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Automating Risk Assessments of Hazardous Material Shipments for Transportation Routes and Mode Selection

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ABSTRACT

The METEOR (Model to Evaluate Transportation Effects of Risk) project at Idaho National Laboratory (INL) successfully addresses the difficult problem in risk assessment analyses of combining the results from bounding deterministic simulation results with probabilistic (Monte Carlo) risk assessment techniques. This paper describes a software suite designed to perform sensitivity and cost/benefit analyses on selected transportation routes and vehicles to minimize risk associated with the shipment of hazardous materials.

METEOR uses Monte Carlo techniques to estimate the probability of an accidental release of a hazardous substance along a proposed transportation route. A METEOR user selects the mode of transportation, origin and destination points, and charts the route using interactive graphics. Inputs to METEOR (many selections built in) include crash rates for the specific aircraft, soil/rock type and population densities over the proposed route, and bounding limits for potential accident types (velocity, temperature, etc.). New vehicle, materials, and location data are added when available. If the risk estimates are unacceptable, the risks associated with alternate transportation modes or routes can be quickly evaluated and compared. Systematic optimizing methods will provide the user with the route and vehicle selection identified with the lowest risk of hazardous material release.

The effects of a selected range of potential accidents such as vehicle impact, fire, fuel explosions, excessive containment pressure, flooding, etc. are evaluated primarily using hydrocodes capable of accurately simulating the material response of critical containment components. Bounding conditions that represent credible accidents (i.e., for an impact event, velocity, orientations, and soil conditions) are used as input parameters to the hydrocode models yielding correlation functions relating accident parameters to component damage. The Monte Carlo algorithms use random number generators to make selections at the various decision points such as crash, location, etc. For each pass through the routines, when a crash is randomly selected, crash parameters are then used to determine if failure has occurred using either external look up tables, correlations functions from deterministic calculations, or built in data libraries.

The effectiveness of the software was recently demonstrated in safety analyses of the transportation of radioisotope systems for the US Dept. of Energy. These methods are readily adaptable to estimating risks associated with a variety of hazardous shipments such as spent nuclear fuel, explosives, and chemicals.

INTRODUCTION

An assessment of the risk of hazardous material release during transport is often required for critical shipments. INL has historically conducted probabilistic risk assessments (PRAs) for the transportation of United States Department of Energy (DOE) radioisotope systems for many types of missions [1]. We have recently combined numerous legacy software packages into a unique software suite capable of automating the PRA process allowing for the optimization for transport route, vehicle selection, container type, etc. Typically, these assessments include the following basic steps:

- Characterize the input parameters such as payload, container type, transportation modes, and potential routes.
- Identify accident initiators and resulting scenarios such as fires, loss of cooling, and plane crash.
- Determine potential accident environments such as impact speed, impact angle, temperature, etc.
- Identify and consider possible failure modes that result in payload release such as material rupture and connection failure.
- Perform probabilistic calculations using established accident rates and route data.

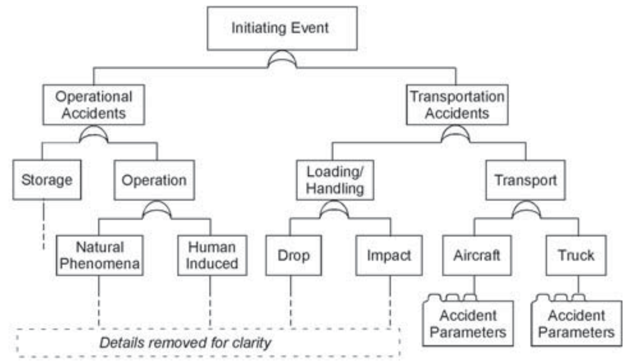

Figure 1. Example Master Logic Diagram, adapted from [1]

SOFTWARE STRATEGY

The METEOR software suite is used to calculate probabilities of an accidental release of a payload (e.g. hazardous substance) along a proposed transportation route or the amount of damage suffered by any cargo in a transportation accident. The user selects from an interactive list of hazardous payloads and common containers/configurations. Alternatively, the user may enter parameters appropriate for a new shipment design. Next, the user selects the proposed mode of transportation, origin and destination points, and charts the route using interactive graphics. Accident rates from historical data for several possible transportation vehicles including trucks and aircraft are available within the software. New vehicle, materials, and location data are added when available. If the risk estimates are unacceptable, the risks associated with alternate transportation modes or routes can be quickly evaluated and compared. Systematic optimizing methods will provide the user with the route and vehicle selection identified with the lowest risk of the applicable hazard.

Master logic diagrams (MLDs) [2] are employed within METEOR to categorize possible transportation accident events. A systematically organized and simplified list of potential accidents is developed through the use of MLDs. An example MLD is shown in Figure 1, which was developed for the transportation of a radioisotope system [1]. The “top” event on the right is a transportation accident with release potential. Probabilistic algorithms perform a random sampling of the set of accident parameters (incorporating statistical uncertainty estimates) resulting in a failure probability solution for each iteration.

Potential input parameters for METEOR include:

- Hazardous Contents
- Critical Assets
- Possible vehicles
- Potential Route
- Origin
- Destination
- Trip Duration
- Temperature Ranges
- Materials
- Storage Facilities

A flow chart for an example METEOR calculation is shown in Figure 2. A simple mission was selected using a cylindrical container of poisonous material transported between Los Angeles, CA and Miami, FL, USA via C-17 Transport Plane. A METEOR screen shot for this scenario is shown in Figure 3. Inputs to METEOR (many selections built in) include crash rates for the specific aircraft, soil/rock type and population densities over the proposed route, and bounding limits for potential accident types (velocity, temperature, etc.). The probabilistic algorithms use random number generators to make selections at the various decision points such as; crash, location, etc. For each pass through the routines, when a crash is randomly selected, crash parameters are then used to determine if failure has occurred using either external look up tables, correlations functions from deterministic calculations, or built in data libraries.

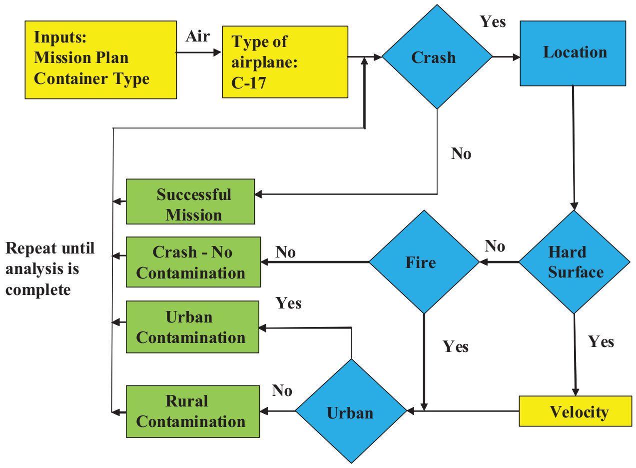

Figure 2. Example METEOR Flow Chart

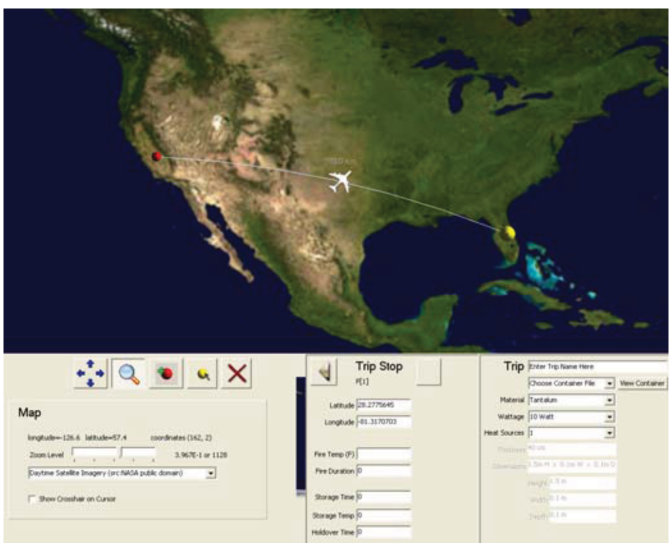

Figure 3. Example METEOR Screen-Shot

Deterministic Simulation Methods

A fundamental first step in this process is the identification of credible failures that result in the release of hazardous materials – basically a breach in the container. For crash events, a hydrocode software package such as LS-DYNA [3] is typically used supplemented with actual crash test data. LS-DYNA is a multipurpose multi-physics simulation code designed primarily to simulate highly nonlinear physical phenomena such as large deformations due to impacts. This software is used to evaluate a bounding set of accident scenarios, which are generated by using the Master Logic Diagram. For example, a bounding set of accident scenarios may include a range of vehicle impact speeds, surfaces, orientations, and temperatures for a given transport container and the resulting damage calculations. The effects of other events such as fire, fuel explosions, excessive containment pressure, flooding, etc., can also be evaluated. An example of a LS-DYNA high-speed impact analysis of a piston/flange component (cut away view) is shown in Figure 4. Red contours indicate excessive equivalent plastic strain.

A significant challenge for all highly non-linear simulations is the development of accurate material constitutive models for significant components. Care must be taken to incorporate rate and temperature dependence in all materials important to the response of the unit being evaluated. During impact simulations, for example, strain rates exceeding 2000 s^{-1} are common for impacts onto hard surfaces. Material data at high strain rates and temperatures are available for the most common materials from the open literature. Less common materials may require testing of sample units and/or specific materials to validate the results derived from simulations.

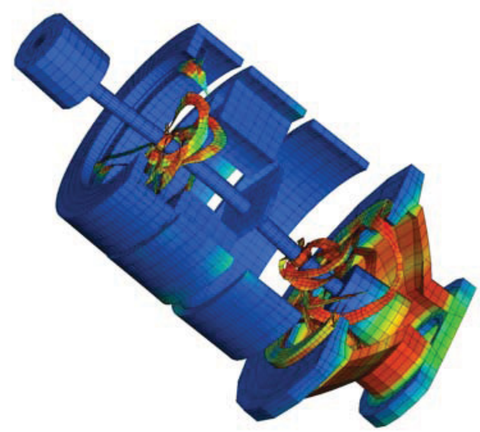

Figure 4. Example of Hydrocode Modeling of an Impact on Concrete at 50m/sec.

Other types of accidents that may be addressed using deterministic analysis techniques include blasts, liquid fuel fireballs, ballistic penetrations, flooding, and extreme overpressures. The analyses required are mission and accident specific. Each analysis will provide estimates of component damage for a range of mission credible conditions. Test data may be needed to validate deterministic models used for accident analysis of critical missions.

Using the bounding set of accident scenarios, correlation functions relating accident parameters (impact velocity, fireball duration, critical component temperature, etc.) to component damage are developed with regression techniques. These correlation functions are then accessed using random sampling to derive a probabilistic approximation of the accident conditions and likelihood of hazardous material release. If payload damage calculations using deterministic analysis techniques are not possible, then a probabilistic technique such as Monte Carlo is used to solve the governing equations.

Risk Determination

Risk assessment is performed by calculating relative probabilities of accident scenarios and corresponding result interpretations (failure/no failure). Our probability 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 speed of 50 m/s at an angle of 12 degrees, in a geographical area of predominantly hard rock. Examples of the correlation functions are presented in Figures 5 and 6. Individual points are data from deterministic simulations. Trend lines show the correlation functions. Figure 5 shows the equivalent plastic strain in a critical member as a function of impact speed for two impact angles. Figure 6 shows stress in a pressure boundary as a function of the internal pressure following an impact of 76m/s into hard rock. Figures 5 and 6 show how correlations from deterministic analyses are used when the probability simulations result in various impact speeds, angles, pressures, etc., which are bounded or perhaps slightly outside the parameters covered by the deterministic predictions.

Although the deterministic models are nonlinear, as is the process of linking data to probabilistic model parameters, the correlation functions link the finite set of deterministic input to the randomly generated transportation conditions. This allows us to interpolate these parameters from values we had previously developed via deterministic analyses to reach a failure probability. This process is repeated (typically 10^5 iterations) until convergence is reached yielding the failure probability distribution. The resulting probability distribution determines the relative probabilities of accident scenarios and a risk assessment can be prepared.

While METEOR is used to calculate the risk of damage to the payload and potential hazardous release it is currently undergoing development to include analysis tools that can be used to predict the effects of human population exposure. This capability could apply, for example, to an analysis of a poisonous chemical transport, where 10^5 transports are simulated as a function of transport phase, normal vs. abnormal conditions, etc. that resulted in the number of failure occurrences and types forming the basis for cost estimates of assets loss and casualties.

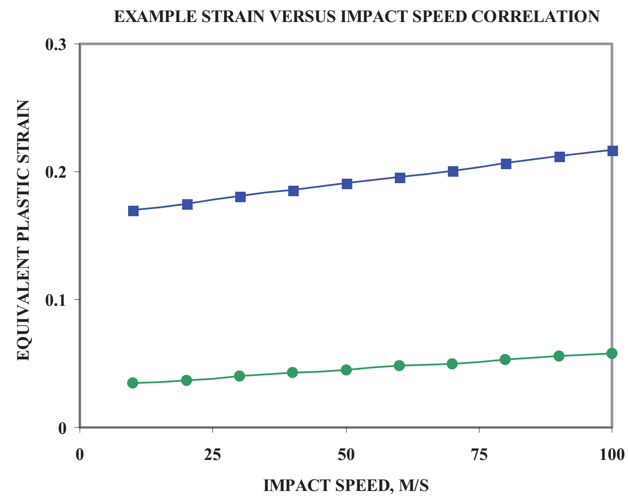

Figure 5. Example of Plastic Strain versus Impact Speed Correlation.

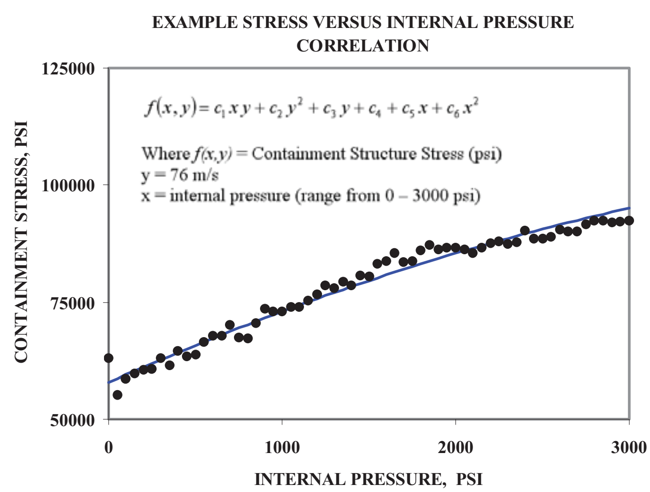

Figure 6. Example of Stress versus Internal Pressure Correlation.

Optimize Transportation Routes and Methods

METEOR allows the user to select the mode of transportation, origin and destination points, and chart the preferred route. Currently under development are capabilities for METEOR to interactively select transportation routes that avoid specific types of critical structures such as refineries and nuclear power plants, significant landmarks such as National

Parks, and large population centers. This will be accomplished primarily using commercially available mapping routines and geographical databases.

Accident rates from historical data for several possible transportation vehicles including trucks and aircraft are available to the software suite via internal and referenced databases. New vehicles, materials, and location data are added when available.

Initial risk estimates are determined using the preferred route and mode of transportation. If the risk estimates are unacceptable (a mission specific criteria), the risks associated with alternate transportation routes and/or modes can be quickly evaluated and compared. Systematic optimizing methods will provide the user with the route and vehicle selection identified with the lowest risk of hazardous material release.

SUMMARY

METEOR is a visually interactive risk analysis software suite and includes the following options the user can select.

- Mode of transport
- Hazard/Asset
- Container type
- Transport route (legs)
- Accident identification
- Deterministic - Probabilistic coupled simulations
- Consequences of failure
- Risk assessment summary

The result is a quantitative probability of an accidental release of hazardous material during transport. This can then be studied and optimized as necessary to meet the mission requirements.

METEOR is currently under development at INL and is undergoing extensive validation. The deterministic simulations necessary to predict critical component damage are compared with available material test results and with test data of full systems. Probabilistic calculations are validated using both simple scenarios with known solutions and by comparisons with other probabilistic software codes.

CONCLUSIONS

The software suite provides a cost effective method for planning hazardous or extremely valuable material shipments worldwide. METEOR by design is extremely flexible allowing the user to add deterministic simulation or test results and is adaptable to a variety of mission specific requirements. Using METEOR, the transportation modes and routes for critical shipments can be optimized to minimize risk.

ACKNOWLEDGMENTS

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REFERENCES

[1] W. D. Richins, J. M. Lacy, S. R. Novascone, and B. H. Dolphin, “Safety Analysis for a Radioisotope Stirling Generator,” Proceeding of Space Nuclear Conference 2007, Boston, MA, Paper 2024, June 24-28, 2007.

[2] I. A. Papazoglou, and O. N. Aneziris, “Master Logic Diagram: method for hazard and initiating event identification in process plants,” Journal of Hazardous Materials, Vol. A97, p. 11–30, 2003.

[3] LSTC, LS-DYNA, Livermore Software Technology Corporation, Livermore, CA, 2009