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SELENIDE ISOTOPE GENERATOR *for the* GALILEO MISSION

MASTER

Galileo-1632

TELEDYNE ENERGY SYSTEMS

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Pictured on the cover is Galileo's drawing of the solar system, which includes the four satellites of Jupiter he discovered in the 1600's. A Renaissance professor, inventor and astronomer, Galileo perfected the telescope with which he made his Jupiter discoveries. The 1982 NASA mission to Jupiter is named in his honor. Like Galileo and his telescope, the NASA mission to the far reaches of outer space will be contributing to Mankind's never ending quest for knowledge.

SELENIDE ISOTOPE GENERATOR

for the GALILEO MISSION

SAFETY TEST PLAN

SIG/GM

TES-33009-33

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II. THE HEAT SOURCE AND ITS FAILURE MODE

There is a single, generic failure mode for the isotope containment system, viz, loss of containment with the consequence of releasing radioactive material, partly respirable and partly in the form of larger, less mobile chunks. This failure mode potentially results from several mechanisms related to individual accident environments and combinations of them.

The containment system comprises five shells or partial shells surrounding the radioactive fuel. Each shell provides varying degrees of containment for the several accident environments. For example, the aeroshell, forming the outer layer of the Isotopic Heat Source (IHS) containment state is quite resistive to thermal environments both with respect to its own integrity and to protecting the inward shells. On the other hand, the aeroshell may provide less protection in certain mechanical environments, notably impact.

In view of its structure, useful failure models for the isotope containment system should account for the response of each shell in the sequence of steps leading to release of fuel. To this end we have defined six states of containment in Figure 1 in which each successive state, starting with the Post Impact Shell Assembly (PISA), is constructed from the preceding state by adding the next protective shell and any associated support structure or parts. The PISA state is formed by enclosing the 1.6 in. diameter fuel sphere in a 25 mil Ir-0.3%W (DOP-26) shell. The Fuel Sphere Assembly (FSA) is formed by adding the Graphite Impact Shell (GIS) to the PISA. In a similar way the eight-pack (EP), Isotope Heat Source (IHS) and, ultimately the RTG are formed by successive enclosure of inner containment states.

The importance of accounting for the state wise response to sequential accident environments is illustrated by considering, as an example, a typical accident postulation

I. INTRODUCTION

The Multi Hundred Watt (MHW) radioisotope thermoelectric generator (RTG) has been used as a power source in the Lincoln Experimental Satellite (8 and 9) and the Voyager 77 missions. In support of safety analyses for these missions, significant testing programs have been performed to characterize the containment capability of the generic MHW heat source. Included in these programs were impact, blast (over-pressure), solid propellant fire and reentry simulation testing.

For the SIG/Galileo mission the Improved Multi Hundred Watt (IMHW) heat source will be incorporated in a Selenide Isotope Thermoelectric Conversion System. Although this heat source is basically the same as that for which extensive testing has been performed, additional tests are required for two primary reasons:

1. The STS launch vehicle will be used for SIG/GM; the prior testing was directed at potential accident environments for the Titan IIID and IIIE vehicles.
2. Some details of the MHW heat source have been or may be modified. These include: changing the post-impact containment shell to the DOP-26 alloy of IR-0.3%W, removing the ablation sleeve, and potentially replacing the POCO aero shell with one of 3D carbon/carbon composite material.

To maximize effectiveness of the limited test program anticipated, it is essential that testing be performed to characterize mechanisms for failure modes deemed to be the most significant risk contributors. The objectives of this plan are to identify these critical failure mechanisms and to recommend experimental approaches for characterizing failure sequences. Using this plan, it is hoped, detailed test procedures may be

formulated by the appropriate laboratory so that results of testing will be useful in the subsequent safety analyses.

In the next section of this plan we describe the heat source, its typical failure mechanisms related to launch vehicle accidents, and our methods of estimating the probability and consequence of accident scenarios leading to release of the radioactive fuel. Following this exposition we summarize the results of analyses providing risk estimates pertinent to the SIG/GM. These results are then used to determine critical failure modes and related accident scenarios. From the critical failure mechanisms and consideration of available data characterizing environments and response of the containment system conclusions are drawn on remaining test requirements.

1 (a) FUEL

1 (b) PISA

1 (c) FSA

1 (d) EP

1 (e) IHS

1 (f) RTG

FIGURE 1. CONTAINMENT STATES FOR THE RADIOACTIVE HEAT SOURCE

resulting from a vehicular malfunction occurring shortly after liftoff. Vehicle failure may be initiated by a structural failure resulting in partial mixing of liquid hydrogen and oxygen. The isotope containment system could then be exposed to a series of environments including blast pressure, penetrating fragments, fireball, impact and propellant after-fires, notably burning chunks of solid propellant.

Figure 2 illustrates two possible histories of containment states versus accident environment. In the first, appropriate for a high-yield explosion, a weak RTG housing/aeroshell/retaining ring structure or combination of the two, the blast produces at least one free FSA, which survives fragment and fireball environments, but fails on impact. In the second, the aeroshell remains intact until impact which produces failure of the remaining containment shells and thus causes fuel release from at least one of the spherical assemblies.

Both of these sequences have been demonstrated experimentally and, in analyses performed for prior missions, have been identified as primary risk contributors for accidents occurring in the launch complex. A preliminary analysis (Ref. 1) performed for the space transportation system (STS) suggests that other sequences might become more important, in part owing to the very large inventory of cryogenic propellants for the STS compared with predecessor vehicles. In any case, the quantities of fuel released vary among trajectories of the type illustrated in Figure 2. Therefore it is important to distinguish the probabilistics for these paths and between release and non-release trajectories.

This is the scope of the problem to be addressed in the safety analysis. The problem may be solved by several different numerical techniques. Regardless of the details of the approach one selects, however, the input information needed is essentially the same.

FIGURE 2. TYPICAL ENVIRONMENT/STATE TRAJECTORIES

What is required is a model which provides an estimate of the level of each significant environment which is necessary to fail each containment shell, and information which can be used to assess the uncertainty of this estimate. When this information is combined with environment levels for the important types of accidents and associated uncertainties, it is possible to predict the conditional failure probability for each shell for each accident under consideration. Systematic combination of these failure probabilities for sequences of environments provides the path probabilities for trajectories of the type illustrated in Figure 2.

III. SIGNIFICANT ENVIRONMENTS

Full characterization of the containment system in terms of its response to all accident environments would be very expensive. Fortunately, it is not necessary to do so for a practical safety assessment program. To restrict the problem to manageable size we make use of results from a preliminary study (Ref. 1) of the consequences of certain types of accidents involving the Space Transportation System (STS) and power conversion systems with Multi Hundred Watt isotopic heat sources. The mission considered was a hypothetical one using the so-called Strategic Satellite System (SSS). The purpose of introducing the results of this preliminary study is to identify the most significant failure mechanisms of the containment system implicit in this combination of heat source and launch vehicle. The proposed test program will address only the critical mechanisms.

Results of the SSS study are summarized in Table 1. This table lists the four major accident types, occurrence and conditional fuel release probabilities, source terms and the risk product. Primary environment sequences are also indicated.

The significant difference between these results and typical results for previous launch vehicles is the importance of accidents occurring in the launch pad environs. This, in turn, results from high-yield explosions and lengthy fireballs created by the substantial propellant inventory of the STS. These are estimated to produce respirable source terms larger by two orders of magnitude than the average impact source term following reentry. Risk factors for reentry accidents were typical for those of earlier launch vehicles, as expected.

The primary accident sequences indicate the special significance of fragment, fireball, and impact effects. Specific consequences of high yield explosions are the

TABLE 1
SUMMARY OF INHALATION RISK CONTRIBUTIONS FOR THE SSS MISSION†

Accident Type	Initiating Mechanism	Accident Probability	Conditional Fuel Release Probability	Average Source Term (Ci)	Risk Product (Ci)	Primary Environmental Sequence
Fallback	SRB Burn thru	3.7×10^{-4}	0.95	142	5×10^{-2}	Fragment/ Fireball
Orbital Decay	No Transfer Burn No Orbital Injection Burn Premature 1st Burn Termination	2.4×10^{-2}	0.22	1.7	9×10^{-3}	Impact
In-Flight Explosion * (late)	Structural Failure Guidance & Control	1.4×10^{-4}	0.29	3.2	1×10^{-3}	Fragment/ Fireball
In-Flight Explosion * (early)	Structural Failure Guidance & Control	3×10^{-5}	0.33	113	1×10^{-3}	Blast/Impact/ Fireball

† Computations based on 5 MHW heat sources.

*Except destruct.

large total source terms (respirable and super respirable particles) produced by fragments and impact. Large explosions were estimated to increase the speed distribution of fragments and reduce their size, both effects contributing to larger probabilities of fragment impact and penetration of the fuel capsules. Ground impact source terms were amplified under certain conditions owing to large downward accelerations attributed to substantial explosive impulses.

Source terms produced directly by the fragment and impact effects would contain only a small mass fraction of respirable particles. However, for the STS, larger and longer fireballs were expected and these two factors combined to produce extensive vaporization of the radioactive material after release from its containment shells.

Thus, preliminary analyses performed for nuclear generators aboard the STS vehicle tend to emphasize risks resulting from explosions involving the substantial cryogenic propellant inventory. These results are preliminary, and although resulting from a fairly detailed analysis, are based on models which should be refined and updated as carefully as possible. The areas requiring particular attention are:

1. Launch vehicle accident modelling.
2. Fragment environment definition.
3. Fragment penetration.
4. Fireball modelling.
5. Impact response.
6. Solid propellant breakup and thermal environments.

The need for updating and refinement of models in areas 1 thru 5 is apparent from the preceding discussion. Although source term enhancement from burning solid propellants was not significant in the results of our preliminary analysis, it is possible that these results followed from two assumptions which may not be in accord with current

estimates of how the solid propellant would behave during a malfunction in the early flight of the vehicle. These assumptions were:

1. Breakup and dispersion of propellant web occurs only as a result of end-on impact of the Solid Rocket Booster (SRB).
2. Only the propellant mass in the leading segment is broken and dispersed.

Other assumptions which require critical evaluation are:

1. Chunk size is distributed so that the total surface area of chunks produced is proportional to the effective yield of the solid propellant deflagration.
2. Solid propellant yield is proportional to the momentum of the impacting SRB.

IV. TEST PLAN

In this section we discuss the test plan for the SIG/GM safety assessment in its present state of development. Not all of these tests are sufficiently well formulated to specify, e.g., the number of test specimens required, and precise test conditions. These will be developed in accordance with schedule requirements, particularly those defining input data requirements for the USAR and FSAR.

As seen in the preceding section, the significant fuel release sequences resulting from launch pad accidents are fragment/fireball and impact/fireball. The test plan outline shown in Table 2 lists test programs which are underway as part of the aeroshell characterization and selection task for the SIG/GM power system as well as new programs introduced in this document.

A. BLAST

While the blast environment has not been emphasized so far, it turns out that impact failures are more likely in the event that the aeroshell fails in the blast environment. This conclusion is drawn from the results of IHS and FSA impact tests completed under the LES 8, 9 and MJS safety programs. Furthermore, while solid propellant fires did not appear as contributors to the leading source terms in Table 1, impact of FSA's released by a blast increases the likelihood of stripping the GIS, permitting direct exposure of the PICS to this potential thermal environment.

For these reasons selection of the SIG/GM aeroshell will largely be conditioned on whether the 3D CC material is significantly better than the POCO graphite with respect to blast survival.

As indicated in the foregoing discussion, the quantitative safety assessment

TABLE 2
SIG/GM TEST PLAN

Environment	Objective	Specimens	Primary Variables/ Observables	Test Facility
A. Blast	Obtain data for Aeroshell and GIS Failure models.	3DCC aeroshell + simulated internals ; GIS + simulated PISA	Failure overpressures Poco/3DCC comparison	LASL
B. Fragment	Evaluate Recht-Ipson model; obtain data for new model if necessary.	Sections of : Aeroshell, internal structure, GIS, fuel-like ceramic.	Penetration threshold; fragment size; angle-of-incidence; multiple layer effects	Kirtland AFB
C. Impact	Develope impact failure model appropriate for DOP-26 PICS. Examine effect of C C aeroshell on distortion of FSAs	IHS (simulated fuel) FSA.	Failure conditions: Impact temperature "Aging" parameters Vibration effects momentum	LASL; Sandia
D. Thermal Stress	Evaluate Poco relative to fracture mechanics model; determine lower limit for C C improvement.	Poco, 3DCC aeroshell ring sections.	Thermal energy flux to failure	SoRI
E. Ablative Recession	Provide data for development on verification of recession rate models.	Aeroshell sections.	Total recession; heat flux, pressure; Oxidation rates vs temperature	NASA/ AMES TES
F. Material Properties	Provide data for modelling mechanical, thermal, and thermochemical failure modes.	3DCC, Poco graphite	Tensile ultimate stress/ strain. } uniaxial Poisson ratio Expansion coefficient Thermal conductivity Heat capacity Density	SoRI
		Ir-0.3% W (DOP-26)	Uniaxial elongation vs temperatures, aging conditions, strain rate ; forming limit data.	ORNL LASL

requires definition of the failure condition for each containment shell and its uncertainty. Because of the potential of multiple blasts according to the preliminary results of the launch vehicle failure modelling team, there is more emphasis for this mission on modelling potential failures of the GIS, assuming aeroshell failure in the first of a multiple blast sequence. For these reasons both IHS and FSA initial states are shown as specimens, the test objective is to determine the failure threshold and its uncertainty.

Preliminary estimates of test conditions are tabulated below:

<u>Test Conditions - Blast</u>			
<u>Specimen</u>	<u>Temp. (°C)</u>	<u>No. of Specimens</u>	<u>Expected Failure Condition</u>
POCO IHS	~ 600	1	200 psi (SSS study)
3D CC IHS	~ 600	3	Unavailable
FSA	~ 800	3	Unavailable

Initial temperatures are uncertain because launch cooling conditions have not been firmly specified and detailed thermal analyses for the heat source and internals are not available. Analytical modelling of 3D CC and GIS failure conditions has not yet been performed, hence it is anticipated that the limited experiments indicated in the test conditions will provide only a rough estimate of failure overpressures.

Some blast tests are now in progress at the LASL facility. This program should be expanded as indicated in the above tabulation.

B. FRAGMENT

The results presented in Table 1 (Section III) emphasize the potential importance of this environment. Models in this case for both environment (fragment flux, size and

speed distributions) and response (penetration requirements) are rough, therefore the primary objective is to increase reliability of the models.

Improvement of the environmental models will be attempted by an intensive review of data contained in the literature; no additional testing is contemplated for the SIG/GM program. The tests shown in Table 2 are intended to evaluate the Recht - Ipson (Ref. 3) penetration model as applied in the SSS safety study and to modify it as required to provide a more reliable method of risk estimation.

Objectives of the test are to evaluate precision of the Recht - Ipson model for single layers of aeroshell, GIS, and a fuel-like ceramic, and the multi-layer model which we have developed. Multi layer tests are to be performed on assemblies which preserve surface relations among the heat source constituents as they are for a selected direction of incidence on an actual heat source. The ceramic material need not simulate the fuel closely; it is more important that its properties which influence penetration are known.

A preliminary specification of test conditions is provided below:

Test Conditions - Fragment Penetration

<u>Specimen</u>	<u>Number</u>	<u>Penetration Speed (10^3 fps)</u>	
		<u>0.2 in.</u>	<u>0.4 in (Fragment Size)</u>
POCO A/S	3-5	4.8	2.5
3D CC A/S		Unavailable	Unavailable
GIS		5.0	2.7
Ceramic		Unavailable	Unavailable
POCO Assembly		Unavailable	Unavailable
3D CC Assembly		Unavailable	Unavailable

Temperature simulation is not critical in this case, since the primary intent is to evaluate and modify an existing penetration model, rather than provide test data

applicable directly to accident conditions. Tests are proposed to be conducted at the Kirtland AFB gas gun facility and would utilize sections of the indicated components rather than full components.

C. IMPACT

Launch complex and post-reentry impact environments have been found to be important risk contributors in quantitative risk assessments. The impact response modelling for FSA's has gradually evolved since the selection of the MHW heat source design concept.

Our version of this model is described in Appendix A which relates the impact failure probability to the difference between PICS elongation and the maximum local strain resulting from an impact sequence.

Maximum local strain depends upon the extent of deformation of GIS and fuel, primarily. Therefore the strain function, which depends on impact temperature and momentum of the FSA, must be determined from FSA impacts.

The elongation function derives from properties of the PICS. It is proposed that it be derived in two stages. The first stage involves material properties testing to determine the dependence of uniaxial elongation on strain rate, aging parameters and test temperature. This information is then combined in the second stage with results of FSA impact testing to develop a regression equation relating measured elongation to the aforementioned strain rate, age, and temperature functions.

The need for additional impact testing derives from consideration of: (1) the new version of the PICS alloy (DOP-26), and (2) lack of data at a range of impact temperatures and speeds. Since elongation modelling requires clad failures it is necessary that test conditions be rather severe. The alternative is to test at mild,

"reference" accident conditions, with, perhaps, no failures and therefore no basis for a quantitative failure model.

A preliminary specification of test conditions is given below:

<u>Test Conditions - Impact FSA</u>				
<u>Impact Speed (fps)</u>	<u>Impact Temp. (°C)</u>	<u>Aging Conditions (Temp. (°C)/time (hrs))</u>	<u>Vibration</u>	<u>Reentry Spike</u>
260	850	(1300/1000)	Yes*	Yes**
320	1100	(1300/8760)	No	No
	1300			

*Vibration conditions to be specified.

**1550°C for 10 minutes (orbital decay).

Impact speeds are representative of the range possible, according to the results of the SSS safety study, for launch complex accidents. Representative post-reentry impact speed (250-280 fps) for the IHS are included in the indicated range. Only two speeds are selected because existing data for clad deformation and strain rate effects are thought to be linear with speed or momentum.

Impact temperatures will vary with accident conditions. The present estimate of the PICS impact temperature is 850°C for accidents occurring in the launch complex. Post-reentry impact temperatures are estimated to be between 1100 and 1300°C. ORNL testing suggests that the elongation temperature dependence may be fit by a quadratic polynomial, therefore three impact temperatures are specified to determine the validity of the functional dependences shown in Appendix A.

Aging conditions specified are approximately representative of conditions during launch and after one year in orbit. However, the intent is to provide data for developing equations representing elongation in terms of aging, in this case, and not to match a "reference" condition. Note that a reentry spike condition is also specified. It is not clear that this will have an effect other than augmenting aging.

Absence of vibration for some specimens is recommended preliminarily, owing to a recent suggestion that vibration may accelerate grain growth. If this is proven not to be the case, this variable will be removed.

It is apparent that a full factorial test would require 48 impacts. We will utilize latin square methods, particularly with respect to the last two variables, to limit individual impact tests to about 10 or 12.

Finally, an impact of an IHS with simulated fuel, similar to the one performed during the LES 8, 9 safety test program, is proposed in the event the 3D CC aeroshell is selected for the SIG/GM. Test conditions should be identical to those for the original test. The purpose of this test is to observe changes in the deformation of FSA's owing to the new aeroshell material.

D. THERMAL STRESS

Although demonstrated not to be a major contributor to the risk of fuel release during interplanetary missions, the thermal stress failure mechanism has always received a great deal of attention at safety review meetings. Testing related to this mechanism is already scheduled as part of the aeroshell selection program. This is justified in part by the expected increase in thermal stresses in the aeroshell compared with Voyager predictions because of removing the ablation sleeve present for the mission.

Ring sections of an aeroshell are to be exposed to rapid heating in RF induction

furnace facilities at SoRI. The experimental demonstration is set up to determine the failure condition for POCO rings and then expose 3D CC rings of comparable configuration to exhibit relative superiority. The testing details have not yet been specified.

If the ring sections are designed properly, the failure data for four or five POCO sections can be used to test the fracture mechanics model developed by Batdorf and Crose, and recently applied to estimate failure conditions for homogeneous graphite under polyaxial stress states, given uniaxial failure statistics (Ref. 4).

While it is not intended to develop a fracture mechanics model for the composite graphite shell, the failure (or survival) data in this case may be used to infer minimum strength data for polyaxial stresses experienced during reentry. Thus a lower limit on the failure probability for a 3D CC aeroshell may be assessed.

E. ABLATIVE RECESSION

Ablation testing at the AFFDL 15 megawatt facility (Wright Patterson AFB) has already been conducted for two high pressure regimens. Ablation testing at the NASA/Ames facility is planned as part of the aeroshell selection program. The primary utility of these data, apart from demonstrating the adequacy or inadequacy of the present aeroshell design using 3D CC graphite, is to evaluate the existing sublimation model and to modify it if necessary. Test conditions are specified in Ref. 5.

Oxidation rates for POCO and 3D CC graphites have been measured at TES. Results are reported in Reference 6. Data reduction to infer activation energy and rate constant will be reported subsequently.

F. MATERIAL PROPERTIES

Primary requirements for properties are for the graphites and Ir-0.3W alloy. Graphite requirements are similar to those of past safety programs and include mechanical and thermal parameters listed in Table 2. Test data should be derived from graphite billets to be used for flight hardware and should be obtained from about 10 samples to provide statistical information. Temperature dependence of properties in the range from room temperature to 4000 °C is needed.

Properties needed for the PICS material have already been discussed under Section C - Impact Testing. Data requirements are similar to those already obtained at ORNL for the various iridium alloys tested in the past. Included are elongation as a function of:

1. Uniaxial impact temperature.
2. Aging conditions.
3. Impact speed or strain rate.

Approximate testing conditions are:

Ir-0.3W (DOP-26) Test Conditions

<u>Impact Temp. (°C)</u>	<u>Aging Conditions</u>		<u>Impact Speed (fps)</u>
	<u>Temp. (°C)</u>	<u>Time (hrs)</u>	
800-1300	~1300	0-10,000	100-300
	~1400	0-1000	
	~1500	0-1000	

Aging conditions should include exposure to any effluents from the fuel or graphites which may have an embrittling effect.

Development of forming limit data to show the dependence of elongation on strain

state may be helpful in understanding results of FSA impact testing in relation to uni-axial clad impact tests. These tests have been performed at LASL and are recommended for the new clad material.

G. SUMMARY

The intent of this safety test plan, as presented in the introduction of this document, is to outline particular kinds of safety tests designed to produce information which would be useful in the safety analysis process. The DOE-sponsored program deals primarily with the response of the RTG to accident environments; accordingly two criteria were established:

1. Safety tests should be performed for environments which are the most critical in terms of risk contribution.
2. Tests should be formulated to determine failure conditions for critical heat source components rather than observe heat source response in reference accident environments.

To satisfy criterion 1. results of a recent safety study were used to rank various accidents in terms of expected source terms. Six kinds of tests were then proposed which would provide information meeting the second criterion above.

The ultimate test of the program's utility is completeness: when the anticipated results of these tests are combined with existing information characterizing accidents and RTG response, will the total meet the needs of a realistic yet practical risk analysis? Figure 3 presents the safety assessment matrix which outlines the role to be played by test data supplied by this program and those areas in which modelling is considered satisfactory.

The matrix deals with the response of each component shell in each major environ-

Containment Shell

Environment	RTG Housing ①	Aeroshell ②	Eight Pack Structure ③	GIS ④	PICS ⑤	Fuel ⑥	Environment Definition ⑦	References Illustrating Existing Models
Launch Complex Blast	A Static Model (SM)	T	→	A (SM)	A	A		⑥ Viking FSAR ⑦ AD889863 Chemical Rocket/Propellant Hazards
Fragment	A	T	→		A	A		②-⑦ AFWL TR-77-161 (also unpublished SSS-Safety Study)
Fireball	A	→						⑥ Unpublished SSS-Safety Study ⑦ Bader-J. Spacecraft & Rockets,
Impact	A	T	→			A		See Appendix A
Fire Solid Propellant	A	→						⑥-⑦ AFWL-TR-77-161
Reentry Thermal Stress	N/A	T	N/A	→		A		② AFWL-TR-77-161
Thermal Response	A	→						①-⑦ Viking FSAR
Ablative Recession	A	T	A	→				①-⑦ Viking FSAR

A—Analytical modeling developed from or confirmed by existing test data

T—Experimental basis provided by this test program

N/A—Not a significant factor in failure sequence

FIGURE 3. SAFETY ASSESSMENT MATRIX

ment. Also shown are fuel response and the approach to environment definition. Entries in the matrix marked with an "A" indicate plans to retain existing models or refine them primarily with information available in the literature. Descriptive references for existing models predicting the failure conditions for each environment for each (numbered) containment shell are also provided.

The matrix illustrates the prominent role to be played in failure modelling by a relatively modest test program. Note that certain continuing test programs, viz., characterization of the thermochemical environment of a burning chunk of solid propellant, are not identified here as part of the safety test program. This work is being done at Georgia Institute of Technology under Air Force funding and at LASL.

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APPENDIX A

PRELIMINARY IMPACT MODEL

Performance of risk analyses for the SIG/GM generator requires, in part, an impact model, i.e. a means for predicting the failure probability of the PICS as it depends on the history of the PICS from manufacture to impact.

We are currently investigating a model (following leads from other laboratories) which depends upon two variables - maximum strain to which the PICS might be exposed, and elongation.

The important part of the strain function for our purposes may be written in the form:

$$\epsilon = \epsilon_0 + \epsilon_1 p + \epsilon_2 T_i + \epsilon_3 T_i p \quad (A-1)$$

where: ϵ = maximum local strain
 p = impact momentum
 T_i = impact temperature

and the coefficients, ϵ_n , are to be determined from multiple regression analysis of FSA impact tests. The strain function depends mostly on the GIS and fuel and to a lesser extent on the PICS.

The elongation function can be written:

$$e = A + Bg(v) + C \alpha (T_a, t_a) + Df(T_i) \quad (A-2)$$

Here again, we would hope to derive the coefficients A, B, C and D from a multiple regression of post-impact elongation measurements on FSA's. The function g , α , and f are to be derived from ORNL experiments where:

$g \equiv$ strain rate function of impact speed, v ,
 $\alpha \equiv$ aging function at temperature T_a , and time t_a ,
 and $f \equiv$ impact temperature (T_i) function.

For example, test data for alloys other than DOP-26 show it is possible to represent these functions in the form:

$$g = g_0 + g_1 v \quad (A-3)$$

$$\alpha = (\alpha_0 + \alpha_1 T_a + \alpha_2 T_a^2) \ln [t_a / t_0] \quad (A-4)$$

$$\text{and } f = f_0 + f_1 T_i + f_2 T_i^2 \quad (A-5)$$

These functional fitting forms appear to be representative of the behavior of elongation with the indicated variables as illustrated in various plots presented in ORNL progress reports during the past 5 years, or so.

The failure probability for the PICS for any discrete set of parameters can be estimated using the strain and elongations appropriate to those parameters combined with the uncertainties implicit in the estimate of each. As an example, if strain and elongation were assumed to be normally distributed about their estimates with errors σ_e and σ_ϵ , the failure probability is:

$$P_f = \eta \left(\frac{e - \epsilon}{\sqrt{\sigma_\epsilon^2 + \sigma_e^2}} \right) \quad (A-6)$$

where: e = estimate of elongation from its regression function,

ϵ = estimate of strain,

and $\eta(x)$ = cumulative normal distribution function.