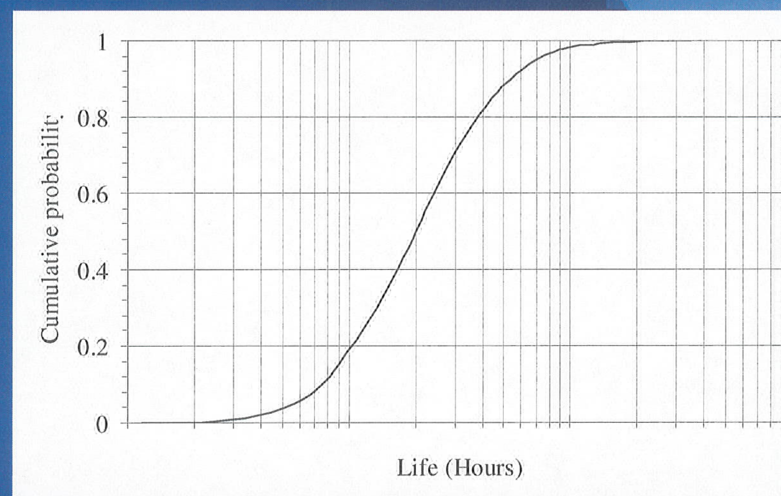
Reliability issues – heater head:

- Creep durability under high temperature is prime design criterion
- Difficult to capture uncertainties in the material behavior, fabrication (geometry), manufacturing process, loads in a limited number of tests
- Time and cost constraints prohibit long term full scale tests

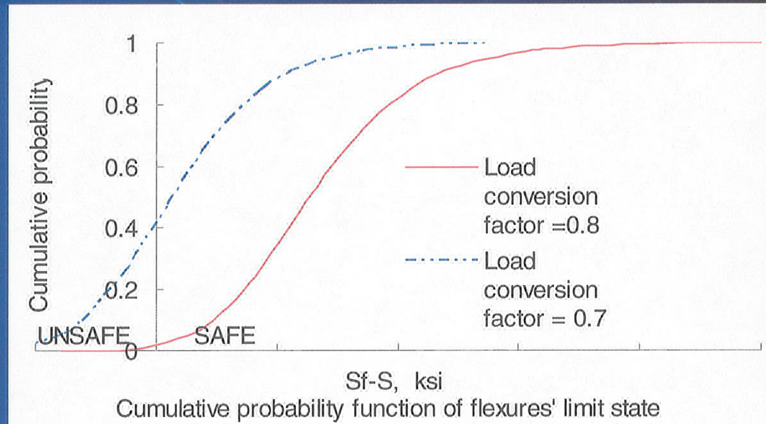
PoS	Life (Hours)
90%	751,000
99%	337,000
99.90%	188,000
99.99%	116,000

Scatter in life = 95.25% (1 Std. Dev.)

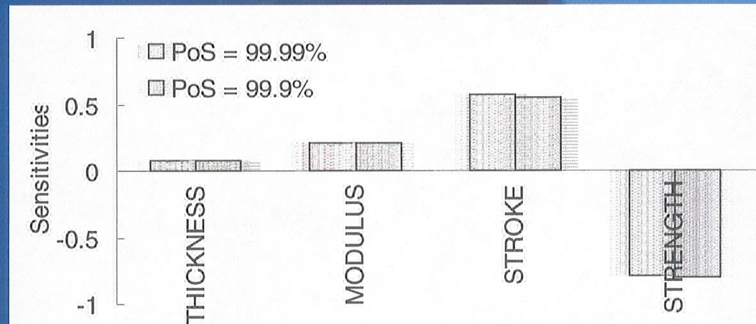


Reliability issues – alternator flexure:

- Required maintain non-contacting clearance and linear motion without rocking and undergo more than 35 billion cycles during 14 years of mission
- Fatigue life reliability is a key design driving factor
- Assuring reliability using limited test data is critical
- Reliability for assumed load conversion factor =0.8 is 98.5%
- Comparison with test data to ascertain true load conversion factor is in the progress
- Uncertainties I n the material fatigue strength and piston stroke are key design variables governing reliability



Cumulative probability function of flexures' limit state



Sensitivity of flexure reliability to design variables (Load conversion factor = 0.8)

Reliability issues – displacer assembly:

- Required maintain gap between the assembly and heater head wall and linear motion
- Displacer flexures are required to undergo more than 35 billion cycles during 14 years of mission
- Fatigue life reliability, loss of spring rate and alignment, abnormal vibration and/or shock loads are key design factors
- Loss of contact between cylinder wall could generate debris or change dynamics resulting in reduction in power
- Uncertainties in flexure material fatigue strength, geometry and loads govern the cyclic fatigue reliability

Reliability issues – linear alternator:

- Most critical part that converts mechanical energy into the electrical energy
- Permanent magnets mounted on stator used to generate power
- Excessive armature reaction to off design temperatures, current surges, oxidation, etc. may result in partial demagnetization
- Uncertainties in the geometry, magnet properties, bond between laminates, oxidation, laminate bond strength, etc. result in uncertain linear alternator performance
- 3-D finite electromagnetic analysis is being performed and reliability assessment is in progress

Reliability issues – regenerator:

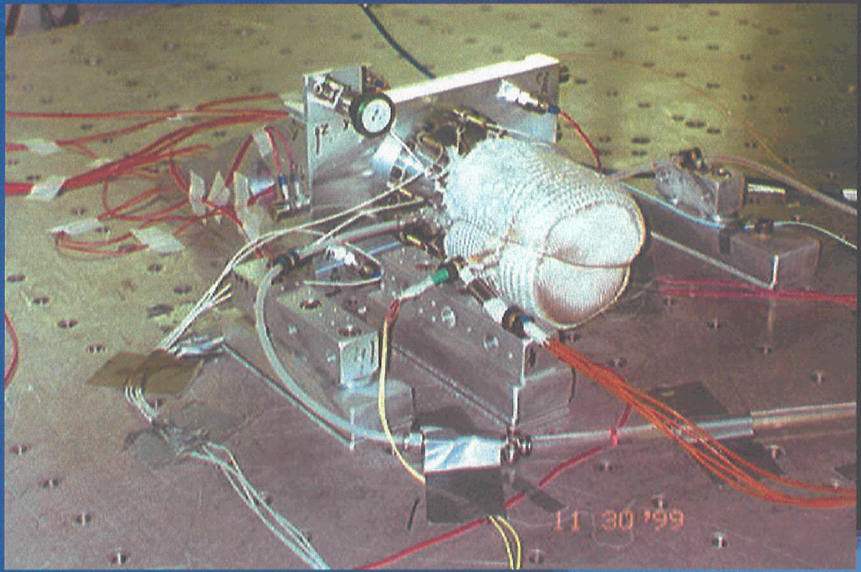
- Requires to transfer heat into and out of the working fluid
- Made of highly thermally conductive material configured to have large surface area to enable radial heat transfer
- Random micro-fibers provides open channels with large surface area and minimum pressure drop
- Randomness of fibers result in random non-uniformity in random flow passages
- Thermal properties and durability of fibers are random in nature
- Possibility of fibers shedding during the mission is an issue
- As a results of above uncertainties performance may have variation during the mission
- Reliability evaluation and comparison with test data are important for SCA reliability

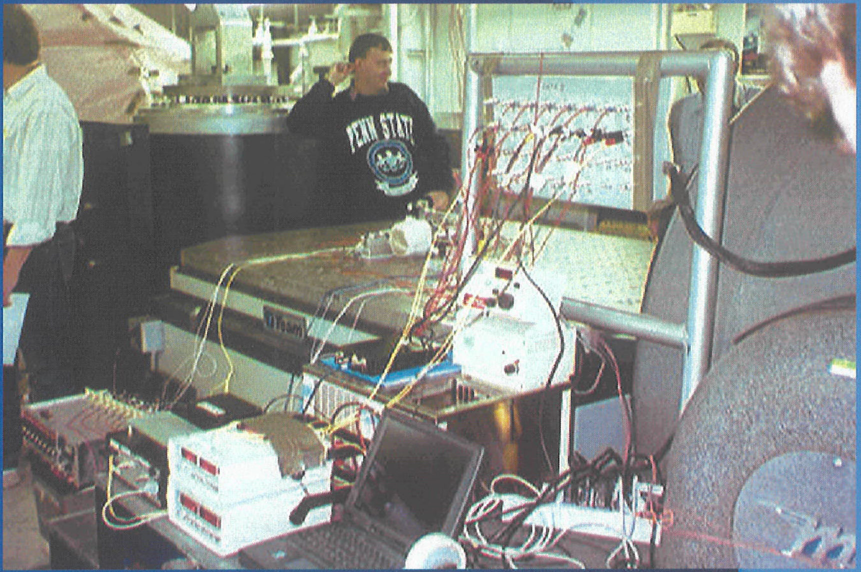
Reliability issues – Fasteners:

- Fasteners and welds are small but critical to integrity of the SCA since it contributes to deformation pattern, stresses in components and could become a weak link
- Mission loads, material properties, fastening process, friction between contact surfaces, o-rings, micro-cracks in welds, welding process, etc. have uncertainties
- Fretting of joined parts at the joining location, long-term effect under deformation, etc. affect the fastener performance during the mission
- Fasteners could fail structurally or functionally and cause vibratory effects, parts to loose clearance, seals ineffective, gas leakage, etc.
- High reliability of fasteners/welds is critical to SCA reliability during the mission

Reliability issues – Launch environment:

- SCA will be subject to steady g random vibration loads in different directions during launch sequence
- Abnormal vibrations amplifies stresses and results in loss of clearance between components/parts and generate piston motions affecting operation
- Random vibrations tests have been performed
- Assuring the SCA reliability is critical to successful launch
- Computational results will be compared with test data to develop confidence in reliability

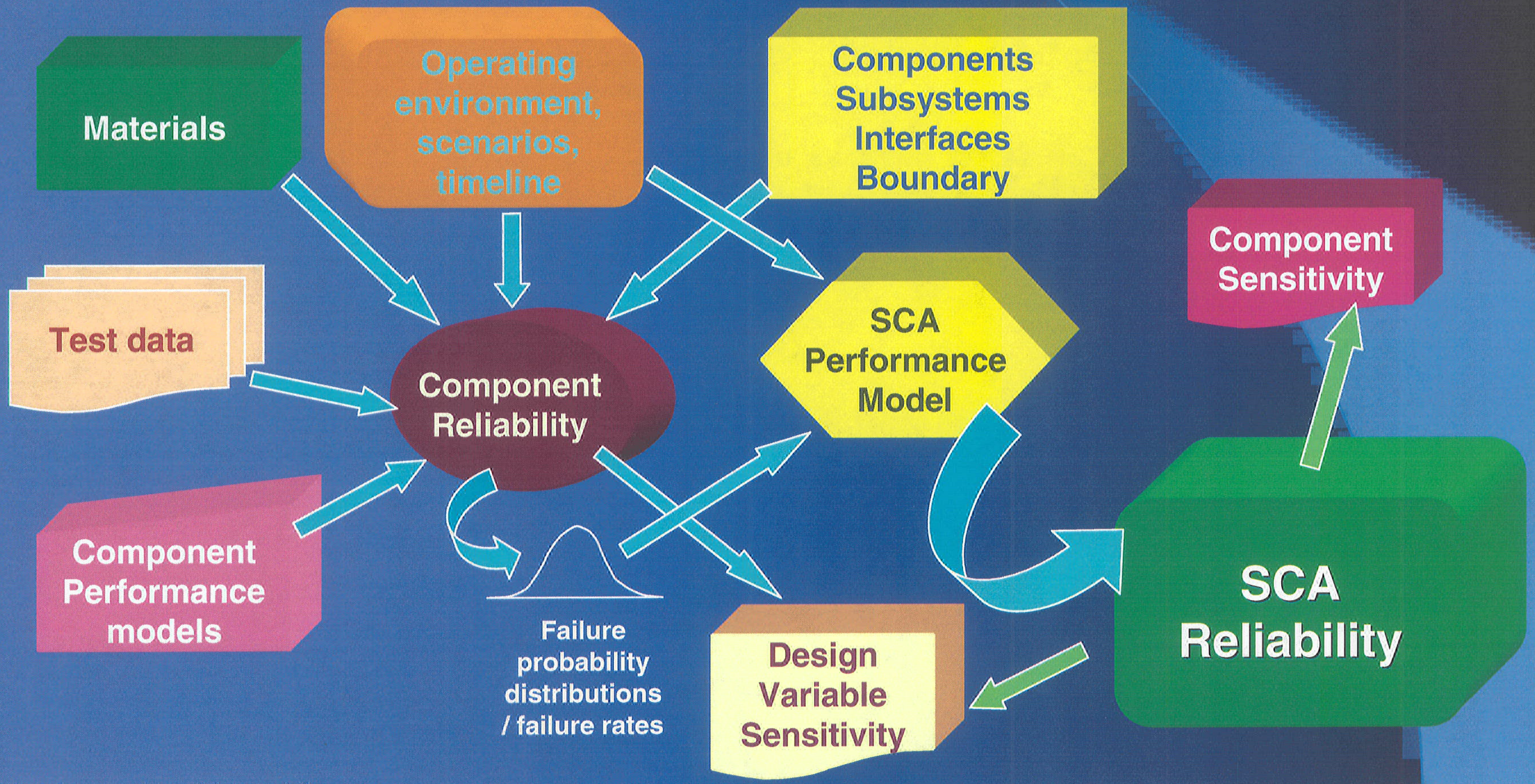




Reliability issues – Miscellaneous:

- Performance and behavior of components and system depends on sensors, controls, health monitoring system, electronics, etc.
- Malfunctioning of these miscellaneous parts could result in thermal spikes, current spikes, pressure surges, etc.
- Failure of these may not be possible to cover using conventional approaches
- High reliability of these small parts is very critical during the entire mission

SCA System reliability quantification flowchart :



Reliability qualification testing:

- Comparison of quantified reliability with the test data is critical to develop confidence in the design and assure mission success
- Accelerated life tests may not be feasible all the time to simulate real conditions and/or accrue failures
- Results of available tests should be used effectively
- Reliability assessment should guide the tests to be performed

Summary:

- Critical Stirling convertor assembly (SCA) components and associated failure modes have been identified
- Discussed
  - Reliability issues of several SCA components
  - Issues related to SCA reliability
- Importance and use of test data in the reliability assessment highlighted
- Presented results of the work performed

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