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Safety Analysis for a Radioisotope Stirling Generator

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Abstract – *The Idaho National Laboratory (INL) is conducting safety analyses of various low-power Radioisotope Stirling Generator (RSG) design concepts for the U. S. Department of Energy. These systems are electrical power generators converting thermal energy from plutonium (^{238}Pu) decay to electrical energy via a Stirling cycle generator. The design and function are similar to the RTG (Radioisotope Thermoelectric Generator) used in space missions since the early 1960's, with a more efficient Stirling cycle generator replacing the proven thermoelectric converter. This paper discusses the methods the INL is employing in the safety analysis effort, along with the software tools, lessons learned, and results.*

The overall goal of our safety analyses is to determine the probability of an accidental plutonium release over the life of the generator. Historical accident rates for various transportation modes were investigated using event tree methods. Source terms were developed for these accidents including primarily impact, fire, and creep rupture. A negative result was defined as rupture of the tantalum alloy containment vessel surrounding the encapsulated plutonia pellet. Damage due to identified impact accidents was evaluated using non-linear finite element software tools. Material models, gathered from a wide variety of sources, included strain-rate and temperature dependencies on yield strength, strain hardening, and rupture. Both individual component and overall system simulation results will be validated by impact testing to be conducted by Los Alamos National Laboratory.

Results from deterministic impact, fire, and creep rupture analyses were integrated into the probabilistic (Monte Carlo) risk assessment by correlation functions relating accident parameters to component damage. This approach presented challenges, which are addressed. Other significant issues include limitations of reliable material data at high temperatures and strain-rates and development of a technique to predict crack size in failed containment material necessary for estimating source terms.

Accident rates have been compiled from historical data for several possible transportation vehicles including trucks and aircraft. Impact analyses completed thus far indicate that the primary containment vessel survives ground based accidents with no release of plutonia to the environment.

I. INTRODUCTION

The Idaho National Laboratory (INL) is conducting safety analyses of various low-power Radioisotope Stirling Generator (RSG) design concepts for the U. S. Department of Energy. These systems are electrical power generators converting thermal energy from plutonium (^{238}Pu) decay to electrical energy via a Stirling cycle generator. The design and function are similar to the RTG (Radioisotope Thermoelectric Generator) used in space missions since the early 1960's, with a more efficient Stirling cycle generator replacing the proven thermoelectric converter. The subject generator design is the product of a collaborative effort by Lockheed Martin, Infinia, and the NASA Glenn Research Center. This paper discusses the methods we are employing in the safety analysis effort, along with the software tools, lessons learned, and representative results. The risk assessment presented addresses the probability of fuel release during ground and air transportation of an RSG prior to delivery and operation.

II. SYSTEM DESCRIPTION

The RSG design discussed in this paper includes an Isotopic Heat Source Module (IHSM), an insulation can surrounding the IHSM, the Stirling Converter Assembly (SCA), and a housing of aluminum alloy (Figs. 1 and 2). The IHSM itself consists of four identical isotopic heat sources (IHS) each fueled with a plutonium dioxide (PuO_2, plutonia) pellet with an iridium cladding. Additional appendages such as electrical controllers (for regulation of electrical output), environmental and instrument monitoring devices, and a transportation container are part of the system but were not considered in our accident analyses.

The RSG assembly has two layers of enclosure to protect against release of the fuel: the IHS containment assemblies and an outer aluminum alloy housing. Each IHS uses a tantalum alloy capsule as the containment vessel surrounded by a nickel alloy outer clad to protect the tantalum alloy from oxidation (tantalum alloy is embrittled when exposed to oxygen). The tantalum capsule provides the primary fuel release barrier and was designed to withstand anticipated internal operating pressures. All IHS components inside the containment capsule are assembled, installed, and inspected before the two parts of the containment capsule are welded together forming a pressure vessel. A graphite module surrounded by an insulation can holds the four IHS units in the aluminum housing. The housing is designed for an internal pressure providing a second fuel containment in the event of primary containment failure due to creep rupture or a defect and provides limited protection to the containment capsules in an impact accident.

III. ACCIDENT ANALYSIS

In the following sections, we present details of our safety analysis approach for ground and air transportation accidents. We used a systematic combination of deterministic and probabilistic steps to accurately predict the likelihood of system failure. The first three steps are; 1) identifying credible accident types, 2) mapping scenarios and consequences into a set of event trees, and 3) evaluating accident event parameters and probabilities.

Failure of an RSG is defined as an accidental release of radioactive material. In the context of this safety analysis, a release is defined as rupture of a tantalum alloy containment capsule surrounding an encapsulated plutonia pellet. Potential release and failure mechanisms are addressed by evaluating the structural integrity of the containment system - when challenged by any of a variety of postulated accidents. Identifying all of the events that potentially lead to such a release is problematic since historically-derived operating data does not exist – i.e., no accidents have occurred with these or similar systems. For simplicity, only transportation accidents are discussed in this paper. We employed master logic diagrams[1] (MLDs) to categorize possible transportation accident events. MLDs systematically organize and simplify the development of a list of potential accidents. Fig. 3 shows an MLD developed for the transportation of an RSG. The "top" event on the right is an RSG transportation accident with release potential.

Prior to operation, an RSG may be transported by aircraft and/or light truck. Potential accident conditions span a range of impact and fire parameters including velocity, orientation, impact surface, fire temperature, and fire duration. Accident models were developed for each mode of transportation to define the range and probability of the possible accident conditions. Transportation accidents include not only events during the actual transport, but also accidents that might occur during the loading and handling associated with transport. This can be viewed as four phases: initial loading and handling at a storage facility, transport from the storage facility to an operational location, return transportation, and final loading and handling. Each of these four phases presents the potential for a number of accidents. A random loss of heat sink (required for stable operation) can occur during any phase of transport. During loading and handling the RSG could be dropped, subjected to impact such as a vehicle collision, or receive damage to its control systems.

The master logic diagrams identified a set of accident initiators and accident types. The accident scenarios encompassing these initiators and accident types have been depicted in a set of event trees for each phase of the RSG life cycle after delivery: storage, transport to operation site, operations, and return. In addition, there are subtrees that look specifically at truck and aircraft accidents.

The aircraft portion of the transportation is modeled as top events in Fig. 4. The first three top events address the likelihood of the cargo plane crashing during take-off, in flight, and upon landing. Crash probability and fuel loading (and subsequent likelihood and duration of a fire) differentiate these three regimes. For each postulated crash, additional parameters regarding the crash site and likelihood of fire are determined. For example, an event determines whether the plane crashes into water, a relatively soft surface (e.g., sand and soft soil) or hard surface (e.g., steel, concrete, etc.). Another event determines if the crash results in exposure of the RSG unit to a fire in addition to the crash impact. Aircraft impacts (and some light truck accidents) will produce pool fires. Temperatures are selected randomly between about 800 and 1230C using a triangular density function. Upon completion of the aircraft segment, the RSG is assumed to be driven by truck and the event tree now determines the likelihood of a truck crash following logic similar to the aircraft accidents. Loss of cooling and high-temperature creep rupture in the containment capsule material caused by loss of cooling are also considered in the event tree logic.

IV. IMPACT ANALYSIS

The fourth step in our safety analysis is using deterministic simulations to accurately predict the response of the fuel containment to these accidents. In support of the accident analyses outlined above, we conducted extensive numerical simulations to estimate the damage sustained by the containment capsules in high-velocity impact accidents. Finite element models of the heat source module, IHS, insulation container, the Stirling Converter Assembly (SCA), and parts of the balance of the RSG unit were created and assembled for simulation by the finite element software, LS-DYNA. LS-DYNA[2,3] is a multipurpose explicit and implicit Lagrangian finite-element code designed primarily to simulate highly nonlinear physical phenomena such as large deformations due to impacts. To generate the finite element models, solid models of each part (Figs. 1 and 2) were created with I-DEAS[4] and used as the reference geometry to generate finite element meshes. HyperWorks[5] and LS-PrePost[2] were used for post-processing.

Impacts were numerically simulated on two target types: hard surfaces represented by concrete and soft surfaces represented by sandy, incohesive soil. Impact velocities of 15, 55, and 76m/s onto concrete and 25, 55, and 76m/s onto soft soil targets were simulated to assess accident conditions within a 95% confidence bound. No credit was taken for protection of the RSG by the aircraft or truck.

A total of 33 impacts were simulated using LS-DYNA for five orientations, two targets, and three velocities per target type. Orientations included end, side, and angled impacts onto both the hot-end (fuel first) and cold-end of the RSG. Because impact dynamics strongly depend on the mass of the bodies involved, the mass of each part was tracked and, where necessary, adjusted to accurately reflect the mass of the actual part. The mass checks show that the final model mass varies from the design unit by less than 0.2%.

The RSG unit is composed of a variety of metals, ceramics, and fiber-reinforced composites operating over a temperature range from room temperature to 900°C. Constitutive models were developed for all heat-source, insulation, and housing components and significant Stirling Converter Assembly components. In all, 33 of the constitutive models developed were employed in the final simulation runs. Care was taken to incorporate rate and temperature dependence in all materials important to the impact response of the unit. During impact simulations strain rates were tracked and recorded for important heat source components, showing that strain rates exceeding 2000 s^{-1} were common for impacts onto hard surfaces. Material data at high strain rates and temperatures were gleaned for the most part from the open literature. As may be expected, high-rate data for materials of interest to the ballistics community (e.g., Ti-6Al-4V) are fairly readily available, while that for refractory alloys can be more difficult to obtain. Other data pertaining to the heat source internals (e.g., the clad fuel pellet and housing) were derived from previous Department of Energy studies supporting RTG development. Impact tests at both the component and system level are scheduled to be conducted at Los Alamos National Laboratory. Material models developed for this safety analysis will be validated to the test data when it becomes available.

The complete RSG model includes 195 parts, 153,509 nodes, and 128,894 elements. The concrete target has 20,700 elements and the soft-soil target has 91,464 elements. Impact targets were generated with the intent that they be as large as necessary to avoid boundary effects, while minimizing the model size and subsequent run-time requirements. Targets were fixed at the base and free at the upper surface. Silent (non-reflecting) boundary conditions were employed on all vertical boundary faces to simulate a semi-infinite medium. An RSG model including significant components of the SCA was used for all impact simulations on concrete. Due to the computational complexity of the soft soil impacts, a reduced model was used that includes all parts except the RSG housing assembly and the SCA. Parameters tracked for each simulation include; 1) overall energy balance and deformation, 2) maximum plastic strain in each containment capsule, 3) void volume (internal volume not occupied by solid material) reduction in each capsule, 4) fuel deformation, and 5) post-impact stress versus internal pressure in the capsule shells and welds.

At the heart of the RSG is a Stirling engine, which converts thermal energy into electrical power through a reciprocating free-piston-spider design. The piston and spider are shown in Fig. 2. From a modeling standpoint, the piston and spider represent projectiles that could pierce the containment capsule. Modeling of these components focused on ensuring the axial alignment was maintained throughout the impact in a realistic manner. To achieve this, a detailed model of the spiral springs was created. The spiral springs align the piston and spider axially and provide the restoring force allowing these components to reciprocate. The spiral springs are shown in Fig. 2.

The hard target (concrete) was modeled as a rectangular block with relatively uniform mesh size throughout the volume. Fig. 5 shows an example impact of the RSG onto concrete at 76m/s. The corresponding maximum effective plastic strains in a containment capsule are shown in Fig. 6 with a peak of 34%. Our failure criterion for the capsule material at operating temperature subjected to impact is 21% effective plastic strain indicating that rupture was predicted for this example impact simulation.

Soft targets, which experience very large deformations, were modeled with strong gradation around the impact site to reduce element distortion and the entailing numerical difficulties. Adequate mesh refinement, along with the very robust soil formulation encoded in LS-DYNA, allowed very large soil penetrations and cratering to be modeled with appropriate accuracy. Fig. 7 illustrates the soil block target and its response to a 76m/s angled impact (velocity vector is through the RSG center-of-gravity). Also shown is the maximum effective plastic strain in a containment capsule. In this case, the strains were well below rupture levels.

Our impact simulations predict rupture of the containment capsules for hard surface impacts at velocities just below 55m/s and higher. Impact simulation results show effective plastic strains above the 21% threshold for all hot-end impact orientations onto a hard surface at 76m/s and several orientations at 55m/s. For all orientations impacting a hard surface, damage was only minor at 15m/s with maximum containment capsule plastic strain of 2% (side orientation). The highest effective plastic strain in containment capsules predicted by our impact simulations is 62%, produced by a 76m/s end impact onto a hard surface, hot-end first. Angled impact simulations (hot-end first through the center of gravity) predict strains up to 44% at 76m/s. Void volume reduction is minor for almost all impacts onto a hard surface. The void volume reduction ratio (ratio of final void volume to initial void volume) drops below 0.90 for two impact simulations onto a hard surface: side orientation (55m/s, 0.886) and side-orientation (76m/s, 0.759).

Impacts onto a soil target produce only minor damage at all velocities and orientations evaluated. Plastic strain in the containment capsules is limited to 7% (side orientation, 76m/s), and the void volume reduction ratio in the containment capsules is 0.996 or greater for all soil target cases. Rupture or penetration of the containment capsules by components of the SCA was shown to be non-credible for all orientations and impact velocities.

V. RISK ASSESSMENT

The final safety analysis step is to perform a risk assessment by combining deterministic and Monte Carlo probabilistic techniques and interpreting the results. Correlation functions were developed allowing us to interpolate between the sparsely populated deterministic results from our impact, fire, and creep rupture analyses. Sensitivity analyses were performed to determine the effects of time, temperature, and material strength on failure of the containment capsule.

Although not yet complete, risk assessment of the RSG shall be performed by calculating relative probabilities of accident scenarios and corresponding result (failure/no failure) interpretations. Our Monte Carlo algorithms perform a random sampling of the set of accident parameters (incorporating statistical uncertainty estimates) resulting in a failure probability solution for each iteration. For example, the sampling process may select an aircraft accident with an impact velocity of 40m/s at an angle of 35 degrees, in a geographical area of predominantly hard rock after 1-year of storage. Our correlation functions allow us to interpolate these parameters from values we had previously developed via deterministic analyses to reach a failure probability. This process is repeated until convergence is reached yielding the failure probability distribution.

Although the deterministic models are nonlinear, (as is the process of linking data to Monte Carlo model parameters) correlation functions we've developed will link the finite set of deterministic input to the randomly generated transportation conditions (e.g., velocity, surface, and temperature). The resulting probability distribution from the Monte Carlo model then shows the relative probabilities of accident scenarios and a risk assessment can be prepared.

VI. CONCLUSIONS

Safety analysis of a Radioisotope Stirling Generator requires a systematic combination of deterministic and probabilistic steps to accurately predict the likelihood of system failure. In this case, system failure is defined as rupture of one or more of the internal containment capsules surrounding the plutonia fuel. To illustrate our methods, we presented detail of the safety analysis for ground and air transportation accidents. Our steps include:

1. identifying credible accident types and their initiators using master logic diagrams.
2. mapping accident scenarios and consequences into a set of event trees for each life cycle phase.
3. evaluating accident event parameters and probabilities using experience, simulations, and test data.
4. accurately predicting the response of the fuel containment to these accidents using deterministic simulations to be verified by testing.
5. performing risk assessment by combining deterministic and Monte Carlo probabilistic techniques. Correlation functions are developed to interpolate between the sparsely populated deterministic results.

Impacts of the RSG onto hard surface and soft soil targets at velocities up to 76m/s with five orientations were simulated to assess accident conditions within a 95% confidence bound. These impact simulations predict rupture of the containment capsules for hard surface impacts at velocities just below 55m/s and higher. Impacts onto a soil target produce only minor damage at all velocities and orientations evaluated. Both individual component and overall system simulation results will be validated by impact testing to be conducted by Los Alamos National Laboratory.

Results from deterministic impact, fire, and creep rupture analyses are being integrated into a Monte Carlo probabilistic risk assessment by correlation functions relating accident parameters to component damage. Sensitivity analyses were performed to determine the effects of time, temperature, and material strength on failure of the containment capsule.

Further information and analysis is required for a precise conclusion regarding potential rupture of the containment capsules during impact accidents. For example, there are limitations of reliable material data at the high temperatures and strain-rates of interest. Development of a numerical simulation technique to predict crack size in failed containment material is necessary. Additionally, components that experience large deformation and/or rupture should be modeled individually, perhaps using an Eulerian code to more accurately simulate penetration modeling.

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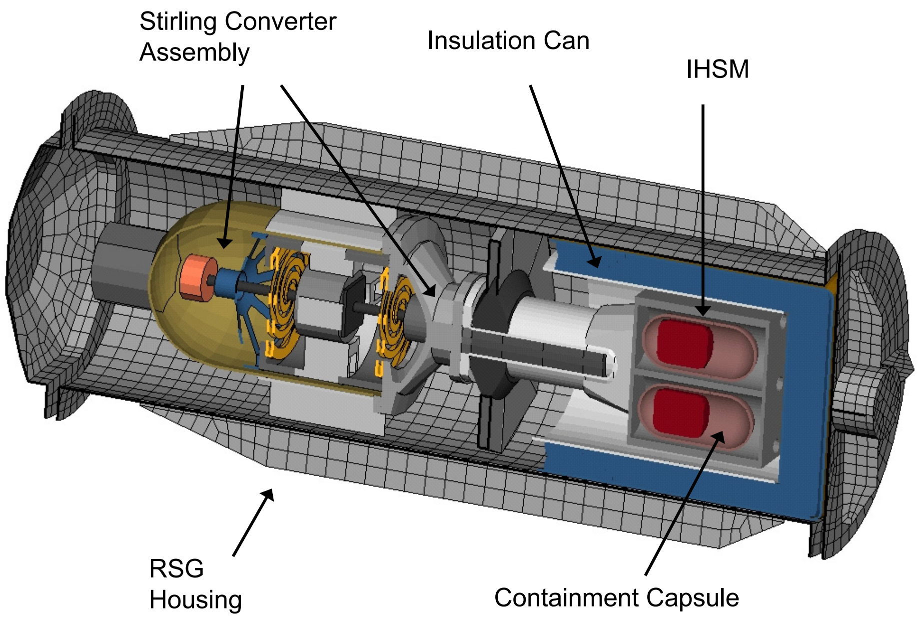

Fig. 1. Radioisotope Stirling Generator Model with Internals – Cut Away View

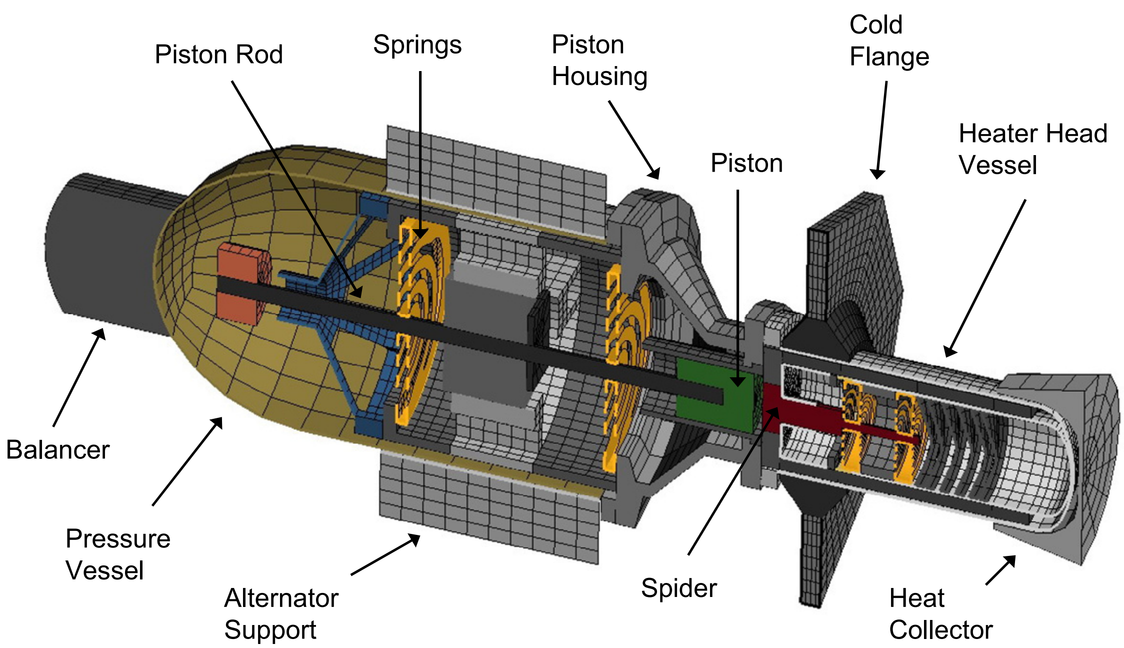

Fig. 2. Stirling Converter Assembly Model with Internals – Cut Away View

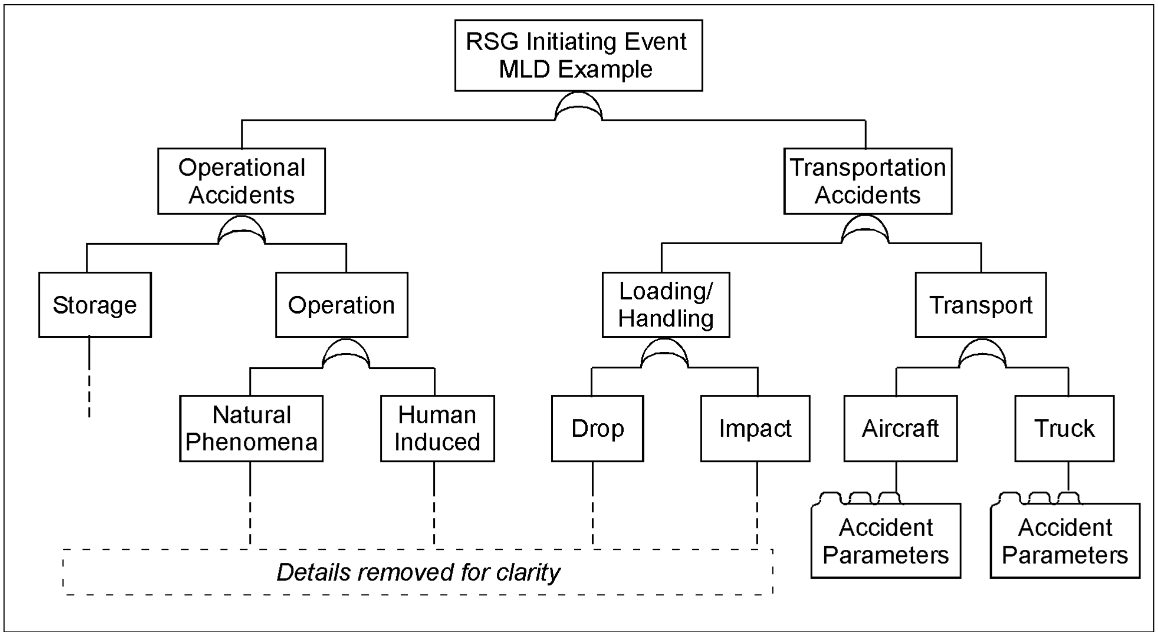

Fig. 3. Master Logic Diagram Example

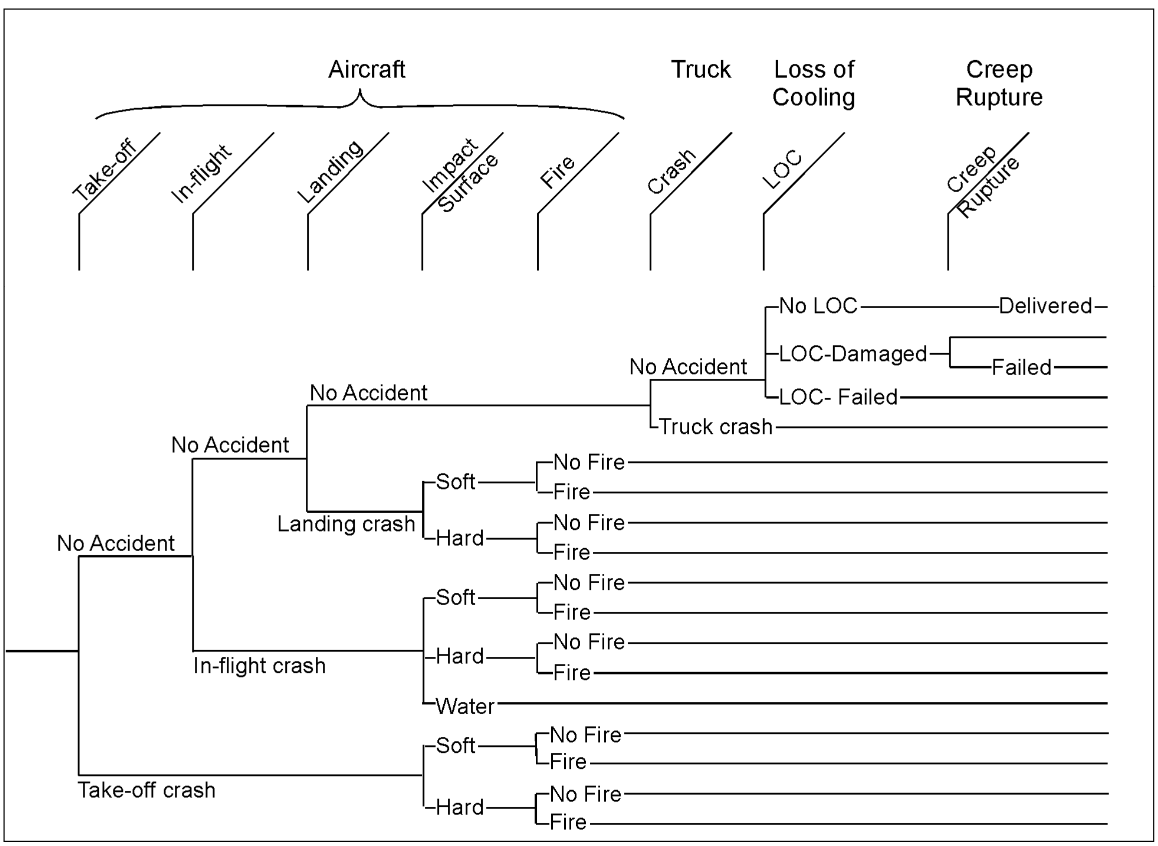

Fig. 4. Event Tree Example

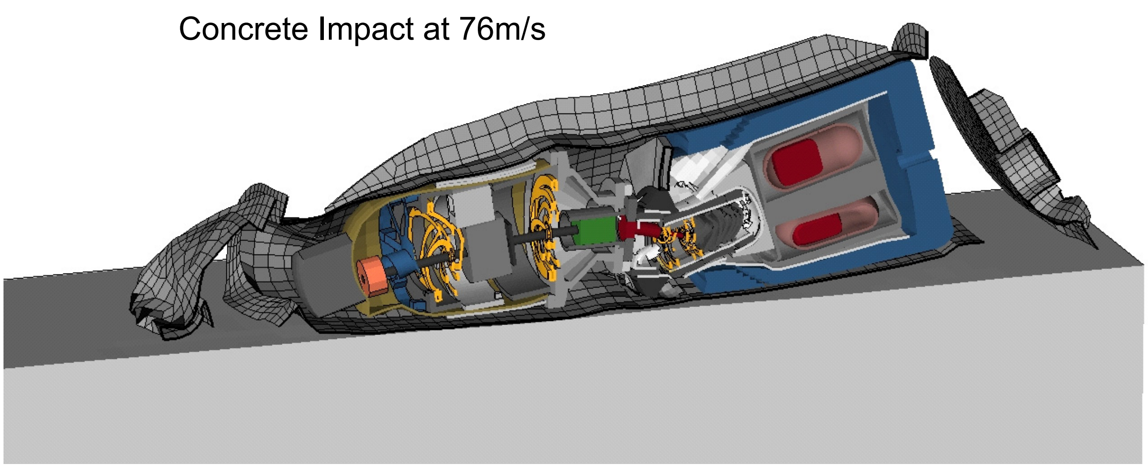

Fig. 5. RSG Impact Simulation at 76m/s onto Concrete – Cut Away View

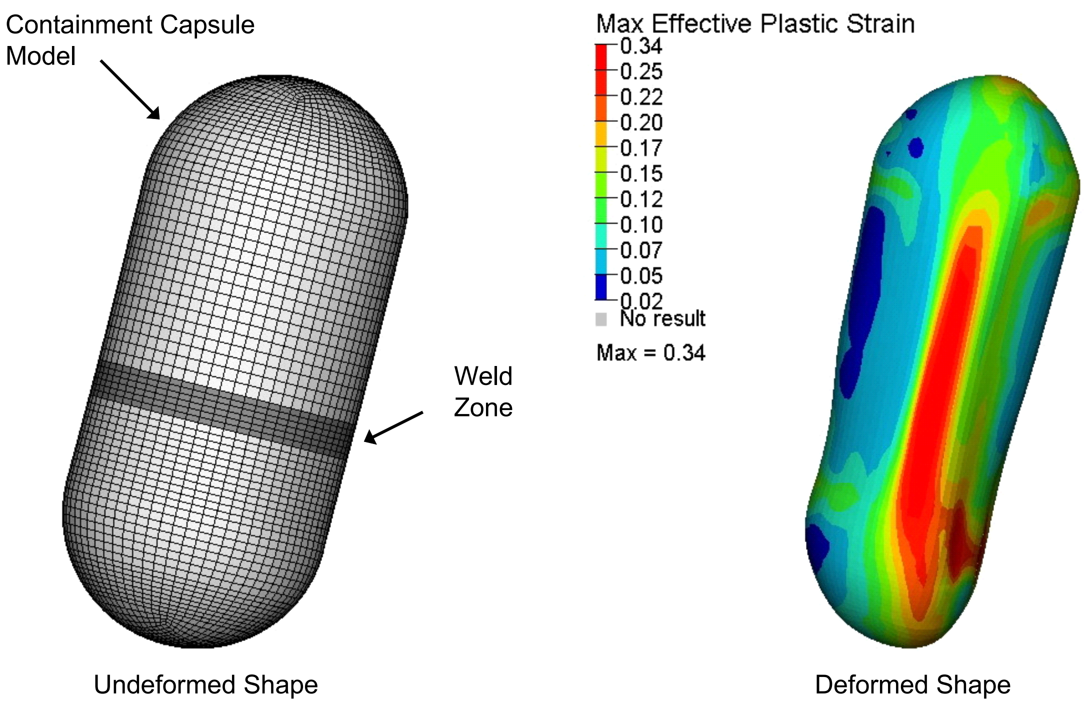

Fig. 6. Containment Capsule Strain and Deformation due to Impact at 76m/s onto Concrete.

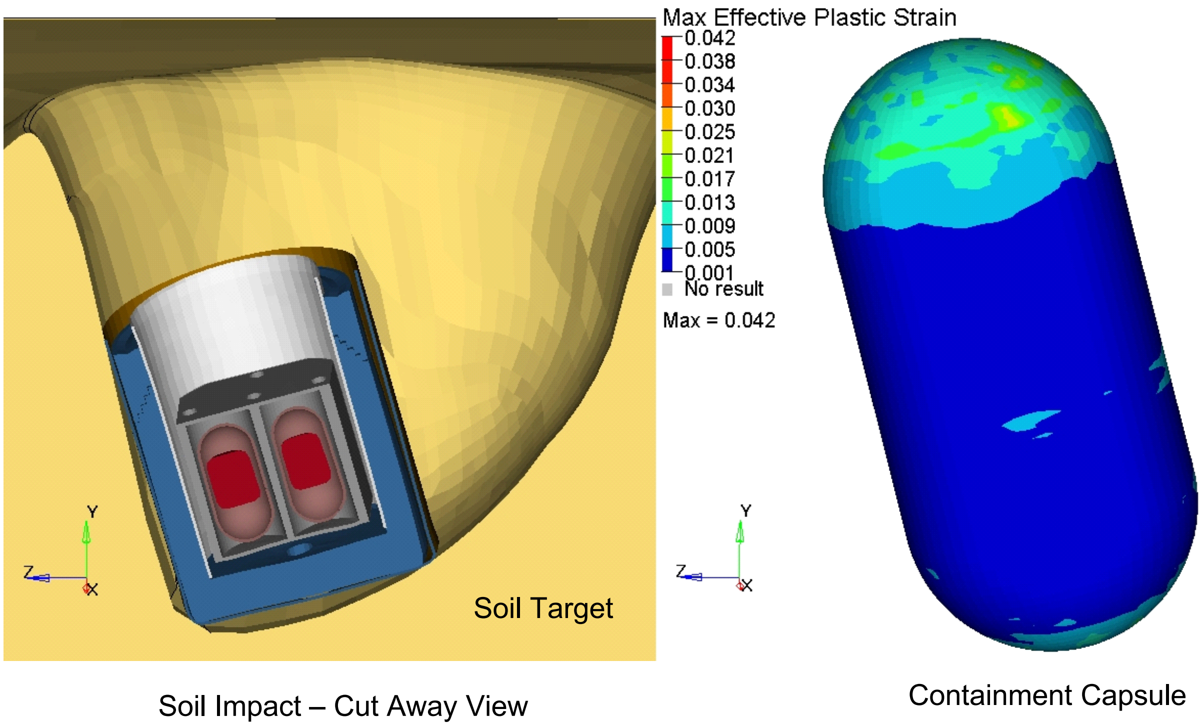

Fig. 7. Soft Soil Impact of IHSM (Cut Away View) at 76m/s and Corresponding Strains in Containment Capsule