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AN OVERVIEW OF THE RISK UNCERTAINTY ASSESSMENT PROCESS FOR THE CASSINI SPACE MISSION*

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ABSTRACT

The Cassini spacecraft is a deep space probe whose mission is to explore the planet Saturn and its moons. Since the spacecraft's electrical requirements will be supplied by radioisotope thermoelectric generators (RTGs), the spacecraft designers and mission planners must assure that potential accidents involving the spacecraft do not pose significant human risk. The Cassini risk analysis team is seeking to perform a quantitative uncertainty analysis as a part of the overall mission risk assessment program. This paper describes the uncertainty analysis methodology to be used for the Cassini mission and compares it to the methods that were originally developed for evaluation of commercial nuclear power reactors.

I. INTRODUCTION

The Cassini spacecraft is a deep space probe whose mission is to explore the planet Saturn and its moons. Following an anticipated launch in late 1997, the spacecraft is expected to perform fly-by gravity assist maneuvers with the planets Venus (twice), Earth, and Jupiter on its way to a rendezvous with Saturn in 2004. The electrical requirements for the spacecraft will be supplied by three radioisotope thermoelectric generators (RTGs) due to the extremely low intensity of solar energy at such great distances from the sun. The spacecraft designers and mission planners must assure that neither the launch nor the gravity assist earth fly-by pose significant human risk.

The space program has a long history of performing risk computations for space missions using probabilistic risk assessment (PRA) techniques. This is especially true for those missions where RTGs are used. However, past assessments have typically yielded quantitative point estimates of risk and qualitative or heuristic assessments of risk uncertainty. The Cassini risk analysis team has determined that advances in the field of risk uncertainty assessment over the past decade warrant a quantitative approach to uncertainty for this mission. The purpose of the uncertainty analysis is to provide adequate information and perspective to a decision maker who must ultimately approve the launch.

There are many parallels between the risk analysis method used for launch accidents and that used for the evaluation of commercial nuclear power plants. The first step is an assessment of the probability that the launch vehicle itself will experience a failure that can either jeopardize the mission or threaten the space probe. This is similar to the "Level I" core damage sequence analysis in a nuclear power PRA in that we are assessing the frequency with which the system is placed into a condition where there is a *potential* for the release of radioactive materials. The second step is an assessment of the conditional probability that the launch vehicle failure will *actually* lead to a radiological release and, if a release does occur, assess the characteristics of the release. This is similar to the "Level II" accident progression and source term analysis in a nuclear power PRA, except that there are dramatic differences between the important release characteristics for a land-based power plant and those for a system that is in flight. The third step is a consequence analysis for the radiological release, and is similar to a "Level III" PRA for a terrestrial nuclear system.

While there are conceptual similarities between the Cassini methods and those used for terrestrial systems, the actual implementations of the methods are quite different, and these differences pose critical problems for the uncertainty analysis. These differences are derived from two major requirements that have been imposed on the uncertainty

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analysis method: (1) the method must support the separation of natural or random variability from state of knowledge uncertainty, and (2) the accident progression, source term and consequence modeling must be accomplished using the existing LASEP-T and SPARRC software. Therefore, the description of the uncertainty analysis methods that we have developed for the Cassini mission must be preceded by discussions of these two constraints.

II. UNCERTAINTY VERSUS VARIABILITY

One of the constraints that was placed upon the development of the uncertainty analysis methodology was that it must support the separation of variability from uncertainty. The terms variability and uncertainty are closely related in the minds of many, and the distinction between them is best drawn by example. Consider the launch of a spacecraft. Given a particular class of vehicle failure, we know that an accident can likely progress along any of a number of possible pathways due to variations in unobserved, unobservable, uncontrolled, or uncontrollable parameters. The path can also be influenced by the inherent stochastic nature of certain physical phenomena. We will refer to these potential pathways as "variability." A traditional risk analysis that seeks to determine all of the possible outcomes from a particular initiating event is seeking to model variability. This helps decision makers to understand the set of potential situations that could occur given the launch of the spacecraft.

However, there are certain observable, predictable, and controllable parameters and phenomena that may be important in the prediction of risk for which we simply do not have adequate knowledge. We may have limited experimental data, inadequate model information, or any of a host of other issues which lead us to be uncertain about our predictions of risk. In this study we will refer to these limitations as "uncertainty." It is important that the major sources of uncertainty be identified and considered in the risk analysis.

To first order, we can think of each variability analysis as representing the universe of possible outcomes *given* a particular "view of the world," and the uncertainty analysis as forcing the analyst to consider alternative world views. If we are to differentiate between uncertainty and variability in this fashion, we must then classify individual features of the risk model (*e.g.*, input parameters, sub-model results, etc.) in this regard. It has been argued by many that there is no such thing as a feature that is either "purely" uncertain or "purely" variable because, in reality, all features contain some aspects of both variability and uncertainty. While this is likely true, the art of trying to determine just how much of the variation of a feature is due to variability versus uncertainty is still the subject of intense academic and practical debate. Since such a separation is beyond the practice of current state of the art risk assessment studies, we will be satisfied for the Cassini study to differentiate between variability and uncertainty on a feature by feature basis. The process for assessing the variability or uncertainty of a particular model feature begins with the analysts examining the available data for that feature and developing a statistical distribution to represent the range of values over which it might occur. This feature must now be classified as either variability or uncertainty. If, in the opinion of the analysis team, the distribution for this feature is dominated by variability, the entire variation in this feature will be classified as variability (even though some portion of it may be due to uncertainty). If, however, the analysis team believes that the variation in the feature is predominantly uncertainty, the entire variation in this feature will be classified as uncertainty in spite of the fact that some portion of it may be due to variability. We believe that this approach allows us to grasp the impact of both uncertainty and variability on the risk results without having to go significantly beyond the currently accepted state of the art.

III. OVERVIEW OF THE RISK COMPUTATION

A second constraint that was placed upon the development of the uncertainty analysis methodology was that it support the use of the existing LASEP-T and SPARRC software for the risk uncertainty assessment. Since the nature of these codes played an important part in the selection of uncertainty analysis methodologies, it is appropriate at this point to briefly describe each of the codes as well as the basic method that is used to perform a point estimate risk computation for the Cassini mission.

A simple step-wise description of a launch-phase risk analysis could be stated as follows: NASA's Jet Propulsion Laboratory provides a set of accident scenarios and environments in the flight vehicle data book.[1] Each scenario consists of a technical description of how the launch vehicle fails and a statistical distribution to represent the conditional probability of this failure scenario given an attempted launch event. The safety analysis team then applies the LASEP-T software to determine the conditional probability that each given scenario will result in a release of radioactive material to the environment, and the characteristics of the release should it occur (altitude, mass, particle size distribution, etc.). The SPARRC consequence software is then applied to determine the consequences (especially health effects) that would be expected to occur in the affected population due to such a radiological release. The flight vehicle data book is taken as "given" input and is not subject to revision or reanalysis during the risk evaluation. The characteristics of the LASEP-T and

SPARRC software and how their results are used to achieve a point estimate of risk are described below.

A. The LASEP-T Software

The LASEP-T computer software has been developed for the Cassini program by Lockheed Martin Company. It is a descendent of the LASEP software that has been used for the analysis of vehicle breakup and RTG safety for previous space missions.[2] LASEP-T performs computations that are equivalent to both the accident progression and source term computations from a traditional terrestrial nuclear power plant risk assessment. The program accepts as input a description of the accident conditions from the flight vehicle data book and the mission flight profile. This includes such information as the range of times during the flight profile during which a particular accident scenario is possible, the component(s) in the launch vehicle that fail, and a statistical description of the characteristics of the environment that the payload might see during such an accident.

LASEP-T uses this input data to perform repeated Monte Carlo based simulations of potential accident environments and fragment fields to determine whether the RTGs in the payload are threatened or breached during the accident and, if so, the mass of fuel that is released, its location, and its particle size distribution. It also tracks any airborne RTG material to its impact point to determine if a fuel release occurs on the ground and, if so, its mass and particle size distribution. The FIREBALL code transforms the LASEP-T release results to incorporate any changes to the release due to the fireball environment that may be predicted to occur during the release scenario.

Each LASEP-T Monte Carlo trial represents an accident scenario that may lead to various combinations of air and ground-based fuel releases and fireball conditions. LASEP-T classifies each scenario that leads to a release according to a set of categories that can be thought of as the end states of a small "accident progression event tree." Once the release category has been determined, LASEP-T records the characteristics of each type of release separately (air, air/fireball, ground, ground/fireball) for mass, particle size distribution, and other important characteristics. These results can then be examined either on a trial-by-trial basis or as aggregate distributions as necessary for the consequence analysis. The conditional probability of each end state is tracked based on the number of Monte Carlo samples that "hit" that end state divided by the total number of samples run during the simulation.

The computational method in LASEP-T can be thought of as equivalent to solving an event tree many times under the constraint that each probability in the tree is either a zero or a one. Monte Carlo sampling is used to determine which branches will have zeros versus ones in each trial. This method works well for obtaining point estimate probability results (given enough Monte Carlo trials). It is also adequate for examining variability (without considering uncertainty) because the sampling of distribution for variable model features is a natural part of the code's normal function. However, performing a Monte Carlo or Latin Hypercube uncertainty analysis on such a model is computationally intractable because it would require us to place a Monte Carlo driver on a Monte Carlo code.

B. The SPARRC Software

The SPARRC computer software has been developed by Lockheed Martin Company. It has been used for the analysis of radiological consequences for previous space missions.[3] SPARRC is a system of codes that is used to investigate Space Accident Radiological Release and Consequences. The SPARRC system consists of three separate codes to evaluate the consequences of different classes of release scenarios. They are: (1) SATRAP (Site-Specific Analysis of Transport and Dispersion of Radioactive Particles) for launch site accident scenarios, (2) GEOTRAP (Global Transport and Dispersion of Radioactive Particulates) for reentry accident scenarios with tractable particles, and (3) HIAD (High Altitude Aerosol Dispersion) for reentry accident scenarios with fine particle aerosols. The three transport codes share common dose calculational modules, which are referred to as PARDOS, output formats, and other features so that their results have a consistent meaning and can be quantitatively combined. SATRAP is the primary tool for Phase I or launch abort type accidents within a 200 km square surrounding the Kennedy Space Center launch facility.

SATRAP implements a Lagrangian-trajectory, gaussian puff model with the capability of handling multi particle-size source terms. The transport and diffusion of material in the puff are governed by meteorological data (supplied by the user) that can vary in space and time. These data include wind components at grid points, stability, height of mixing layer, and roughness length of the surface below. Each source cloud can have its own independent set of characteristics such as particle size, cloud dimensions, and initial coordinates. Each cloud is independently tracked in time steps through a four-dimensional (x,y,z,t) wind field.

When the source cloud reaches a level where interaction with the earth's surface occurs, SATRAP calculates air and ground concentrations at grid points on the surface. SATRAP then computes the doses and health effects to exposed populations based on user-supplied population density, land usage, and food production and consumption patterns. Dose Conversion Factors (DCF) for the different dose pathways are computed based on ICRP-30 methods.

The SPARRC code system is deterministic in nature. For the Cassini analysis, we select source term input (mass of fuel released in each particle size category, altitude, etc.) based on the results produced by LASEP-T. An individual SPARRC run also requires as input the specific weather conditions and other non-source term information that are to be used for this particular computation of consequences. Note that some of these features are subject to random variation and, hence, have distributions that must be sampled. Since SPARRC does not perform statistical sampling on its own, its variability distributions are sampled by the LHS Latin Hypercube Sampling computer software.[4,5] The LHS results are used to set up input for the many individual SPARRC analyses necessary to account for variability.

C. Risk Computation

At its most basic level, the computational methodology for the Cassini risk analysis study is as follows: run LASEP-T for each accident scenario postulated in the NASA JPL data book to generate conditional probabilities and source terms for each end state; evaluate the radiological consequences of the source terms using SPARRC; aggregate the results over the scenarios as necessary; and present the results as a plot with probability on one axis and consequences on the other axis. If the number of source terms generated by LASEP-T is very large, this method may not be computationally feasible, so the number of LASEP-T results to be processed is reduced through binning and data clustering techniques.

IV. UNCERTAINTY ASSESSMENT PROCESS

In a perfect world, one would consider accident variability by constructing statistical distributions for the model features that are considered variable (both in LASEP-T and in SPARRC) and sample these input variables in a Monte Carlo fashion over many LASEP-T trials (within a single code run) and many SPARRC runs (using the LHS code) to account for variability. Distributions would also be generated for model features that are considered uncertain, and these input parameters would be sampled for an uncertainty evaluation. The variability analysis process would then be repeated for each observation in the uncertainty analysis in order to produce a complete picture of variability for each Monte Carlo observation in the uncertainty analysis. This process, while intellectually satisfying, would likely take years of computational time even on the fastest computers available today because it requires the separate application of a Monte Carlo uncertainty process to a Monte Carlo modeling code.

The objective of the Cassini risk assessment is to come as close to the ideal solution as is feasible within the fiscal and time constraints of the project and within the practical constraints of the current state of the art. We are approaching the problem in two phases: a detailed variability analysis, followed by a combined variability-uncertainty analysis. We begin by performing a detailed variability analysis that approximates the computational methodology described in previous sections. Since the variability analysis already involves Monte Carlo sampling, it is evident that we cannot successfully "surround" the variability analysis with a Monte Carlo shell to perform a ideal uncertainty analysis. For this reason, we have developed three different approaches for using the results of LASEP-T and SPARRC computations in an overall variability and uncertainty analysis methodology: (1) a direct substitution method, where the amount of uncertainty data that can be propagated through the analysis is severely limited, (2) a "replica event tree" approach in which an event tree is constructed to mimic the results of the Monte Carlo simulation code, and (3) a statistical deconvolution process in which uncertainty is deliberately intermixed with variability during the analysis, and the two are mathematically separated after the fact. While the methods each have their own distinct probabilistic interpretations, they can all be based on and derived from a single set of LASEP-T and SPARRC runs (provided that those runs are properly designed). The following sections present an overview of each method and explain the relative advantages and disadvantages of each. A concluding section will then describe how the final risk computations will be performed for the Cassini program.

A. The Direct Substitution Method

The direct substitution method, which can be thought of as a "sample by sample method," involves performing an uncertainty analysis without making any direct use of the detailed variability analysis results. The objective of this method is to mimic the methodology that has been developed and proven for commercial nuclear power reactor analysis. This method provides an assured success path because it is a demonstrated method that will produce predictable results even if neither of the two more advanced uncertainty analysis methods (described below) were to prove satisfactory.

The direct substitution uncertainty analysis method parallels the traditional nuclear power method as follows: recall that each LASEP-T run computes the conditional probability for the realization of a series of potential release categories, which can be thought of as the end states of a small event tree model. These end states can be compared to the end states of an "accident progression event tree" (formerly called a "containment event tree") from a terrestrial nuclear power plant risk assessment study (e.g., NUREG-1150[6,7]) as, for both methods, each end state represents one description of what can happen to the system to allow radionuclides to be released to the environment. In terrestrial nuclear power plant risk assessment studies, each group of similar accident progression end states is associated with a source term and a set of consequences (early fatalities, latent cancers, etc., computed to account for the variability in weather at the time of the accident). Thus, the complete set of accident progression end state definitions can be viewed as an approximation of the variability inherent in the accident progression (although the analysts who constructed those models have not usually made any real differentiation between variability and uncertainty in the sense that we are attempting here).

In a terrestrial reactor Monte Carlo uncertainty analysis, the sampling of the event tree provides many complete sets of accident progression end states which, as a group, can be viewed as a representation of the uncertainty (with the variability contained in the list of end states for each Monte Carlo observation). Each end state or group of similar end states is associated with a different source term for each observation (Monte Carlo trial) in the uncertainty analysis. This analogy, while not completely valid for the Cassini study, provides a convenient way to look at the direct substitution uncertainty methodology.

The direct substitution uncertainty analysis method is intended to mimic the terrestrial nuclear power reactor method described above to the extent that it is possible to do so using the computational tools that are available. In order to make it computationally feasible to perform a stratified Monte Carlo uncertainty analysis for the Cassini mission, we are required to reduce the level of detail in each variability analysis. Whereas in the detailed variability analysis we viewed every LASEP-T *trial* that resulted in release as a separate contributor to variability, we now simplify our consideration of variability and treat each LASEP-T *end state* as being similar to a terrestrial reactor accident progression end state (the characteristics of the individual trials that lead to that end state are viewed as representing uncertainty even though they are based on a sampling of both variability and uncertainty). In the detailed variability analysis our Monte Carlo engines were permitted to sample only those model features that were categorized as being dominated by variability. In the uncertainty study, all model features for which distributions have been developed are sampled concurrently.

We can use the characteristics of the individual trials that lead to an end state as the basis for distributions that represent, in this formulation, the uncertainty in the characteristics that describe that end state. The major difference between this method and the terrestrial reactor method is that a terrestrial reactor event tree will typically produce dozens or even hundreds of end state groups per observation while only a few such end states would be produced for the Cassini assessment.

The uncertainty methodology for the SPARRC side of the analysis is very similar to that used in the detailed variability study, although a simplification of the variability results for the sake of the uncertainty analysis is also required here. In the variability analysis, the results of each SPARRC run were viewed as separate contributors to variability. Under the uncertainty method, we draw a number of samples using the LHS code sampling both uncertain and variable model features concurrently. Each sample contains the information necessary to perform a *series* of SPARRC runs based on variations in weather and source term. The results generated by all of the SPARRC runs for a single observation are now viewed as representing variability, while the set of all observations taken as a group represent uncertainty. One risk exceedence frequency curve is generated for each observation to represent variability. When this process is performed for all observations, it produces a family of curves that, when taken together, represent the risk uncertainty. These individual curves can then be summarized to produce a mean curve and various appropriate uncertainty quantile curves. The individual end state results can also be aggregated over all scenarios to present a similar family of curves that represent our uncertainty in the overall risk for the mission.

We understand that this approach necessarily intermingles variability with the uncertainty results both within LASEP-T and SPARRC, but this is consistent with practice in current state of the art terrestrial reactor risk studies. We accept this fact and the other stated drawbacks as known limitations of this uncertainty method, and view them as a price that must be paid in order to establish an assured success path for this analysis.

B. The Replica Event Tree Method

While the direct substitution method does provide a guaranteed success path, it does suffer from some serious drawbacks. The drastic simplification of the treatment of variability that it requires has been mentioned previously. Another problem, however, derives from the fundamental structure of the LASEP-T code. Recall that LASEP-T determines the conditional probability for each end state based on the typical Monte Carlo formulation of a number of hits divided by the total number of trials. While the simplified treatment of variability allowed us to gain some insights about uncertainty in the consequence arena, it could do nothing to illuminate the uncertainties in this key conditional probability.

It would be very helpful if we could find a method that would allow us to consider uncertainties in the frequency domain (such as those described above) while at the same time staying as close as possible to the guaranteed success path described in the previous section. This would provide us with an evolutionary (instead of a revolutionary) approach to this risk assessment problem. Therefore, we have developed a method that uses all of the same computations described in the previous section for the consequence uncertainty analysis. The only changes are related to the computation of probabilities.

In the direct substitution method, LASEP-T categorized releases according to the end states of a small event tree. The probability of each end state represents conditional probability that a particular accident scenario (as defined by the flight vehicle data book) will result in a release of radiological material with characteristics that meet the definition of that end state. LASEP-T of necessity generates only a point estimate of each probability. Thus, in that method, the only uncertainty in the frequency domain comes from the distribution for each accident scenario's initiating event frequency (as found in the flight vehicle data book).

A second method can be used to gain some insights into the uncertainties in the frequency domain. We could construct a replica of the small event tree used by LASEP-T to categorize its results. Point estimate values for the branch probabilities in this event tree model would be mathematically derived from the LASEP-T results. Sensitivity analyses performed using the LASEP-T code would then be used to provide information for experts to estimate statistical distributions for each branch probability in the event tree (obviously, the expert distributions must be consistent with the point estimate data computed by LASEP-T). Given, the model and the branch probability distributions, the event tree would then be solved and subjected to a Monte Carlo uncertainty assessment using software such as Sandia's SETAC/EVNTRE code suite.[8] The result would be estimates for the uncertainty of each of the end state conditional probabilities. These uncertain conditional probabilities can then be convolved with the uncertain accident likelihoods to find the uncertainty in the overall likelihood of fuel release.

The estimation of branch fraction probability distributions is admittedly an inexact science, but it is conceptually similar to the estimation of release fraction conditional probabilities that was performed for the INSRP Ulysses uncertainty analysis.[9] While this method does propagate an estimate of the uncertainty in the frequency domain, it does not provide any better opportunity to understand the dominant contributors to uncertainty than does the direct substitution method since all of the potential contributors to uncertainty must be factored into the conditional probability distributions constructed by the experts. Thus, this method offers limited additional insights at the expense of requiring additional model construction and probability distribution development. For these reasons, this method is viewed as having only limited utility to the Cassini risk analysis.

C. The Deconvolution Method

The third method for characterizing uncertainty represents a fundamental change from previously proven methods. This method, as proposed and developed by Lockheed Martin Astro Space, is based on a concept from linear systems theory that is commonly applied in electrical signal analysis: the use of Laplace or Fourier transforms to deconvolve an output distribution function into its original components. In theory, the deconvolution uncertainty analysis method will allow for a more complete separation between variability and uncertainty without forcing the drastic simplifications that were required under the direct substitution method.

The fundamental idea for the deconvolution uncertainty analysis method is as follows: if we can construct one distribution that represents the system risk considering only variability, and a second distribution that represents the system risk with uncertainty and variability fully intermingled, then by application of Laplace or Fourier transforms we should be able to reconstruct a distribution that represents only the effect of uncertainty on the variability distribution to obtain the combined uncertainty-variability distribution. The following discussion is intended to provide an overview of deconvolution methods. The reader is referred to a detailed mathematical text for a more rigorous treatment of the mathematical deconvolution. The details of this particular method, its mathematical justification for this class of problems, and its limitations will be the subject of another paper.

Let us *assume* that there exists a distribution function which, when convolved with the detailed variability distribution, produces as its result the combined uncertainty-variability distribution. If this distribution function could be found, it would represent the "pure" effect of uncertainty on the variability distribution. Mathematically this could be written as

$$R = U * V$$

where R is the risk distribution from the combined uncertainty-variability analysis and is found by the convolution of an as yet undetermined pure uncertainty distribution U with the detailed variability distribution V. Recall that for both the Laplace and Fourier transforms, the convolution operation becomes a multiplication operation. Thus, if we hope to find the unknown distribution U through the deconvolution of R and V (both of which are known), we must divide their Laplace or Fourier transforms as

$$U^* = \frac{R^*}{V^*}$$

where the * denotes that the relation holds in the transform domain. The remaining task, then, is to invert the Laplace or Fourier transform for U^* back into the real domain U.

Once the inversion is accomplished, we can plot the overall system risk as a family of curves that is similar to that described for the direct substitution method. The result would be a family of parallel curves that would be generated by a numerical convolution of U and V. In this case, each curve has the basic shape specified by the detailed variability distribution (V), but is transformed based on the action of the uncertainty distribution (U) to obtain the complete range of possible variability curves.

The deconvolution uncertainty analysis method clearly pushes beyond the current state of the art in PRA methodology, and there are aspects of the method that remain to be fully demonstrated. For example, mathematical rigor would require that all of the transfer functions in our study (LASEP-T, SPARRC) be linear in order for the underlying mathematical theory to be applicable. This is clearly not the case for our system. However, initial applications of the method to nonlinear transfer functions have shown promise. Successful application of this method would produce a distribution U that represents the separate effect of uncertainty on the system, and in doing so, would overcome some of the limitations described for the direct substitution method. This method can make use of the exact same LASEP-T and SPARRC computations described for the direct substitution method.* The only additional computations would be the generation, manipulation and inversion of the transform variables. These functions are not computationally intensive (by comparison with LASEP-T and SPARRC) and are currently available in commercial software packages.

* Recall that under the direct substitution method, our computations would consist of a detailed variability analysis in which only model features classified as being dominated by variability would be sampled, followed by a detailed uncertainty-variability analysis in which all model features for which distributions are generated would be sampled concurrently. Under the direct substitution method, the detailed variability computations serve as information only and are not used in the uncertainty-variability analysis. Under the deconvolution method, however, these same computations form the basis for the distribution V and, thus, must be performed in a manner that is consistent with the uncertainty-variability analysis.

V. APPLICATION TO CASSINI

While the methods described in the preceding section provide the theoretical underpinnings for the Cassini uncertainty analysis, there are a number of practical issues related to computational feasibility that must be resolved before these methods can be implemented. Specifically, it is not feasible to compute consequences for every known set of weather data and every individual LASEP-T trial that leads to a radiological release. The number of possible release/weather combinations is very large — too large even for a fast-running code such as SPARRC.

The objective is to design a scheme to select SPARRC runs that meets the following criteria: (1) the overall set of runs selected must be a fair representation of the spectrum of results that would be expected were we able to run all cases, (2) the selection of runs must not be completely random in order to assure that high consequence situations are deliberately sampled in spite of their low probability of occurrence, (3) the method should rely on the use of actual measured or computed data wherever possible (it should avoid homogenizing information from "similar" data points into a single surrogate data point), and (4) the scheme must be compatible with the constraints imposed by the uncertainty analysis methods. Constraint (2) is of particular importance because the first impulse might be to use random sampling techniques to draw a "representative" subset of data points from a larger group. However, if this were to be done, one would be likely to completely miss those rare large release scenarios and pathological weather scenarios that might lead to elevated consequences.

To counter these problems, the following selection scheme was designed: weather scenarios and LASEP-T release trials are each grouped into a relatively small number of clusters. The Latin Hypercube sampling that occurs as part of both the detailed variability study and the uncertainty analysis then selects one weather scenario from *each* weather cluster, and one release trial from *each* release cluster for *each* sample observation. We then run each selected release trial with each selected weather scenario for that observation to obtain the spectrum of risk for that observation. Note that the clusters need not all contain the same number of data points. Thus, for the sake of mathematical consistency, each cluster is assigned a conditional probability of occurrence based on the number of points that it contains compared to the total number of data points that were clustered.

Weather scenarios are divided into clusters based on the consequences they generate for a set of preliminary representative releases. Most of the groups represent reasonably homogeneous weather conditions, but a single group is reserved for weather scenarios that produce particularly high consequences for one or more of the representative releases. This group of "high consequence days" contains only a few individual weather scenarios so that we are sure that every entry in this group will be selected at least once given the number of random samples that will be selected in the Latin Hypercube sampling process. The LASEP-T release scenarios are also clustered in such a way that there is a small cluster of "high release" trials where we can be sure that every entry in this group will be selected at least once in the Latin Hypercube sampling process.

This clustering method has two distinct benefits: first, the weather and release data that SPARRC uses is from actual data points instead of from homogenized surrogate points, and second, we assure that the high consequence days are well-represented in the final results. This eliminates the danger that the rare nature of these special days will cause them to be omitted from the final risk calculation.

VI. SUMMARY

The designers and mission planners for the Cassini spacecraft are using PRA techniques to help assure that potential radiological accidents involving the spacecraft do not pose significant human risk. This paper has described the methodologies that have been developed to allow a quantitative uncertainty analysis to be performed for the Cassini PRA study. These methods provide an opportunity for analysts to differentiate between the effects of variability and uncertainty on the overall risk results while maintaining the use of the computational tools that were developed for use in point-estimate risk assessment studies. While all of the methods have some similarity to those developed previously for nuclear power reactor studies, the deconvolution uncertainty analysis method clearly represents a fundamental change from previously proven methods. If this application is successful, it may lead to fundamental changes in the way uncertainty analyses are pursued in other probabilistic risk analysis domains as well.

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REFERENCES

1. Lockheed Martin Astro Space, "Cassini Titan IV/Centaur RTG Safety Databook," NAS3-00031, Prepared for NASA Jet Propulsion Laboratory, Pasadena, California, 1995.

2. NUS Corporation, "Final Safety Analysis Report for the Ulysses Mission," ULS-FSAR-006, Prepared for the U.S. Department of Energy Office of Special Applications, Washington, D.C., 1990.

3. General Electric Astro Space, "Final Safety Analysis Report for the Galileo Mission," 87SDS4213, Prepared for the U.S. Department of Energy Office of Special Applications, Washington, D.C., 1988.

4. Iman, R.L., and Shortencarier, M.J.,"A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use With Computer Models," NUREG/CR-3624, Prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Washington, D.C., 1984.

5. Wyss, G.D., and Daniel, S.L., "Recent Enhancements to Probabilistic Risk Assessment Software at Sandia National Laboratories," paper presented at the DOE EFCOG Integrated Risk Management Workshop, Albuquerque, New Mexico, 1994.

6. U.S. Nuclear Regulatory Commission (USNRC), "Reactor Safety Study — An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," WASH-1400 (NUREG-75/014), Washington, D.C., 1975.

7. U.S. Nuclear Regulatory Commission (USNRC), "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," NUREG-1150, Washington, D.C., 1990.

8. Griesmeyer, J.M., and Smith, L.N., "A Reference Manual for the Event Progression Analysis Code (EVNTRE)," NUREG/CR-5174, Prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Washington, D.C., 1989.

9. Interagency Nuclear Safety Review Panel, "Uncertainty Analysis Report for Ulysses," INSRP 90-07, Washington, D.C., 1990.

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