Stirling Convertor Fasteners Reliability Quantification

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Abstract

Onboard Radioisotope Power Systems (RPS) being developed for NASA's deep-space science and exploration missions require reliable operation for up to 14 years and beyond. Stirling power conversion is a candidate for use in an RPS because it offers a multifold increase in the conversion efficiency of heat to electric power and reduced inventory of radioactive material. Structural fasteners are responsible to maintain structural integrity of the Stirling power convertor, which is critical to ensure reliable performance during the entire mission. Design of fasteners involves variables related to the fabrication, manufacturing, behavior of fasteners and joining parts material, structural geometry of the joining components, size and spacing of fasteners, mission loads, boundary conditions, etc. These variables have inherent uncertainties, which need to be accounted for in the reliability assessment. This paper describes these uncertainties along with a methodology to quantify the reliability, and provides results of the analysis in terms of quantified reliability and sensitivity of Stirling power conversion reliability to the design variables. Quantification of the reliability includes both structural and functional aspects of the joining components. Based on the results, the paper also describes guidelines to improve the reliability and verification testing.

Nomenclature

DC	Displacer Cylinder
FSR	Forward Stator Ring
GRC	Glenn Research Center
HH	Heater Head
PH	Piston Housing
PV	Pressure Vessel
SCA	Stirling Convertor Assembly
SRG	Stirling Radioisotope Generator
FEM	Finite Element Model
CDF	Cumulative Distribution Function
$\bar{x}$	$(x_1, x_2, ..., x_m)$ - Set of m random variables
$G(\bar{x})$	Performance or limit-state function
$f_x(\bar{x})$	Joint probability density function of $\bar{x}$

I. Introduction

Owing to the requirement that any new radioisotope power system for NASA's science and exploration missions must perform without failure and maintenance for up to 14 years, high reliability is of paramount importance over the life of the mission. This includes pre-launch handling, assent, space flight, and possible descent to a planetary surface. An RPS that is currently being developed is the 110 watt Stirling Radioisotope Generator (SRG110). The SRG110 is being developed by the Department of Energy, with the System Integration Contractor Lockheed Martin of Valley Forge, PA, and their subcontractor Infinia, Corporation (formerly the Stirling Technology Company) of Kennewick, WA. This generator will make use of Stirling power conversion to significantly increase the power

conversion efficiency. The Stirling convertor is a free-piston device consisting of many components, materials, electronics, etc.. Design of the SRG110 for a space science mission involves multiple disciplines. The convertor does make use of some moving parts however, all of the principal wear and life limiting mechanisms have been eliminated by design. Even with the elimination of wear, the key critical components, and the system as a whole, need to be assessed to ensure reliable operation. Additionally, the SRG110 that is being developed is based on a technology that does not have flight heritage as a power conversion system for space missions. Therefore, there are many issues related to the quantification of reliability that must be investigated. The purpose of assuring the reliability is to ensure that the SRG110 will not experience malfunction or failure under any condition, even during off-design operation.

The possibility of failures always exists in any system. The occurrence of failures may be very rare by virtue of the design, using high margins of safety, extensive testing, verification, quality control, inspections, etc. An effective way to enhance reliability is to clearly understand the failure modes, scenarios that may cause failures and then design remedial measures to address and reduce the impact on the overall performance without sacrificing mission objectives. Understanding the issues related to the reliability of the SRG110 is a key to the flight qualification, certification and mission success.

The Stirling Convertor Assembly (SCA) is an assembly of several components that are joined together[1] using fasteners and welds. Fasteners of critical importance are those between the piston housing (PH) and the heater head (HH), the forward stator ring (FSR) and the aft stator end ring, the displacer spider and the PH, and the pressure vessel (PV) and the PH. The integrity of the SCA to function as one unit is dependant of the fasteners and welds that join different parts together. Although the fasteners are small, their significance to the integrity of the joints is very high, since they contribute to the deformation patterns and stresses in the components being joined. Hence, any failure of joint could impair the functionality of the convertor and result in mission failure. It is possible for the fasteners to fail structurally or functionally. Considering the conservative nature of designs, the fasteners may not fail structurally; however, function/performance of the joint due to fasteners and joining flange behavior may be impaired. During operation under pressure, the flanges rotate and deformation of joint occurs. The flexibility of the flange and preload on the fasteners control the magnitude of the flange rotation. Excessive rotation of the joint may separate the contacting surfaces and open the joint. Additionally, if the fasteners relax, the joined parts could become loose resulting in gapping or could allow the potential for gas leakage. Preventing gas leakage is the most important task faced by the bolted flanges of the convertor. For metal-to-metal flanges a reliable seal can be achieved by assuring that no reciprocal deformation (gap and/or slippage) exists between the flange surfaces during assembly, welding, and the mission. In order to analyze the effect of the fasteners on convertor performance, a detailed 3–D finite element model (FEM) deterministic analysis was performed at NASA GRC for the design fastener preloads and mission load profiles.

Several important variables that impact the joints behavior are flange geometry profile, material properties, amount of torque (preloads), pattern and sequence of those applied during the tightening process, friction between the contacting surfaces, fretting of joining components, long term effect of deformation under load, etc.. In addition to these, human variability during assembly process may also contribute to the fasteners performance. High reliability of joints can be achieved if correct flange profiles are selected and factors and variables affecting the reliability are examined thoroughly.

This paper presents an assessment of fastener and joint reliability as they influence structural and performance failure of the convertor in the presence of uncertainties in material properties, fabrication, and loading conditions. The assessment is based on (1) non-linear finite element modeling for deterministic stress analysis, (2) statistical models for initial pre-loads, mission loads and material properties, and (3) computational methods for structural and performance reliability.

II.   Reliability Analysis Approach

The objective of this study was to quantify the structural and performance reliability of the SCA fasteners due to uncertainties in material properties, fabrication, and loading conditions. The following steps were implemented for the reliability assessment:
-   Adopt a finite element model that was received from NASA GRC.
-   Identify design variables and related uncertainties that affect the reliability of the joints. These variables include fasteners and flange geometries, material properties, and environmental conditions.

- Perform parametric analysis to establish performance functions, which define relationship between the design variables and the performance of the fasteners under different environmental/loading conditions. These performance functions reflect two dominating failure modes associated with the joints: (1) functional failure and (2) structural failure. The functional failure is related to possible opening of the bolted joint under mission loads, whereas the structural failure relates to the yielding of the fasteners and/or the corresponding flange. A functional failure may occur due to insufficient initial clamping force or relaxation during the mission, or lack of joint stiffness. Structural failure could occur when stresses in the flanges and/or fasteners exceed respective tensile and/or bending strengths of the material.
- Perform reliability analysis of fasteners, and joint performance and quantify its sensitivity to the design variables.

A. Basis of Deterministic Analysis

The primary goals of the SCA fastener analyses were:
1) To determine the tendency of critical joints separation
2) To ascertain unyielding performance of all components in the SCA.

In order to achieve the above stated goals, GRC developed a three-dimensional FEM of the SCA that simulates structural behavior/performance during different stages of the mission. The model incorporates critical SCA components such as the HH, displacer, forward stator ring, and PV. These critical components are assembled with the fasteners as listed in Table 1. The components were modeled using brick elements with eight nodes and three degrees of freedom at each node. The model neglects bolt holes in the flanges and each fastener was modeled using beam elements connected to the solid elements at the top and bottom of the flanges. Pretension elements available in ANSYS were used to simulate initial fastener preloads. All flange joints analyzed in this paper were without gaskets. Therefore, two-dimensional contact elements that can handle sliding, sticking friction and separation were used to simulate contact between the joining surfaces. It is worth noting that a non-structural weld has been used in this design to prevent gas leakage from the SCA. These welds were modeled as non-structural and do not contribute any strength to the SCA behavior/performance.

Table 1. Fasteners modeled in the GRC FEM

Fastener set	Number of Bolts	Jointed components
1	4	Piston Housing – Displacer Spider
2	10	Piston Housing - Heater Head
3	18	Piston Housing - Pressure Vessel
4	8	Piston Housing - Forward Stator Ring

The model incorporates the following boundary and loadings conditions:
1) Initial fastener preloads
2) Service operational loads
3) Loads experienced during launch.

B. Sources of Uncertainties

Optimal tightening of fasteners in a joint enhances the reliability of the joint. However, due to a variety of reasons such as clamping configuration, measuring instruments, human aspects, etc. scatter in the initial fastener preload is inevitable and has been observed in many cases during the assembly process.[2] Fastener preload variation must be accounted for in the aerospace design practice.[3] There exists no general rule that defines the initial uncertainty in the bolt preload. These values are strongly dependant on the specific methods used for preload measurement and stiffness of the joined components. According to Ref. 4, the typical preload uncertainties for torque-measurement of lubricated bolts might be in the range of ±25 percent. Also, during different stages of the mission, additional variability in the fastener loads (other than preloads) is expected. This could lead to bolts relaxation or tightening that may cause variability in the SCA structural and functional performance. Thus, there is a need to model these uncertainties and its effect on fastener/joint failure/performance and its reliability. Uncertainties in the design variables can be modeled by treating them as random with appropriate statistics and probability distributions. Statistics characterizing random variable may be based on a survey of test or field data, or by using engineering experience and judgment in the absence of data.

Three sources of uncertainties were examined in the presented study.

1. *Uncertainties in Initial Bolt Preload*

Table 2 lists the variability in the initial bolt preload for the four joints that were studied. Variability in preload has a basis from the allowable bounds and other sources of data[5]. The maximum variability in the initial preloads was observed for the HH-PH and the PV-PH joints while the minimum scatter was observed for the FSR-PH joint. The maximum and minimum bounds are related to ±3 standard deviations. It is noteworthy, that the bolt set scatter may be non-uniformly distributed due to the pattern and sequence of tightening, however, this effect is not discussed in this paper.

2. *Uncertainties in Material Properties*

Currently the FEM incorporates linear elastic properties of the material being used. However, the structural analysis performed is non-linear owing to the contact problem. Due to temperature differential (the temperature varies from the 660 °C in the heater collector area to 15 °C at the cold end of the PV), the elastic modulii were considered to vary linearly with respect to temperature, while Poison's ratio remained constant. Uncertainties in the material properties for major component materials are listed in Table 3. For simplicity, it was assumed that the magnitude of uncertainties in the temperature at all locations along the axis of SCA was same.

3. *Load Uncertainties*

Operational loads include internal pressure and temperature in each section of the assembly. Although internal pressure and temperature are supposed to be well controlled, in reality it is not possible to avoid some variability. Changes in the pressure and the temperature will result in variability in the stresses and strains of the components. Since the uncertainties in the temperature have not been large and possible impact of temperature variations on fasteners was judged to be negligible, this analysis ignored the uncertainties in temperature. Table 4 lists the uncertainties in the pressure at three SCA sections where mean internal pressures are different.

Table 2. Initial scatter in bolts preload

Bolt set	Max	Min	Mean	Scatter, % (3 Std. dev)
PH-DC	415	314	364.5	13.85
PH-HH	1018	630	824	23.54
PV-PH	2240	1465	1852.5	20.92
FSR-PH	1018	794	906	12.36

Table 3. Scatter in elastic moduli

Components	Min, ksi	Max, ksi	Mean, ksi	Scatter, % (3 Std. Dev.)
Bolts	29100	30900	30000	4.50
Heater Head	28665	30135	29000	3.75
Displacer	15360	16640	16000	6.00
Piston Housing & Pressure Vessel	26600	29400	28000	7.50

Table 4. Variability in internal pressures

SCA components	Max	Min	Mean	Scatter, % (3 X Std. Dev.)
Heater Head, psia	429.5	400.5	415.0	5.25
Displacer, psia	388.3	365.7	377.0	4.50
Pressure Vessel, psia	400.4	369.6	385.0	6.00
Lateral load, g	46.25	57.50	50.00	7.50

Launch loads consist of concentrated point and surface distributed loads that were applied locally, and acceleration loads that were applied to the whole assembly. There is some uncertainty in these loads, which may vary in magnitude and in the direction. However, preliminary analysis indicated that locally concentrated loads have no significant effect on the performance of the fasteners or stresses. Therefore, to reduce the computational time, uncertainties in the local point or surface loads were eliminated in the reliability assessment. Thus, only the effect of variation in the lateral acceleration was considered as shown in Table 4.

C. Probability-Based Joint Modeling

A probabilistic analysis that includes previously discussed uncertainties was performed to assess the reliability. The approach simulates uncertainties in the structural response or functional performance and indicates which design parameters have the greatest influence on reliability, including the order of sensitivity. The reliability assessment included application of the deterministic FEM to obtain component deformation and behavior in terms of a set of design variables, which were then integrated with reliability methods in order to quantitatively predict the uncertainty in the performance and the response variables such as stress, displacements, etc. Reliability of fasteners is defined as the probability that they will perform as specified under the given operational conditions during the mission without structural and functional failure. As was previously stated, the performance of the fasteners is controlled and affected by several parameters that represent the initial bolt preloads, material properties, and applied loads. The design variables were treated as random and characterized by their respective probability distributions, standard deviation and distribution type. The reliability method used specification of the performance function or limit-state function $G(\bar{x})$. The reliability, P_S is defined as the cumulative probability that the system capacity (or "strength"), $S(\bar{x})$ is higher than the system response, $R(\bar{x})$ and expressed mathematically as:

$$P_S = \mathrm{Prob}\big[G(\bar{x}) < 0\big] = \int_{G(x)\,<\,0} f_x(\bar{x})\,d\bar{x}$$

Exact evaluation of the above integral for more than two random variables is difficult since the joint probability density function is unknown. Two alternatives that can be used are the Monte Carlo simulation and the numerical method. The Monte Carlo simulation is straightforward, easy to implement and can converge to the exact solution. However, due to the size of model it would be computationally intensive and time consuming. Alternatively, numerical methods are more efficient and computationally less intensive. The reliability analysis presented in this paper uses the fast probability integration method.

Limit-state functions related to material failure and functional performance of the fasteners were defined. Functional performance reflects potential opening or gapping of the bolted flange joints. Intuitively, closed flange joints with no gapping do not guarantee complete fluid containment under loads. Therefore, the fluid containment is accomplished through the use of small, non-structural hermetic seal welds. Nevertheless, prediction of the flanges' tendency to gap (open up) was considered crucial in the design. For the structural failure mode, fastener deformation and stresses were of interest. The fasteners yield stress was chosen as system capacity and stresses in fasteners/flanges are considered as system response.

III.   Results of the Analysis

A total of fifty-five FEMs were prepared and run to determine the two types of limit state functions. Results of stress in the bolts and the joint opening for all four joints were collected. Analysis for the assembly stage included only the fasteners initial preloads. Analyses showed that all bolts are structurally safe with high reliability (greater than 0.9999). During the assembly stage the bolts appear to experience only axial loads. However, under the influence of internal pressure and temperature during the flight stage, some of the bolts begin to experience additional bending stress. The most critical increase in bending stress was observed for the PV-PH and FSR-PH fasteners. High level of bending in the bolts was thought to be the result of modeling the bolt as beam element and the corresponding applied constraint. In reality, it can be expected that the presence of the bolt head and the nut will constrain some rotation of the flanges and reduce bolt bending and stresses. In order to verify that the true bending stresses are indeed low enough to neglect, a more refined local model was developed and analyzed. The local refined analysis demonstrates the verification and the details are presented in the Appendix.

D. Reliability Assessment of the Bolts

A fastener is considered to have failed structurally when the stress, S in the fastener exceeds the material "strength", R. Mathematically, failure is defined as R-S < 0, called the limit state function. In this study, the fastener material yield stress was chosen as material "strength" for the structural reliability assessment. Since the

material strength varies due to variations in the manufacturing process and granular structure of the material and evidenced by test data, it was considered as a random variable with a Weibull distribution, with the mean value of 160 ksi and the standard deviation of 4 ksi (Coefficient of variation equal to 2.5 percent).

The cumulative distribution function (CDF) of the stresses in the bolts for each joint was computed and the structural reliability as well as the sensitivity factors was quantified. Figure 1 shows the CDF of the maximum bolt stress computed for the PH–PV joint, which appeared to be the most critical joint. Results of the other joints are not reported here for the sake of brevity. The mean value and the standard deviation of the maximum stress in the PH-PV joint are 118.9 and 6.4 ksi, respectively. It can be seen from Fig. 2 that the uncertainties in the initial bolt preload dominate the bolt stresses at all cumulative probability levels. The uncertainties in the bolt stress could be reduced if quality control measures were implemented that minimize the uncertainty in the bolt preload. Uncertainties in the bolt preload can generally be attributed to the instrumentation used, human variability, and the pattern and sequence of bolt assembly.

Computed CDF of the limit state function for the structural failure of bolts, Fig. 3 indicates that the probability of the structural failure of bolt is extremely low (less than at least 0.0001). As expected, the reliability of the bolts is most sensitive to the initial preload in the bolts as well, Fig. 4.
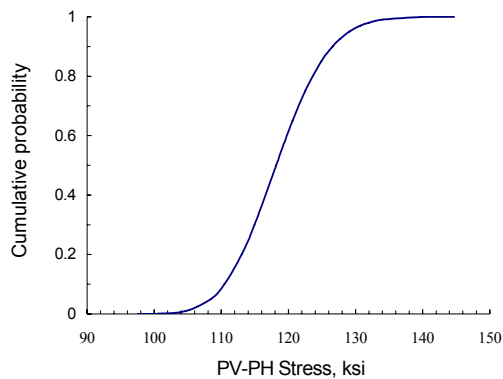

Figure 1. Cumulative probability distribution function of stresses in PV-PH bolt.
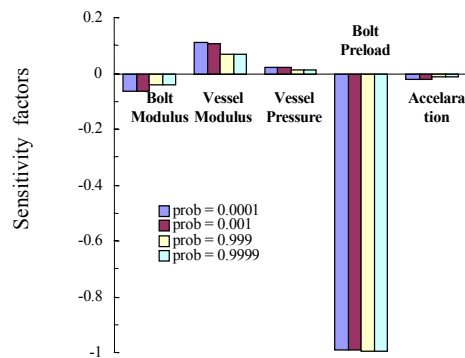

Figure 2. Sensitivity of the stresses in PV-Ph bolt to the design random variables.
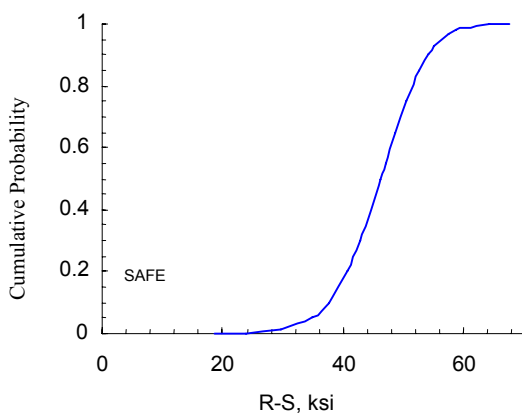

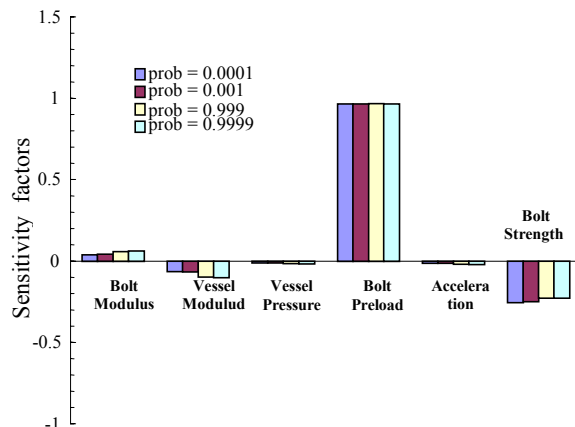**Figure 3. Cumulative probability distribution function of the limit state function for PV-PH bolts.**

Figure 4. Sensitivity of the structural limit state function to the random variables for PV-PH bolts.
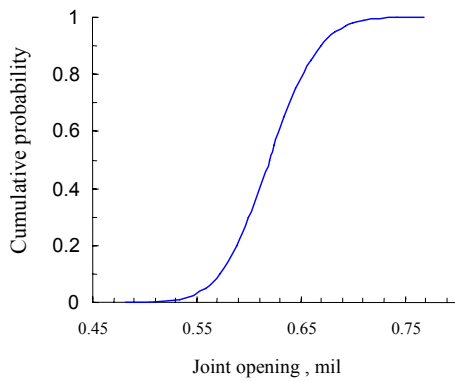
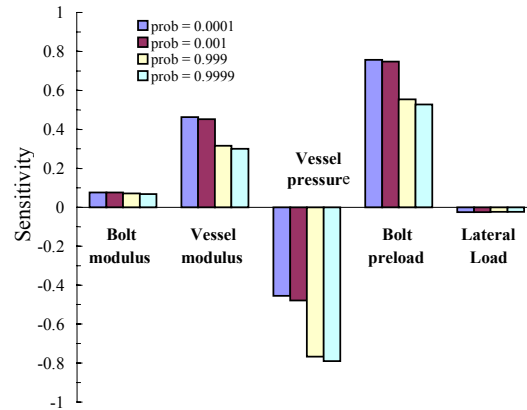**Figure 5. Cumulative distribution function of PV-PH joint opening**

Figure 6. Sensitivity of the of PV-PH joint opening to design variables

E. Reliability Assessment of the Joints Opening

The CDF and the sensitivity factors for the maximum flange opening at the PH–PV (critical for flange opening at the tabbed location) interface are shown in Figs. 5 and 6, respectively. The tabbed flange profile has four bolt holes located at the tabs moved radially outward, not on the same bolt circle as the other fasteners. For this flange geometry, the bolt bending is insignificant. However, the extended flange dimension resulted in rotation under the internal pressure. Consequently, separation is eminent between the mated surfaces. Engineering judgment and the local model analysis suggest that the opening in the area of the tab is controlled primarily by the geometrical configuration and not the bolt load. The calculated mean value and standard deviation of the flange opening are 6.2×10^{-4} and 3.77×10^{-5} inches, respectively. Present design criteria suggest that the opening not be greater than 1×10^{-4} inches. However, the mated surfaces must be in compression at all times to ensure no gas leakage and prevent the seal weld from being stressed. Therefore no opening should be permitted. The reliability for the suggested design value of the opening (1×10^{-4} inches) is much lower than 0.999 (or in other words, the probability that the opening may be greater than 1×10^{-4} inches is higher than 0.001). Probabilistic sensitivity factors for the 0.0001, 0.001, 0.999, and 0.9999 cumulative probability of the flange opening are depicted in Fig. 6. Reliability of the design for not exceeding the maximum allowable flange opening is most sensitive to the bolt preload followed by the internal pressure. Therefore, in order to make the PH-PV joint more reliable against the gas leakage, the uncertainties in the bolt preload and the internal pressure should be reduced, which requires tight quality control and accurate instrumentation. Also, consideration may be given to increasing the flange thickness to provide higher stiffness and limit the rotation.

IV.   Conclusion

The PV-PH joint fasteners have been found to be the most critical in the SCA from the reliability of fasteners point of view. For all other joints that were studied, the reliability analysis showed that the joints are highly reliable against joint opening as well as fastener failures. The PV–PH joint opening was found to be critical due to flange rotation, and its reliability is most sensitive to the initial bolt preloads, internal pressure and material properties of the flanges. At low probability levels, the fasteners preload is the most dominant, while the internal pressure controls the opening at the higher probability level. Bolt modulus has low effect and the external loads have insignificant effect on the joint performance and fastener failure. The flange rotation could potentially lead to deformation that could risk the non-structural seal weld present at the joint. All fasteners have been found to have a reliability of at least 0.9999 against structural failure.

Appendix

Due to the limitations of the current global FEM that was used in this analysis, excessive stiffening of pressure vessels and over prediction of flange rotation along with bending of the bolts may occur. A refined local model was created to evaluate the local stresses in the joining components more accurately and investigate the likelihood of flange rotation and bending of the bolts when internal pressure is applied. Flange rotation and bending of the bolts can be attributed to the profile of the PV-PH flanges due to additional mounting tabs. The location of the bolts make two bolts circles: one through the bolts on the flange (standard) and the other through bolts shifted toward the mounting tabs (extended flange). A simplified two-dimensional axisymmetric non-linear FEM was created as shown in Fig. 7. The model neglects the presence of individual bolts and bolt holes. Instead, the effect of bolts is simulated as a continuous bolt ring located at the bolt center and running along the circumference of the bolts circle. Viability of this approach has been studied intensively elsewhere.[6] The FEM included the pressure vessel flange, bolt, and spacer as shown in Fig. 7. The model was implemented in the ANSYS® code using first order plane 42 element, second order plane 82 element to model solid entities, and contact 172 element to simulate contact interaction between the flange and bolt head. For comparison, two models which correspond to the standard flange profile, Fig. 8 and the extended flange profile, Fig. 9 have been studied. These two models differ in outside diameters of the flange and bolt circle diameters. Results showed that bolt circle diameter has the most influence in defining the flange rotation and the joint opening. The standard bolt circle diameter analysis, depicted in Fig. 8, showed that the joint opening is unlikely during the mission. However, larger bolt circle diameter for the tabs (extended flange) increases the possibility of the joint opening as shown in Fig. 9. Moreover, the analysis for the extended flanges showed that additional bolt tightening does not provide more clamping. Therefore, the joint was found less reliable against opening. Axial stress distribution in both cases was practically the same, indicating that the bolt is exposed to little bending, and therefore, one may neglect artificial bending imposed on the bolts in the global SCA model. Reliability of the joint opening which uses the extended flanges or tabs will be lower than the joints with the standard flanges.
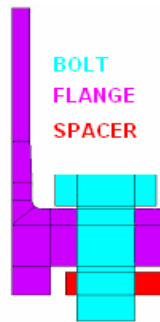

**Figure 7. Schematic model of
flange joint assembly.**

**Figure 8. Local stresses in standard flange
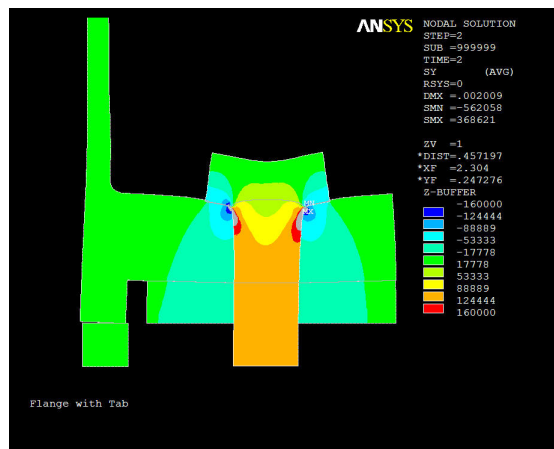(no joint opening indication)**

**Figure 9. Local stresses in extended flange
(joint opening is likely)**

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13. ABSTRACT (Maximum 200 words)

Onboard Radioisotope Power Systems (RPS) being developed for NASA's deep-space science and exploration missions require reliable operation for up to 14 years and beyond. Stirling power conversion is a candidate for use in an RPS because it offers a multifold increase in the conversion efficiency of heat to electric power and reduced inventory of radioactive material. Structural fasteners are responsible to maintain structural integrity of the Stirling power convertor, which is critical to ensure reliable performance during the entire mission. Design of fasteners involve variables related to the fabrication, manufacturing, behavior of fasteners and joining parts material, structural geometry of the joining components, size and spacing of fasteners, mission loads, boundary conditions, etc. These variables have inherent uncertainties, which need to be accounted for in the reliability assessment. This paper describes these uncertainties along with a methodology to quantify the reliability, and provides results of the analysis in terms of quantified reliability and sensitivity of Stirling power conversion reliability to the design variables. Quantification of the reliability includes both structural and functional aspects of the joining components. Based on the results, the paper also describes guidelines to improve the reliability and verification testing.

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