**SEVENTH SYMPOSIUM
ON SPACE
NUCLEAR POWER
SYSTEMS**

PROCEEDINGS
(IN TWO PARTS)
PART TWO

**INSTITUTE FOR SPACE NUCLEAR
POWER STUDIES**

Chemical and Nuclear Engineering Department
THE UNIVERSITY OF NEW MEXICO
Albuquerque, NM 87131

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Albuquerque Convention Center
Albuquerque, New Mexico
January 7-10, 1990

CID # 6829
CALL # 41-03

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PROCEEDINGS OF THE SEVENTH SYMPOSIUM ON SPACE NUCLEAR POWER SYSTEMS

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ON THE RESPONSE OF THE ULYSSES RTG TO THE IMPACT OF LARGE SRM-FRAGMENTS

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INTRODUCTION

The successful launch of the Galileo spacecraft has allowed the launch approval review team to turn its attention to the upcoming Ulysses launch. Several spacecraft-unique variables have been identified for the Ulysses configuration and their effect on the Ulysses safety analyses will be discussed.

The Galileo Radioisotope Thermoelectric Generator (RTG) longitudinal axis was oriented parallel to the Space Transportation System (STS) thrust axis. The primary early time threat to the integrity of the Galileo-RTG $^{238}\text{PuO}_2$ -containment system was from large Solid Rocket Motor (SRM) casing fragments impacting orthogonal to the RTG longitudinal axis. The Galileo arrangement almost precluded the impact of SRM fragments on the end of the RTG. Further, this arrangement provided only one degree of freedom for the distortion of the RTG fueled clads. The Ulysses RTG is mounted such that its longitudinal axis is orthogonal to the STS thrust axis. This orientation increases the probability that the RTG will be hit end-on by an SRM fragment. Unlike the Galileo mounting, this orientation allows two degrees of freedom for clad distortion caused by end-on impacts.

It will be shown that end-on impacts, which are more likely to occur with Ulysses than with Galileo, will produce greater average fueled clad distortion than was typical of Galileo. Fortunately, the predicted distortions remain well within the Galileo data base. It will also be shown that the two-dimensional (2D) calculations which were performed for the Galileo configuration were indeed valid in that application and are also valid for the Ulysses configuration.

METHODS

The analytical approach used to predict fueled clad distortion was closely coupled to an experimental program in a predictor-corrector manner. One protocol of this approach was to require that predicted distortion results be available prior to conducting any experiment. This approach had the effect of reducing the number of experimental surprises encountered as well as focusing the mind of the analyst to the job at hand. A flow chart of the manner in which fueled clad distortion-prediction methods were developed is presented in Figure 1. A detailed description of the analytical models and validation techniques employed in making fueled clad distortion predictions has been presented previously [1].

Figure 1. Analysis/Test Interaction Flow Chart.

A comparison of fueled clad distortion predictions to values observed experimentally is presented, for a urania simulant case, in Figure 2. The calibrated analytical techniques were subsequently used to predict the distortion which would occur in a plutonia-fueled clad under a number of assumed loading conditions. The results of these calculations were used in the Galileo Final Safety Analysis Report (FSAR) [2]. The FSAR depended on analyses to determine the distortion values shown in Figure 3 because a facility which could handle large-high-velocity fragments and also contain any plutonia which might be released does not exist.

Figure 2. Comparison of the Predicted and Observed Distortion of Forward Cups from the LFT-1 and LFT-2 Events⁽¹⁾.

⁽¹⁾LFT-1 Impact Velocity = 115 m/s; LFT-2 Impact Velocity = 212 m/s; Note That Maximum Observed Values are Strongly Driven by Results Which Were Caused by Secondary Impact. Calculation is Very Conservative in Diameter Prediction due to Clad-Length Constraint ($E_{TT} = 0$).

Figure 3. Position 2 and 3 Fueled Clad Distortion as a Function of Fragment Thickness, Velocity and Plutonia Mechanical Properties.

The plateau shown in Figure 3 has raised considerable controversy. A number of critics of the analytical methods employed have suggested that this plateau is the result of analytical shortcomings brought about by the 2D modeling used. This is not the case. The predicted plateau is the result of the zero y-velocity boundary condition imposed by symmetry on each module in the RTG stack, the total void volume within the module and the basic laws of physics. These parameters are presented conceptually in Figure 4.

Initial Geometry	Bare Module Response	FGT Response	LFT Response
<p>There is a large void volume within the module at initial impact</p>	<p>(SVT)</p> <p>The upper and lower surfaces of the module are free to move in the Y direction and offer little resistance to clad dilation</p>	<p>The FGT geometry has a single-module-mass mock-up on either side of the fueled module. This provides some resistance to clad dilation. This resistance is primarily due to the inertia of the mass mock-ups.</p>	<p>The LFT geometry offers significant resistance to the movement of the module upper and lower surfaces. At high velocity, the front face of the aeroshell is driven into the CBCF void space before the relatively high inertia fuel can spall and react. Since the upper and lower module surfaces are constrained by symmetry, this front face material prevents clad dilation into the space which had been occupied by the CBCF. Since physics teaches that two bodies cannot occupy the same volume at the same time, the capsule simply has no place to go (in two-dimensions).</p>

Figure 4. Comparison of the Effects of Several Impact Test Boundary Conditions on Resultant Fueled Clad Geometry.

Two orthogonal calculations were performed to show the validity of the concepts presented in Figure 4. The predicted geometries resulting from four calculational cases are shown in Figure 5. The top-view case shows that a degree of freedom exists which eventually allows fueled clad failure even though no failure mechanism is apparent in the side-view calculations. A distortion plateau is clearly evident in the first panel of Figure 6 where both urania and plutonia fueled clad distortion tend toward a common upper limit. No such limit is apparent in the second panel of Figure 6; neither is there any indication of closure of the plutonia and urania fueled clad distortion curves.

The Ulysses RTG configuration causes an increase in the number of potential RTG end-on impacts. These end-on impacts have one more degree of freedom than is available in side-on impacts. This concept is illustrated in Figure 7. Models were constructed to investigate the effects of face-on and edge-on fragment impacts on the end of the Ulysses RTG. The results obtained from exercising these models are presented below.

RESULTS AND CONCLUSIONS

The disruption resulting from the impact of a large SRM-fragment on the end of a Ulysses RTG is shown for two velocities in Figure 8. As can be seen, little fueled clad distortion occurs at the mid-stack position for impacts of this type. The distortion resulting from edge-on impacts on the end of the Ulysses RTG is greater for the bottom stack position than was observed for the edge-on side-on case typical of the Galileo geometry. This is especially true when the fragment edge is aligned with a fueled clad centerline, as shown in Figure 9. Fortunately, SRM-fragments tend to glance off the RTG end and cause the module stack to buckle out of alignment before many modules can become involved. This effect is apparent at all velocities of interest as is shown in Figure 9 and Figure 10.

Figure 5. Weak Plutonia Fueled Clad Length Increase Resulting from the Impact of an SRB Quadrant on an RTG (LFT Geometry)⁽¹⁾

⁽¹⁾Geometry Shown for Stack Positions Four and Five Strain Rate ($\dot{\epsilon}_{TT}$) is Zero into the Plane of the Paper

Figure 6. Weak Urania and Plutonia Fueled Clad Diametral and Length Distortion Predicted to Result from the Impact of an SRB Quadrant on an RTG (LFT Geometry)⁽¹⁾

⁽¹⁾Traces Shown Derive from the Top View Model Shown on the Previous Chart The Top View and Side View Models Constitute Two Orthogonal 2D GPHS Module Representations

Figure 7. Effect of Module Stack Inertia on Fueled Clad Degrees of Freedom.

Figure 8. Effect of Fragment Velocity on RTG Response to the Impact of a 56 X 56 Inch Fragment Orthogonal to the RTG Axis.

Figure 9. Effect of Fragment Velocity on RTG Response to the Impact of a 56 X 56 Inch Fragment Along the Fueled Clad Axis.

Figure 10. Effect of Fragment Velocity on RTG Response to the Impact of a 56 X 56 Inch Fragment Along the Fueled Clad Axis.

The results of calculations performed using the models described in this paper are summarized in Table I. Examination of this table shows that some low-stack-position fueled clads incur high distortion when impacted edge-on by SRM fragments with velocities near 100 M/S. Fortunately, few fragments having velocities this high exist at early MET [3] after accounting for the structural attenuation of the orbiter.

It is concluded that the Ulysses orientation introduces a new impact threat to the integrity of the RTG fuel containment system. Detailed calculations suggest that this new threat does not result in any fueled clad distortion which is outside the bounds of the Galileo test database.

Acknowledgments

The work summarized in this paper was supported by the U.S. Department of Energy, Office of Special Applications under contract DE-AC01-88NE32137. The authors thank J. Turi, the Director of the above office, for his permission to publish. The authors also thank K. Yates and R. Crites of Fairchild Space Company for their assistance in data reduction and preparation of this manuscript.

Table 1. Fueled Clad Response to Impact of a 56 Inch Square STS-SRM Fragment on the End of the Ulysses RTG,

Impact Velocity m/s	Fragment Axis Orthogonal To RTG Longitudinal Axis							
	Ellipticities of Fueled Clads, %							
	Position 1		Position 2		Position 4		Position 5	
	Fueled Clad 1	Fueled Clad 2	Fueled Clad 1	Fueled Clad 2	Fueled Clad 1	Fueled Clad 2	Fueled Clad 1	Fueled Clad 2
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	30.5	30.5	25.0	25.0	7.1	7.1	5.7	5.7
100	46.0	46.0	38.6	38.6	17.6	17.6	5.5	5.5
25 75 100	Fragment Axis Aligned with RTG Longitudinal Axis							
	7.4	7.4	0.0	0.0	0.0	0.0	0.0	0.0
	57.7	57.7	41.8	41.8	27.7	27.7	9.4	9.4
	70.0	70.0	61.5	61.5	-	-	-	-
25 75 100	Fragment Axis Aligned with RTG Fueled Clad Centerline							
	10.4	0.0	4.4	0.0	0.0	0.0	0.0	0.0
	61.5	30.5	50.0	9.6	3.70	0.0	0.0	0.0
	79.6	39.1	66.7	10.1	-	-	-	-

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