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Title: A Method for Evaluating Fire After Earthquake Scenarios for Single Buildings

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A Method for Evaluating Fire After Earthquake Scenarios for Single Buildings

Abstract

Department of Energy Standard DOE-STD-3009-94 Change Notice 3 (DOE-STD-3009), *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses* (Ref. 1) directs that earthquake induced fires be evaluated for non-reactor nuclear facilities. The standard also allows a probabilistic frequency cutoff for natural phenomena hazards, i.e. it is not a Design Basis Accident, if the annual probability of occurrence is less than 10^{-6} based on a conservative calculation. The challenge is to be able to defend the conservatism of the calculation, yet provide a calculation that is not so overly conservative that it is not useful.

The statistical method developed in *Modeling the Number of Ignitions Following an Earthquake: Developing Prediction Limits for Overdispersed Count Data*, (Kelly and Tell, Ref. 2) provides a context for assessing the conservatism of various fire scenarios. The statistical method uses data for fires following earthquakes from 1906 to 1989 in Alaska and California. This method is applied to an example facility to evaluate the probabilities of the number of randomly occurring ignitions after an earthquake of a given intensity affecting an area of a specified size.

In addition to the randomly occurring fires, an evaluation is conducted to determine processes and/or activities unique to the facility. These processes and activities are reviewed to identify associated ignition mechanisms. Should the ignition potential be judged to be highly probable if an earthquake occurs, these ignitions are assumed to occur in addition to any randomly occurring ignitions.

Finally, the detailed fire modeling for the facility is discussed and a procedure for establishing fire parameters is offered. The DOE Toolbox fire modeling code, CFAST (Ref. 3), is used to model temperatures in the hot gas layer and fire driven gaseous flows for the example facility.

Overview

The method presented herein is intended for Hazard Category 2 and 3 facilities as defined in DOE-STD-3009.

There are any number of approaches one could take to deal with fire after earthquake evaluations. One approach is to develop a site specific seismic hazard curve in accordance with DOE orders, standards and guides, along with the seismic capacity for each item of concern. The items should include radiological material containers and the structures enclosing and/or supporting the containers, along with potential fire initiators such as electrical equipment. Stochastic methods could then be applied. This would be largely a probabilistic approach with associated uncertainties, and is not particularly compatible with the bounding scenario approach to exposure calculations described by DOE-STD-3009. The probabilistic approaches by their nature consider many scenarios, whereas the bounding scenario approach only considers the dose calculation for that one scenario. For a large complex facility the probabilistic approach is a laborious process and requires a substantial commitment of time and resources.

The proposed method in this paper is intended to conform to DOE-STD-3009 while providing a reasonable basis for the number of fires occurring during the bounding scenario. The method divides post seismic fires into two groups, random and deterministic.

Random fires occur due to the ignition mechanisms present in the general built environment, and the probability of occurrence is estimated using a statistical model of ignitions based on data for fires following an earthquake in the general built environment. Deterministic fires are due to ignition mechanisms identified as having a higher probability of starting a fire than conditions in the general built environment when the associated process is in a vulnerable status.

There is precedent for using statistical methods to determine some aspects of the bounding scenario. Historical weather data has been used in dispersion calculations to determine the 95th percentile calculated dose to the Maximally Exposed Offsite Individual (MEOI). The dose thusly calculated has been accepted as bounding.

For the fire after an earthquake method, the statistical method of Kelly and Tell is applied to estimate the probability of 1, 2, 3 or any number of random fires occurring after an earthquake.

A bounding scenario dose calculation is based upon a seismic event with high confidence that there is a low probability of exceedance, i.e. an event with a peak ground acceleration (PGA) at the high end of the range, regardless of the annual fire probability.

The method presented here, while partially dependent upon the statistical method of Kelly and Tell, does **not** follow a probabilistic approach to determine the fires that may occur immediately after an earthquake. Nor does the method attempt to describe the overall annual probability of fire from all earthquakes; it is intentionally scenario focused to conform with DOE Standard 3009 for comparing calculated dose consequences from a postulated bounding event to the evaluation guidelines.

The Kelly and Tell method is used to compare the estimated probabilities of one, two, three, four or more randomly occurring fires due to an earthquake with a specific PGA affecting a specific area. Note that when the annual probability is less than 10^{-6} for a single fire after an earthquake event with a return frequency according to the Seismic Performance Category Mean Seismic Hazard Exceedance Level of DOE-STD-1020-2002, *Natural Phenomena Hazards Design and*

Evaluation Criteria for Department of Energy Facilities, (Ref. 4) it could be argued that a random fire need not be considered as part of the bounding scenario. The same criterion could be applied to the consideration of 2, 3, 4 etc. random fires.

The statistical method of Kelly and Tell can also be applied to multiple structures for evaluation of building fire potential within a geographical area that could be affected by the same earthquake. Fire departments could use the method as a disaster planning tool for estimating the potential number of fires after an earthquake within a jurisdiction.

The Method

- Assume that all fire possibilities are either random or deterministic

  Randomly occurring fires can be estimated by statistical methods. Deterministic fires are those with a high propensity of occurrence due to circumstances not ordinarily found in the general built environment.

- Use the statistical method of Kelly and Tell to determine a reasonably conservative number of randomly occurring fires

  By dividing the estimated probability of fire(s) after an earthquake event by the return period of the earthquake of interest, the annual probability of a fire from that earthquake can be calculated. If the annual probabilities are less than 10^{-6}, fire(s) may be considered incredible. For DOE Hazard Category 2 and 3 facilities, always consider at least one randomly occurring fire.

- Determine the compartments of interest

  Convene a panel (the Panel) composed of operations personnel, facility personnel, safety analysts, and fire protection personnel. Review operations, processes and storage locations for radiological materials, and designate each room where the materials are vulnerable to exposure to a fire as a compartment of interest. Document the deliberations and findings.

- Rank the compartments of interest by potential dose consequence

  Utilize the Panel to rank on a descending scale the compartments with the greatest potential for a dose consequence to the public based on the quantities, forms and types of radiological materials. Materials within safety class or equivalent containers need not be included.

- Review operations and processes within the rooms of interest for circumstances unlike those equivalent to what is found in the general built environment

Large quantities of combustible/flammable liquids and pyrophoric metals should be considered for their likelihood of ignition.

- Judge the operations and processes determined to be unusual for their propensity to ignite or cause an ignition during or immediately following an earthquake

  Operations unique to DOE facilities should be evaluated by the Panel for ignition potential if exposed to an earthquake.

- Categorize the rooms of interest with a high likelihood of ignition as deterministic fire compartments

- Assign the random fires to the highest ranked remaining rooms of interest

- Survey the determined and random fire rooms for fuels, ignition sources and locations of fuels and ignition sources

  The Panel should pay attention to the total quantity of fuels within the rooms and the separation distances from individual fuel packages. Fuel packages in close proximity should be considered one fuel package.

- Determine the worst case credible fuel package for each fire room

  The Panel should agree on the worst case credible fuel package. Over stating the possible fuel quantities is not necessary or advisable.

- Bound and characterize the worst case fuel packages using available fire test data

  The fire protection professionals assigned to the Panel, should search for fire test data that best represents the fuel packages. A good source is NIST's *Fire on the Web*, http://www.fire.nist.gov/.

- Model the fire rooms using CFAST assuming the available fire test data as input

  Model each fire individually to predict the temperatures of the hot gas layers and the mass flows out of the fire rooms using the worst case fuel package regardless of proximity to the hazardous material. These predictions can then be used for further analysis, such as a MELCOR model to predict the flow of contaminants to the environment.

  Modeling the fires individually provides some conservatism because the fires burning simultaneously would be competing for the oxygen available in the building.

  Consideration must be given to the potential for ignition of fuel packages at a distance from the worst case fuel package. CFAST cannot model synergistic effects of multiple fires interacting, so adjustment may need to be made or another fire model considered.

Should any of the hot gas layer temperature or heat flux at the floor predictions approach a flashover condition (usually taken as 600°C or 20 kW/m^2), consideration should be given to use of a different fire model to predict temperatures and mass flows.

- Provide CFAST predictions of temperatures and mass flows from the fire rooms for further considerations applicable to the facilities and scenarios of interest

The Example Facility

This example assumes an 80,000 ft^2 (*MMSF* = 0.08) cast-in-place concrete building that is classified as Type I (4,4,2) per National Fire Protection Association (NFPA) Standard 220, *Standard on Types of Building Construction*, (Ref. 5) with a Industrial Occupancy (with ordinary hazard contents) per NFPA Code 101, *Life Safety Code* (Ref. 6). This building can be thought of as consisting of multiple Single Family Equivalent Dwellings (SFED) (or rooms) (Ref. 7) that are independent in terms of ignitions.

NFPA 220 describes a Type I (4,4,2) building as having exterior bearing walls with 4 hour fire resistance rating, interior bearing walls supporting more than one floor, columns or other bearing walls with 4 hour fire resistance rating (3 hour rating if supporting one floor or roof only), columns supporting more than one floor, columns or bearing walls with 4 hour fire resistance rating (3 hour rating if supporting one floor or roof only), beams, girders, trusses, and arches supporting more than one floor, columns or bearing walls with 4 hour fire resistance rating (2 hour rating if supporting one floor or roof only), floor-ceiling assemblies with 2 hour fire resistance rating, roof-ceiling assemblies with 2 hour fire resistance rating, and interior and exterior nonbearing walls with noncombustible or limited-combustible materials (with some exceptions).

NFPA 101 describes an industrial occupancy as “ Industrial occupancies shall include factories making products of all kinds and properties used for operations such as processing, assembling, mixing, packaging, finishing or decorating, repairing, and similar operations.” Ordinary contents are described as “Ordinary hazard contents shall be classified as those that are likely to burn with moderate rapidity or to give off a considerable volume of smoke”.

The utility services for the facility are electrical and water; there is no gas or liquid fuel utility service.

The facility has a fire suppression water sprinkler system.

The example facility houses light manufacturing and contains limited quantities of flammable or combustible liquids. The construction of and operations within the example facility are highly regulated by direct governmental oversight.

Of the forty rooms within the facility, five rooms contain hazardous materials.

Two of the rooms containing hazardous materials also contain small scale furnace operations that melt pyrophoric metal in an inert gas environment. These furnace operations are subject to tipping over in an earthquake and the inert environment is likely to be lost, resulting in burning of the metal should the furnace operation be underway at the time of the earthquake. These two rooms are designated as compartments of interest with greater than normal likelihood of ignition during an earthquake when compared to the general built environment.

Separate Fire Possibility into Random and Deterministic – Random Fires

Data Used in the Kelly and Tell paper are conservative for the example facility for all rooms except the two identified above.

The fires reported in the data involve structures in the general built environment, including residential, commercial, institutional, and industrial structures. There is a substantial amount of additional data and statistics in the TCLEE (ASCE/NFPA) Monograph [Ref. 7] that prove the application of the approach in Kelly and Tell is conservative as it is applied to the example:

- *…data from the 1994 Northridge earthquake, which indicate that about 50% of earthquake-related fires are reported within several hours of the earthquake* [Ref. 7, p. 115]. It can be expected that about 50% of the fires reported in the data occurred more than several hours (up to several days) after the earthquake events.
- *A typical cause of these later ignitions is the restoration of electric power. When power is restored, short circuits that occurred due to the earthquake become energized and can ignite fires* [Ref. 7, p. 115]. It is presumed that in the highly regulated environment of the example, restoration of electrical power will be orchestrated in detail with intense supervision, unlike what has occurred in the general built environment. Therefore, fires ignited after an earthquake because of the restoration of electrical power are not credible; data that incorporate a substantial portion of such fires is conservative to use for predictive estimates of ignitions in the example.
- *…the number of post-earthquake fire ignitions related to natural gas can be expected to be 20% to 50% of the total post-earthquake fire ignitions* [Ref. 8]. After the 1994 Northridge earthquake, 26% of the general sources of ignition were described as *gas-related* [Ref. 7, Table 4-3]. Of the 48 known materials first ignited after the 1994 Northridge earthquake, 13 were identified as *natural gas* and one was identified as *LP gas* (liquid petroleum gas) [Ref. 7, Table 4-6]. Data that include reports of fires attributed to fuel gases will be conservative to use for predictive estimates of ignitions in the example because the example is not served by a fuel gas utility.
- *A spark from a short circuit more likely turns into a fire in a wood building than in a non-wood building* [Ref. 7, p. 112]. The data are dominated by reports involving residential wood buildings. Of the 77 fires reported by the Los Angeles Fire Department after the 1994 Northridge earthquake, 55 were in residential uses [Ref. 7, Table 4-4]. Construction in the example facility is either poured concrete or metal-stud-framed. Data dominated by reports of fires in residenses (i.e., the general built environment) will be conservative to use for predictive estimates of ignitions in the example facility because the facility has no wood walls, ceilings, or floors.

- Of the 48 materials known to be first ignited after the 1994 Northridge earthquake, 37 are not present in the example facility [Ref. 7, Table 4-6]. Earthquake fire data from the general built environment will be conservative to use for predictive estimates of ignitions in the example facility.
- The American Society of Civil Engineers and the National Fire Protection Association [Ref. 7, p. 130], report ignition rates by occupancy per million square feet (see following Table).

Ignition Rates in Two PGA Ranges
(occupancy per million square feet)

PGA Range 0.18 to 0.34 *g*	
Occupancy	**Ignition Rate per Million ft^2**
Residential	0.071
Commercial	0.019
Industrial	0.005
PGA Range 0.34 to 0.65 *g*	
Occupancy	**Ignition Rate per Million ft^2**
Residential	0.177
Commercial	0.047
Industrial	0.012

Clearly residential properties are expected to have higher rates of ignition after an earthquake. Data dominated by fires in residences (i.e., the general built environment) will be conservative to use for predictive estimates of ignitions in the example facility.

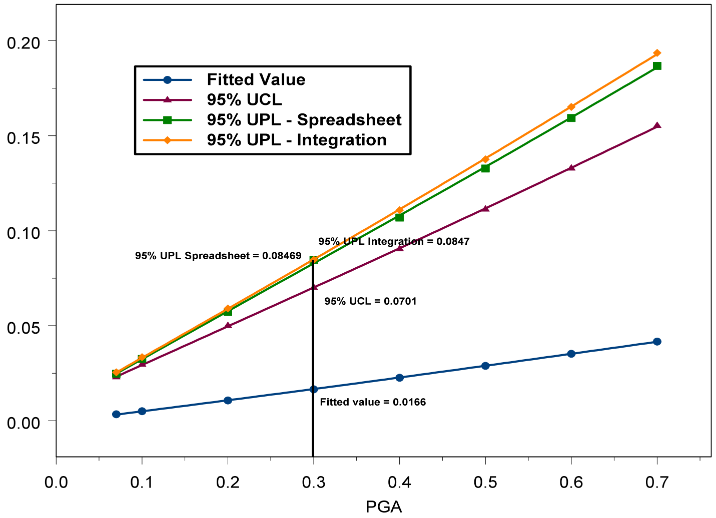
Similar supporting data and statistics can be found in *Causes of the Seismic Fires Following the Great Hanshin-Awaji Earthquake-Survey* [Ref. 9].

Evaluating the Number of Random Fires for the Example Facility – Kelly and Tell Approach

The figure below shows the expected number of ignitions $\hat{\mu}$ (fitted) as a function of PGA for $MMSF = 0.08$. The figure also contains the upper 95% confidence limit for μ (95% UCL). In addition, the upper 95% UPL for a new observation, m, is given both for the spreadsheet calculation method and for the numerical integration method (which is more accurate). The values for $PGA = 0.3$, are marked with a line on the figure.

A conservative spreadsheet estimate of the probability that there are one or more ignitions following an earthquake with $PGA = PGA_0$ and $MMSF = 0.08$ is given by: $1-F(0, m_0)$, where F is the cumulative Poisson distribution with parameter m_0 (the UPL adjusted for possible under reporting of fires in the Monograph data (see Kelly and Tell). For example for *PGA* = 0.3 and *MMSF* = 0.08, UPL(95%, *m*) is 0.08469 and m_0 = UPL*(95%, m) = 1.37*0.08469 = 0.1160, thus, the spreadsheet estimate of probability of one or more ignitions following an earthquake is 1-*F*(0,0.1160) = 0.1095. (Note that the probability based on the more accurate numerical integration technique is 0.0316). The spreadsheet estimate of the probability of two or more ignitions is 0.00623 (numerical integration value = 0.00159, the probability of three or more ignitions is 0.00024 (numerical integration technique = 0.000133). These probabilities are not meant to be exact, but to provide a context for assessing the conservatism of these fire scenarios following an earthquake.

Figure. Fitted values for μ ($\hat{\mu}$), the 95% UCLs for μ and the 95% UPLs for m (from the spreadsheet approach and from integration) as functions of PGA for MMSF = 0.08. The black line marks the values for PGA = 0.3



The spreadsheet estimate of the probability that IGNS is less than or equal to one (based on using the UPL for the Poisson parameter) is 99.4%. Using numerical integration produces a more accurate result and this approach shows that even with the 1.37 multiplier for possible under reporting there is a 99.8% probability that IGNS is less than or equal to one and a 99.99% probability that IGNS is less than equal to two.

A seismic geological evaluation predicts a 0.3 g *PGA* seismic event with a return frequency of once every 2000 years. Under this assumption, the spreadsheet estimate of the frequency of one or more ignitions in a given year from an earthquake event with this PGA is 0.1095 x 1/2000 = 5.5E-5 (note that the more accurate numerical integration result is 1.6E-05, the spreadsheet estimate of the frequency of two or more ignitions is 3.1E-6 and the result from numerical integration is 7.9E-07, the spreadsheet estimate of the frequency of three or more ignitions is 1.2E-7 and the result from numerical integration is 6.7E-08. These estimated frequencies indicate that an earthquake of this magnitude followed by a fire in such a structure would be an infrequent event, and the frequencies of an earthquake of this magnitude followed by multiple fires in such a structure range from very rare to incredible events. Note that these frequency values are for a particular PGA and are not the annual risk of ignition from all potential earthquake events.

Since the annual probability of two fires is greater than 10^{-6} for the spreadsheet method and only slightly less for the numerical integration method, the approach taken is to consider that there will be two random fires caused by the seismic event. This gives a total of four fires, which is considered conservative. The recommendation for Hazard Category 2 and 3 facilities is that one random fire be considered at a minimum, regardless of the annual probability.

Determine Compartments of Interest

All five rooms containing hazardous materials are considered compartments of interest for this facility.

Rank Compartments of Interest by Potential Dose Consequence

The fire rooms are ranked in descending order based on the potential for harm to the public in the event of a fire.

Review Operations and Processes Within the Rooms of Interest for Conditions Different Than in the General Built Environment

The two rooms containing small scale furnace operations that melt pyrophoric metal in an inert gas environment are different enough from the general built environment to be determined as fire rooms, leaving three rooms of interest remaining.

Assign the Random Fires to the Highest Ranked Remaining Rooms

The two highest ranked remaining rooms are designated fire rooms ignited by randomly occurring processes that exist in the general built environment.

Survey the Determined and Random Fire Rooms for Fuels, Ignition Sources and Locations of Fuels and Ignition Sources

Survey performed by The Panel convened for this purpose.

Determine the Worst Case Credible Fuel Package for Each Fire Room

Led by fire protection professionals, The Panel should agree on the worst case credible fuel packages. Consider fuels in close proximity to be a single fuel package, and that combustible/flammable liquids will spread if spilled.

Bound and Characterize the Worst Case Fuel Packages Using Available Fire Test Data

The fire protection professionals assigned to The Panel, should search for fire test data that best represents the fuel packages. A good source is NIST's *Fire on the Web*, http://www.fire.nist.gov/.

CFAST Model of the Example Facility

A fire protection professional well versed in CFAST fire modeling should build the models in accordance with the Department of Energy's *CFAST Computer Code Application Guidance for Documented Safety Analysis* (Ref. 10).

The resulting predictions should be further evaluated for potential exposure to the public and/or the environment.

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