A MONTE CARLO METHOD FOR ESTIMATION OF THE PROBABILITY OF COMBUSTION-INDUCED CONTAINMENT FAILURE

M. Khatib-Rahbar and M. Zavisca
Energy Research, Inc.
P. O. Box 2034
Rockville, Maryland 20847-2034 USA

Abstract

A method is presented for probabilistic assessment of combustion-induced containment failure. This approach is used to illustrate the significance of hydrogen generation, ignition and combustion, and of various phenomenological and modeling uncertainties, in the assessment of the likelihood of combustion-induced containment failure in Pressurized Water Reactors (PWRs) with large-dry containment design. The analysis results show that the overall probability of early and very early containment failure is estimated to be essentially zero for most PWRs with large-dry containment. On the other hand, the likelihood of late containment failure due to combustion is estimated to range from negligibly low values for sub-atmospheric designs to as high as about 0.1 for some of the atmospheric plants.

BACKGROUND AND OBJECTIVE

The Probabilistic Safety Assessments (PSAs) have shown that the probability of combustion-induced containment failure for Pressurized Water Reactor (PWR) plants with large-dry containment (including sub-atmospheric design) is relatively small [1]. These studies typically portray the containment failure probabilities as weighted average estimates across a range of severe accident sequences, and often, the PSAs have not assessed the significance of the phenomenological uncertainties in key assumptions such as combustible gas generation (i.e., quantity of hydrogen and carbon monoxide), and the role and significance of the random ignition process (e.g., electrostatic discharge, sparks due to electrical equipment, combustible gas contact with hot molten debris, etc.), on the estimated likelihood of containment failure.

Moreover, the PSAs have not treated consistently, the various components of the combustion issue in an integrated fashion, in which the outcomes of prior combustion-related events influence the probabilities of later events. For example, combustion in the early phase of accident progression will influence the atmospheric conditions (e.g., concentration of oxygen) pertaining to later combustion. Also generally neglected in the analysis is the possibility and treatment of multiple combustion events within a given time frame.

The assumptions inherent in the existing approach to the quantification of hydrogen combustion-induced containment failure include inadequacies in:

- The treatment of uncertainties associated with in-vessel metal oxidation and hydrogen generation
- The treatment of uncertainties associated with combustion of pre-existing hydrogen (i.e., ignition source and likelihood of ignition), and
- The treatment of additional combustible gas (hydrogen and carbon monoxide) generation due to protracted period of Molten Core Concrete Interaction (MCCI).

The objective of this paper is to present a consistent method for assessment of the likelihood of containment failure in PWR plants with large-dry containment design during severe accidents, and its application to all Westinghouse-designed plants in the United States.

METHODOLOGICAL FRAMEWORK

In the present probabilistic framework [2], the likelihood of containment failure due to combustion of hydrogen and carbon monoxide is estimated using an event tree approach that considers the following three phases:

- Phase 1 – extends from start of the accident (or alternatively, from the onset of rapid Zircaloy oxidation) up until the time of reactor coolant system (RCS) or reactor pressure vessel (RPV) breach (period prior to RCS/RPV breach)

- Phase 2 – corresponds to RCS/RPV breach period.

- Phase 3 – corresponds to the period following Phase 2 and Molten Core Concrete Interaction (MCCI) and during the period that containment conditions would be conducive (i.e., not steam-inerted) to combustion.

For each phase, the likelihood of combustion-induced containment failure is decomposed into the following:

- The likelihood that an ignition source is available.

- The likelihood of flammability (ignition), given an ignition source exists.

- The likelihood that containment can fail, given a combustion event.

In this treatment, the conditional probability of containment failure in each subsequent phase is directly dependent on the existence of ignition sources and flammability in the prior phase (or phases). Therefore, for those event tree paths on which prior combustion events have taken place, a substantially smaller hydrogen mass will be available for a later combustion (note that the combustion of CO is only applicable to Phase 3). On the other hands, for event tree paths that involved no prior combustion events, a larger quantity of hydrogen could be available for later combustion.

The likelihood that an ignition source is available is subjectively assigned for the three phases, and depends primarily on the availability of power or other sources (e.g., electrostatic, hot core debris, etc.), as will be discussed in the next section.

The likelihood of containment failure, given a combustion event, is dependent on the magnitude of pressurization load, and the convolution of the uncertainties in pressure load and containment fragility, as governed by the following stress-strength interference integral:

$$\text{Conditional Failure Probability} = \int_0^{\infty} P(P_c = p)\left[\int_0^{p} P(P_f = p')dp'\right]dp \qquad (1)$$

Here $P\ (P_c)$ is the probability density function, P_c is the peak pressure in the containment, and P_f is the containment failure pressure. In performing this integration, the uncertainty distributions in both the imposing containment load and the containment structural strength are essential.

The overall application of the probabilistic framework for each of the three phases considered is shown schematically in Figures 1 and 2, and is further discussed in the next section. It is seen that the quantification of the uncertainties associated with the combustion-induced pressurization loads is impacted by a number of factors.

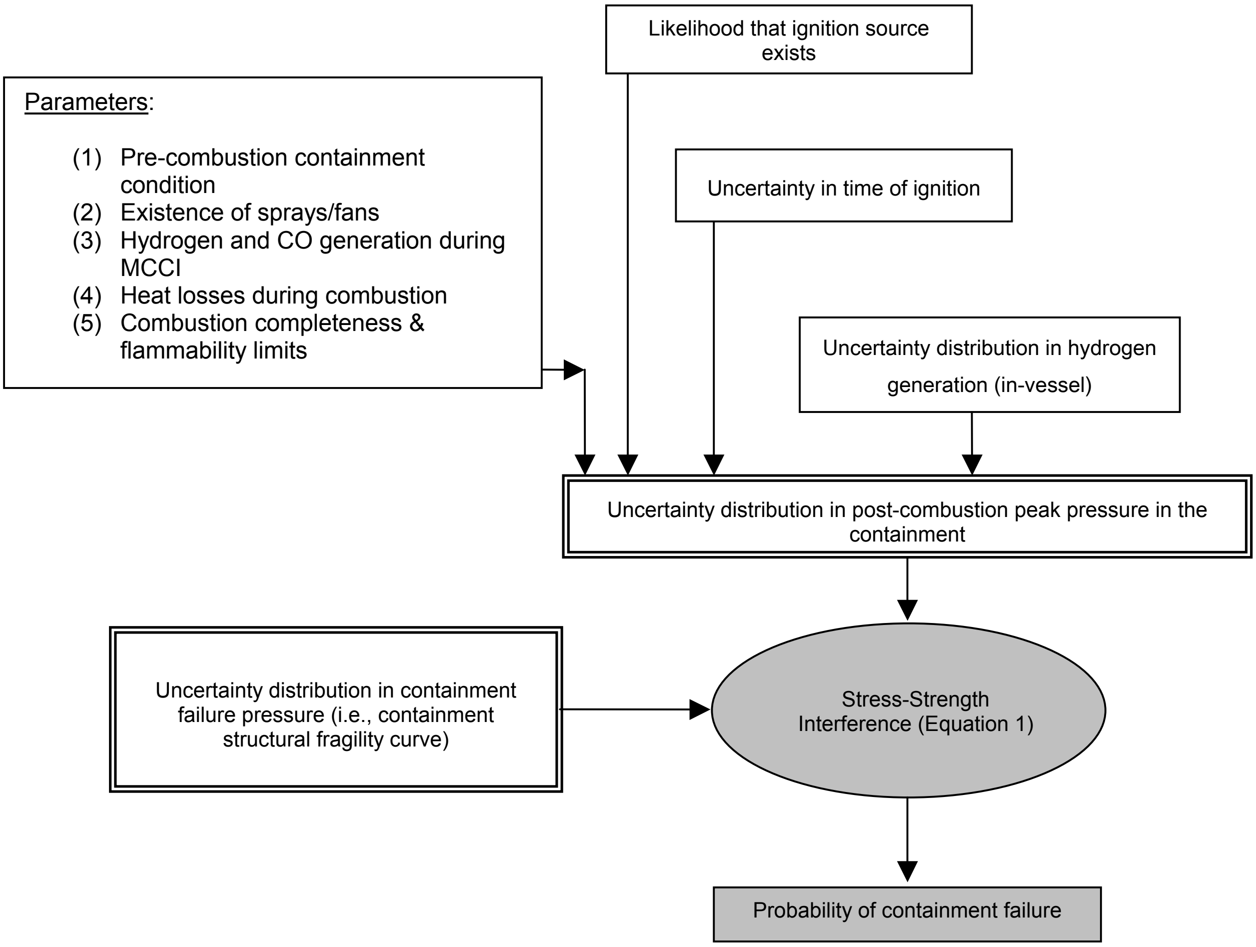

Figure 1 The probabilistic framework for containment failure due to hydrogen and carbon monoxide combustion [2]

QUANTIFICATION OF INITIAL CONDITIONS AND UNCERTAINTIES

In general, the quantification of containment failure probability due to combustion involves the decomposition of the issue into various contributing factors, some of which have associated phenomenological uncertainties, including:

- In-vessel metal oxidation and hydrogen generation
- Ex-vessel metal oxidation and MCCI leading to generation of H_2 and CO
- Transport and distribution of various gases (e.g., hydrogen, steam, air, etc.) in the containment atmosphere
- Ignition (including the presence of active ignition sources, if any)
- Combustible gas control systems
- Activation of containment cooling systems (i.e., sprays and fans)
- Combustion completeness
- Flammability
- Mode of combustion
- Estimation of deflagration-induced combustion loads

The progression of severe accidents is also impacted by the nature of the accidents and their evolution, which could impact the uncertainties associated with the key initial and boundary conditions.

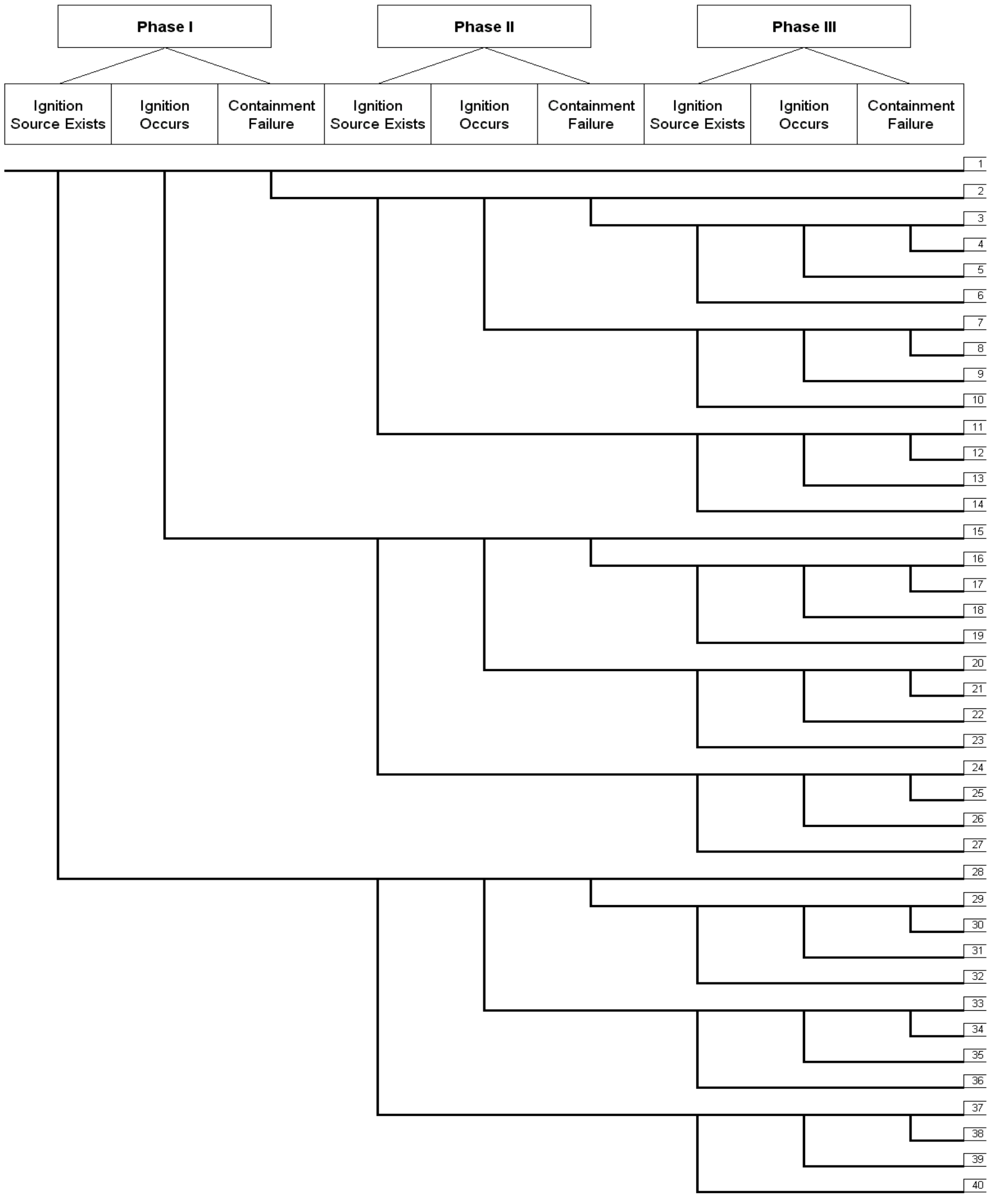

Figure 2 Event tree representation of the three analysis phases

In-Vessel Oxidation and Hydrogen Generation

Variation in the fraction of zirconium that can oxidize during the in-vessel phase of the accident of about a factor of 1.5 is not uncommon, due to choice of empirical constants used in the Arrhenius rate equation. The Zircaloy and steel oxidation (hydrogen generation) process is also impacted by a number of other factors, the most notable of which include blockage formation in the core; steam availability and rate; and melt relocation.

In general, Zr oxidation occurs predominantly prior to the occurrence of any significant core relocation. Furthermore, most of the remaining unoxidized Zr is predicted to be permanently retained in core blockages, with any Zr remaining in the melt appearing as a eutectic with other oxidic constituents. Therefore, this zirconium is not particularly conducive to interaction during relocation into the lower plenum water.

Steaming rate through the core is impacted by system pressure, while the availability and velocity of steam through the core are strong functions of the propensity for natural circulation of hot steam through the core. This enhanced circulation due to buoyancy effects would significantly increase the potential for metal oxidation prior to melt relocation into the lower plenum water. In fact, this is one of the more important distinguishing aspects between high- (e.g., transient events) and low-pressure (e.g., LOCA events) accident scenarios that influence metal oxidation. In addition, any reflood following core degradation (if it were to occur) would significantly increase the production of hydrogen, as shown as part of the OECD/LOFT/FP2 and the German CORA and other experiments.

Figure 3 shows the proposed uncertainty distribution of in-vessel oxidation (up to the time of vessel breach). Given the variability that is observed from the plant-specific code calculations, the uncertainties that are associated with severe accident progression, natural circulation effects, and the phenomena governing hydrogen generation; the most likely (i.e., the median of the distribution) in-vessel effective Zr oxidation is assumed to correspond to about 50%, while the 95th percentile of the distribution bounds the uncertainties as reflected by the very high oxidation prediction (i.e., 67%) by recent analyses. On the other hand, the 5th percentile of the proposed distribution reflects the lower end of the oxidation predictions (i.e., about 35%) also calculated recently under different accident conditions.

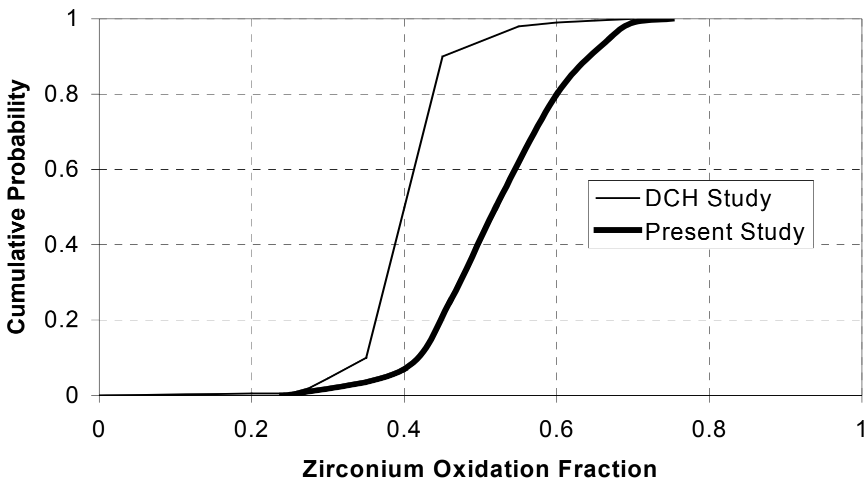

Figure 3 Uncertainty distribution proposed for fraction of in-vessel Zr oxidation, and comparison with distribution used in Surry DCH study [3]

Note that distinctions between high-, medium- and low-pressure scenarios, in terms of in-vessel metal oxidation are not made, even though, in general, a lower extent of metal oxidation (especially in the higher quantiles of the distribution) is expected for medium- and low-pressure scenarios. Nevertheless, given the uncertainties in severe accidents, and the process of metal oxidation, the variability associated with accident scenarios would be difficult to distinguish, and it is essentially captured by the relatively large uncertainty reflected by Figure 3.

Figure 3 also shows that the proposed distribution as compared to the distribution used in Reference [3], assigns a larger probability to higher in-vessel oxidation. On the other hand, the extreme bounds of the two distributions are not significantly different.

Ex-Vessel Hydrogen and Carbon Monoxide Generation

In a large-dry containment, the melt discharged from the vessel, after the short-time-spreading process, will attack the basemat concrete. The concrete ablation process, which is accompanied by generation of decomposition gases, occurs at a much lower temperature than the melt temperature, resulting in substantial erosion of the basemat concrete. The ablation process can continue for an extended period if a crust is formed on the melt upper surface, practically eliminating the heat loss from the melt upper surface. The rate of ablation in this limit would be governed by the melt heat generation rate and the ablation enthalpy of the concrete employed in the basemat. The gas generated during the concrete ablation process is directly related to the concrete composition.

The concrete decomposition gases will react with Zr and other metallic constituents of the melt, generating a significant quantity of heat. The rate of reaction is limited only by the rate at which reactive gases are evolved from the concrete, which in turn is controlled by the heat flux from the corium melt.

Based on the recent MELCOR calculations, the extent of hydrogen and carbon monoxide generation is significantly impacted by the duration of MCCI; however, the impact of an overlying water pool is only to delay the erosion process, without a significant overall impact on combustible gas generation. On the other hand, more gaseous concrete aggregates (e.g., limestone/common sand) are found to result in a significant increase in combustible gas generation (i.e., carbon monoxide).

Transport and Distribution of Gases

Models and computer codes are available to calculate, with varying degrees of accuracy, the transport and mixing of various gases, including hydrogen, during postulated severe accident conditions. These range from models that are based on finite-difference solutions to multi-dimensional Navier-Stokes equation, to those that are based on a control-volume approach (e.g., MELCOR, MAAP, etc.).

The modeling of gas transport in the control-volume codes is based on the principle that the relative density difference between any two compartments as governed by temperature and concentration gradients will lead to relative motion between various "compartments" defined by discrete user specified control volumes. This generally leads to gas flows in the direction of higher density. These codes can generally predict the hydrogen mixing behavior well during forced convection (e.g., under blowdown conditions), but they tend to over-predict the rate of mixing of buoyant flows.

During core damage progression (not considering the initial blow-down period, or the period involving relocation of the core debris into the lower plenum water that would entail large flows promoting global mixing in the containment), the reactor coolant system flows of steam and hydrogen mixture entering containment are of low enough momentum that they can be considered to behave as buoyant plumes. Even under these unfavorable conditions, the concentration gradients inside large-volume containments are not significant, and the peak local hydrogen concentrations are not vastly greater than the volume average concentration. Furthermore, strong global mixing processes would reduce the potential for build-up of regions of relatively high concentrations.

Therefore, for the purpose of the present analysis, it is assumed that the containment atmosphere is well mixed leading to a uniform concentration of gases (including combustibles, air and steam) inside the containment.

Ignition

The combustion process requires that the gas mixture be flammable and that there must be an ignition source present. Experimental data show [4] that in the range of 8 to 10 volume percent of hydrogen, 0.1 to 0.2 m-joules of ignition energy are required for ignition, which is very small. At low temperatures (e.g., below 850K), slow volumetric reactions (that require an ignition source) are expected; while high temperatures (e.g., >850K) can produce auto-ignition (e.g., in a very dry environment inside the cavity following a period of protracted MCCI).

Table 1 summarizes the assumed subjective probability that an ignition source would exist inside containment under a variety of postulated conditions.

Table 1 Probability of existence of an ignition source under various postulated conditions [2]

Condition	Probability
AC power available	0.99
SBO prior to VB	0.10
SBO at VB	0.50
SBO – During MCCI, dry cavity	0.30

Combustible Gas Control System

All PWRs with large-dry containment are equipped with combustible gas control systems that are designed to maintain combustible gas concentration to a level below the flammability limit for all Design Basis Accidents (DBAs) (i.e., metal oxidation that is less than or equal to 5% of core Zircaloy content). The combustible gas control systems consist of (a) hydrogen sampling system, (b) hydrogen/air containment mixing system, (c) hydrogen recombiner system, and (d) containment purge system.

These systems are active (as opposed to the passive systems such as passive autocatalytic recombiners that have been installed in several European plants), and are not designed to cope with the level of combustible gases that is expected following severe accidents. Therefore, the impact of the existing combustible gas control system on the likelihood of combustion-induced containment failure is not considered in the present paper.

Modes of Combustion

Deflagration is a slow combustion process (i.e., time scale of the order of a few seconds) that is essentially the same as an ordinary flame. Under deflagration conditions, the pressure is spatially uniform in containment and it is bounded by the Adiabatic Isochoric (constant volume) Complete Combustion (AICC) pressure. The loads on containment would be quasi-static (i.e., equal to those caused by a constant pressure of equal magnitude). The combustion of a lean (note that a mixture containing too little hydrogen to burn is referred to as “lean“, while a mixture containing too little oxygen to burn is called “rich”.) of approximately 8% hydrogen-air mixture at the Three Mile Island 2 (TMI-2) containment is an example of a deflagration with quasi-static loads. More serious conditions could result from hydrogen mixtures that are closer to 30% hydrogen in dry air, (i.e., closer to a stoichiometric mixture with two hydrogen molecules for each oxygen molecule namely $2H_2 + O_2$ resulting in $2H_20$) [5].

If the hydrogen-air mixture is more energetic than the lean TMI-2 mixture, a very fast-moving deflagration or even a detonation can occur. A detonation is a combustion front moving at supersonic speed; a deflagration is subsonic. For either a very rapidly moving deflagration or a detonation, the pressure in the containment will no longer be spatially uniform. The peak pressure can be higher than the AICC pressure. The loads on the containment will be due to dynamic loads in addition to the quasi-static loads.

If hydrogen is released from the reactor coolant system into the containment in the form of a jet, it could burn as a diffusion flame. Under such conditions, combustion rate is controlled by rate of mixing of hydrogen and oxygen. Furthermore, for combustion to occur, it is necessary for the hydrogen-air-steam mixture in the jet to be within the flammability limits. A diffusion flame can start either because of an external ignition source or because the mixture temperature is in the range of 788 to 858K (i.e., the spontaneous ignition temperature).

Accelerated flames occur when a combustion front accelerates to near sonic velocities but does not become supersonic. Flame acceleration has been observed with hydrogen concentrations down to 10%, even in the presence of a substantial quantity of steam. However, other things being equal, peak dynamic pressures for accelerated flames are lower than for detonations, even though the integrated dynamic load (i.e., impulse) can be comparable.

Combustion of hydrogen below the auto-ignition limit requires an ignition source. Furthermore, a mixture of combustible gases within the “detonability” limits can be made to detonate by making the rate of chemical reaction locally fast enough to initiate and sustain a leading shock wave. Experiments [6] suggest that at elevated temperature, hydrogen-air mixtures could become detonable even at hydrogen concentrations less than 9 to 11%. The presence of diluents (e.g., steam, N_2, CO_2, etc.) tends to decrease the sensitivity of a mixture to detonation. A 20% dilution by steam or other gases is estimated to increase the lower bound of the lean detonation limit inside containment to about 13% hydrogen [6].

In general, an assessment of the potential for DDT requires a good knowledge of temperature, pressure, gas composition, scale, geometry, and configuration (presence of obstacles, mixing fans, etc.).

Analyses performed for other PWRs with large open-volume containments have shown that the atmosphere is generally well mixed except for very small plume regions (i.e., near the point of release from the reactor coolant system into the containment) with locally high hydrogen concentrations. But the regions of high hydrogen concentration also involve relatively high steam content (i.e., due to entrainment into the plume), and are geometrically relatively open (i.e., promoting transverse venting). In addition, the regions of high hydrogen concentration are typically very small (relative to the total containment volume), and typically away from the containment structural boundary. Therefore, even if detonations were to occur, the likelihood of detonation-induced containment failure is not expected to be significant, especially for large, open volume containments.

Detailed analysis of the likelihood of DDT potential is beyond the scope of the present work and requires a separate study (e.g., see Reference [5]). Therefore, the remainder of this paper focuses on the assessment of deflagration-induced containment challenges.

Activation of Containment Heat Removal Systems

Activation of containment heat removal systems at any time during the accident would render the containment atmosphere de-inerted by condensing the steam from the containment atmosphere. This de-inerting process would cause the concentration of hydrogen to reach conditions that would enable deflagration to take place. Note that, if the containment heat removal systems were to be recovered and activated late in the accident when a substantial quantity of hydrogen and carbon monoxide may be present in the atmosphere that could reach limits for global detonation, nevertheless, the atmosphere would transit through a region of deflagration prior to reaching the detonable concentration regime [7]. Therefore, even under fast steam condensing conditions, deflagrations are expected to dominate the mode of combustion, especially, in large, open-volume containments.

Combustion Completeness

In general, the minimum limit for hydrogen combustion is slightly over 4% in dry air. Since dry air is about 20% oxygen and 80% nitrogen, a mixture of hydrogen and 5% oxygen corresponds to about 75% hydrogen, 5% oxygen and 20% nitrogen. Addition of any steam or other diluents would reduce the hydrogen volumetric concentration and increase the threshold for combustion.

Generally, combustion is incomplete at hydrogen concentration less than 8%, and it becomes essentially complete at hydrogen concentrations exceeding 10% in a steam-rich environment. Combustion completeness is strongly impacted by the amount of steam and other inert gases in the containment. The combustion completeness can be calculated using empirical data as discussed in Reference [8].

Flammability

Experimental evidence suggests that, given an ignition source, the hydrogen ignition probability is high once the molar concentration of hydrogen is within the flammable range. In general, at lower than 4% molar concentration of hydrogen, ignition is not possible, while, at concentrations higher than 4%, combustion is highly likely to occur given the presence of an ignition source. Therefore, for purposes of this study, no special consideration needs be given to whether a mixture with a particular concentration of hydrogen is flammable or not; at concentrations less than about 4%, burn completeness would be calculated as 0%, which is equivalent to no combustion taking place. Factors other than the concentration of combustible gases will affect mixture flammability, including the concentrations of oxygen and inert gases.

Pressurization due to Deflagration-Induced Combustion

The calculation of pressurization inside the containment is based on a single volume adiabatic[1] isochoric combustion model that is incorporated within the ERPRA-BURN code, developed by Energy Research, Inc. (ERI) in the early 1990s.

In general, the post-combustion pressure due to combustion of hydrogen and carbon monoxide is determined based on conservation of mass and energy during the burn process that results in:

[1] As indicated by Eq. 4, the impact of heat losses during combustion is considered through a combustion efficiency that is derived based on more detailed calculations that consider the effect of heat losses during deflagration process.

$$P_b = Function(T_i, P_i, Q, \eta) \quad (4)$$

Where T_i is the initial temperature, P_i is the initial pressure, Q is the heat of combustion, and η is the efficiency of the combustion process (directly proportional to the heat losses from the process) that varies from ~0.75 for scenarios with active containment heat removal systems (e.g., sprays or fan coolers), to ~0.90 for scenarios without active containment heat removal.

Combustion Simulation

The calculation of the combustion event progression is performed with the ERPRA-BURN code using a simple Monte Carlo technique. A large number of possible evolutions or "histories" of the events (typically from 2000 to 5000) are simulated starting from the beginning of in-vessel hydrogen generation until late into the accident (i.e., through all three time phases introduced earlier). Thermodynamic conditions in the containment are modeled, as are the releases to the containment of gases from in-vessel oxidation and MCCI. When appropriate conditions are met, combustion events are simulated using the single-volume formulation to determine the maximum pressure loads. Random and uncertain input parameters are modeled through the use of random numbers.

In order to generate data adequate to reconstruct all of the needed branch probabilities from the results, four separate sets of histories are simulated. These history sets differ with regard to the assumptions used for the availability of ignition sources. To represent all combinations of the availability or unavailability of an ignition source in Phases 1 and 2, four separate sets of assumptions are required. Since Phase 3 is the final one and has no impact on the prior phases, it may always be assumed that there is an ignition source in Phase 3 for all simulation sets[2]. In summary, the following history sets cover all possible combinations of interest.

- In the first set, ignition sources are assumed to be available in Phases 1 and 3, but none in Phase 2.
- In the second set, ignition sources are assumed to be available in Phases 2 and 3, but none in Phase 1.
- In the third set, ignition sources are assumed to be available in all three Phases.
- In the fourth set, an ignition source is assumed to be available in Phase 3, but none in Phases 1 or 2.

In sets where an ignition source is guaranteed for a particular time frame, the distribution for time-until-ignition is weighted for the first event so as to insure that at lease one ignition event occurs. In the summary calculations, the results from each history set are weighted by the probability associated with the assumptions regarding ignition in Phases 1 and 2. For example, all results from the first history set are weighted by a factor $P_{iG,1}\left(1 - P_{iG,2}\right)$, where $P_{iG,1}$ is the probability that an ignition source exists in Phase 1 and $P_{iG,2}$ is the probability that an ignition source exists in Phase 2.

[2] For instance, no additional information could be gained by considering a history set that assumes an ignition source is available in Phases 1 and 2, but not in Phase 3.

The main rationale for the use of history sets (rather than just sampling the existence of an ignition source as another random variable in the Monte Carlo simulation) is that it permits properly weighted consideration of unlikely circumstances. For instance, conditions may be posed where the probability of ignition in each time frame is 0.99. Under these conditions, containment failure in one phase could conceivably be dominated by sequences involving no combustion in the prior phase; however, these would constitute 1 in 100 (or fewer) of the samples generated by simple Monte Carlo. With the use of history sets, there will always be at least one set of results (with thousands of simulated sequences) that include the limiting set of conditions, and the weighting factors insure that the final probabilities are correctly accounted for. With a limit of about 5000 samples, conditional probabilities less than about 0.001 cannot be calculated with any degree of accuracy without resort to some stratified Monte Carlo method.

During each simulated history, the time-dependent number of moles of each gas component is modeled so that containment conditions can be calculated at any instant. Initially, prior to the beginning of the accident, the atmosphere consists of a mixture of nitrogen, oxygen, and water vapor at 100% humidity. At various times during the accident, sources of various gases are modeled as boundary conditions. Also, as combustion occurs, instantaneous changes in the molar composition may change as combustible gases are consumed and reaction products as added.

Figure 4 illustrates qualitatively, the time-dependent behavior of each gas in the containment atmosphere as modeled by ERPRA-BURN. For the example history depicted in this figure, there are two incomplete burns in Phase 1; one incomplete burn in Phase 2; and two burns in Phase 3, of which the second is complete.

Ignition sources, when available, will cause the potential for burns to occur at particular instants in time. Having established that a total probability that one or more ignition events will occur within a given time period of the accident, using the values assigned in Table 1, it remains to construct a methodology through which the time(s) of ignition can be calculated. It is assumed that ignition is a process that has a constant probability density function per unit time of occurrence equal to some rate λ per hour. Under this assumption, the cumulative probability that ignition will occur within *t* hours is given by

$$F(t) = 1 - e^{-\lambda t}. \tag{5}$$

The rate λ is uniquely determined from the total probability of ignition *P* (from Table 1) and the total duration θ by the requirement that $F(\theta) = P$, that is:

$$\lambda = -\frac{1}{\theta}\ln(1 - P) \tag{6}$$

The result is that the cumulative probability of ignition from Eq 5 may be alternately expressed as:

$$F(t^*) = 1 - (1 - P)^{t^*}, \tag{7}$$

This has the advantage of being expressed in dimensionless time $t^* = t/\theta$ so that it is not necessary that actual durations in units of hours be specified. In ERPRA-BURN, Eq. 7 is used as the stochastic basis for determining the length of time between successive ignition events in the containment. That is, a uniform random number *u* is generated and the time t^*_{next} until the next ignition event is determined such that $F(t^*_{next}) = u$. This results in the formula

$$t^*_{next} = \frac{\ln(1 - u)}{\ln(1 - P)}. \tag{8}$$

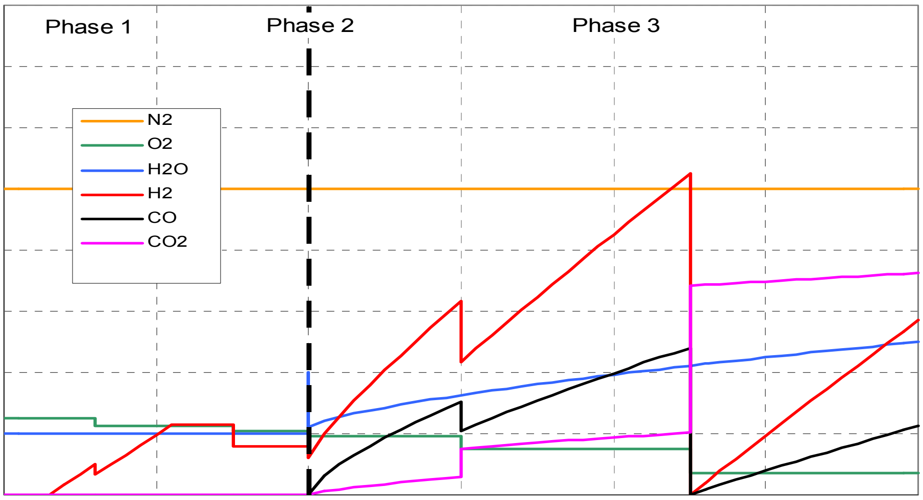

Figure 4 Qualitative behavior of time-dependent molar composition in containment atmosphere as modeled by ERPRA-BURN (note that sharp discontinuities represent assumed combustion events)

The relative time at which combustion takes place, as well as the amounts of non-condensable gases remaining since the last ignition (or since the beginning of the time phase), uniquely determine the containment conditions at the instant of ignition.

Additional requirements in ERPRA-BURN for allowing a burn to occur include a minimum oxygen concentration of 0.05, and a maximum concentration of inertants (steam and carbon dioxide) of 0.55.

Based on the results of the four sets of history simulations, the branch and total probabilities of Figure 2 are calculated as described in Ref. [2].

RESULTS

The analysis in this paper consists of a number of scenarios for a typical Westinghouse-designed PWR with a large-dry, sub-atmospheric containment (as the reference plant), and analysis of an extensive number of cases that assess the impact of parametric variations encompassing some of the design characteristics, and several miscellaneous sensitivity studies to assess the effects of other modeling parameters.

The calculated ERPRA-BURN results for a station blackout (SBO) scenario for the reference plant are shown in Figure 5 and Table 2. The sampling of uncertainty distributions for various parameters including in-vessel hydrogen generation and flammability results in a probability of 0.62 for combustion occurring prior to vessel breach. However, the upper-bound post-combustion pressurization load is about 4.5 bar-abs. Therefore, the probability of containment failure in this time frame is essentially zero. During Phase 2 (the blowdown phase immediately following vessel breach), the mole fraction of steam in the containment always exceeds 0.55; therefore, the containment atmosphere is inert, a condition which precludes combustion.

During Phase 3, concentrations of MCCI gases (including the inertants of steam and carbon dioxide) gradually build up in the containment. There is a relatively short time window (i.e., of the order of less than 0.2 hour in duration) following the start of

MCCI during which the mole fraction of steam and carbon dioxide is below the inerting threshold. Due to the small quantities of combustible gases generated during this interval, calculations employing the probability distribution for time until presence of an ignition source described earlier lead to a probability of at most 0.002 that combustion can occur. During this time frame, relatively small concentrations of combustible gases (hydrogen and carbon monoxide) could accumulate inside containment, resulting in a relatively small containment pressure load of about 5.8 bar-abs. As in the earlier time frames, the containment failure probability is also zero during Phase 3. In fact, under the circumstances found to pertain in the containment during Phase 3, the only factors expected to materially affect the outcome of the SBO scenario would be those tending to significantly extend the length of time available before the atmosphere becomes steam-inerted.

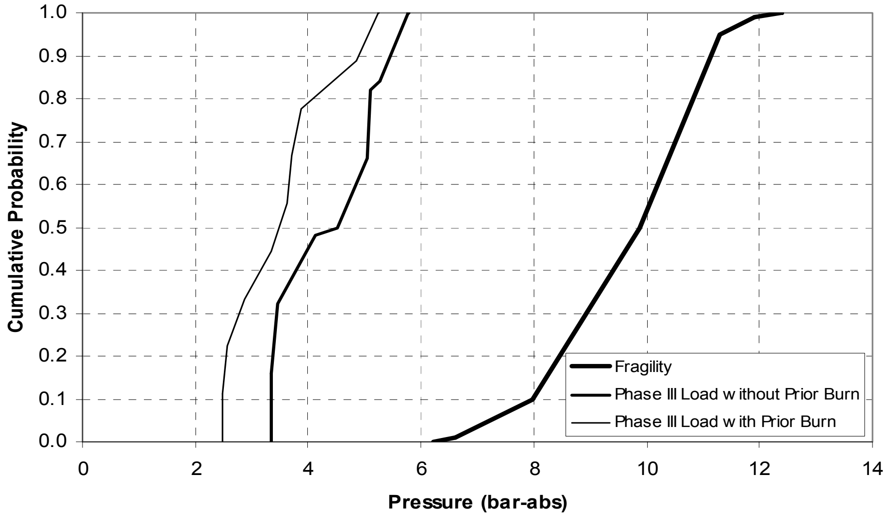

Figure 5 Phase 3 containment loads and fragility for SBO with high RCS pressure at vessel breach (VB)

Table 2 Probability results for SBO with high RCS pressure at VB

Time Frame		Phase 1	Phase 2	Phase 3
Ignition Probability (see Table 1)		0.10	0.50	0.30
Burn Probability	With Prior Burn (Given Ignition)		0	$1x10^{-3}$
	Without Prior Burn (Given Ignition)	0.62	0	$2 x10^{-3}$
	Net	0.06	0	$3 x10^{-4}$
Containment Failure Probability	With Prior Burn (Given Combustion)		N/A	0
	Without Prior Burn (Given Combustion)	0	N/A	0
	Net	0	0	0

Application of this approach to a large number of PWRs with large-dry containment (i.e., both sub-atmospheric and atmospheric designs) within a sensitivity analysis framework shows that from the standpoint of combustion behavior, most severe accident scenarios could be classified into one of the two following categories:

- Scenarios that involve the failure of containment heat removal systems (e.g., sprays), and which are therefore inerted by steam soon after vessel breach. The limiting factor for these scenarios is the length of time (and hence the maximum amount of combustible gases that can build up in the containment) before steam-inerting. The only factors that strongly influence the analysis results for these scenarios are those which tend to extend the duration of flammable conditions early in the post-vessel-breach phase (for example, a containment with more heat sinks, or larger amounts of pre-existing non-condensable gases).

- Scenarios that involve operating containment heat removal systems. In these scenarios, large quantities of combustible gases are generated during MCCI, and the containment environment is flammable for the entire duration of the accident. However, the amount of pre-existing oxygen limits the extent of combustion that can take place (considered either in aggregate or in terms of the maximum single burn magnitude). Combustion loads in these scenarios are relatively insensitive to most factors other than the quantity of pre-existing oxygen (i.e., equivalent to the initial operating pressure of the containment).

Some scenarios may include sufficient heat removal to substantially extend the time of steam-inerting while still elevating the base pressure inside containment. These scenarios tend to result in the highest combustion loads and the largest probabilities of containment failure.

The PWR containments most likely to be vulnerable to combustion-induced containment failure as determined by the analyses, would be those that have a low power-to-containment-volume ratio, operate at atmospheric pressure, and are structurally weaker. Other factors can also contribute (e.g., basaltic concrete composition and a high zirconium mass) to combustion-induced pressure loads; however, their effects are minor in comparison. The counter-intuitive result that containment failure probability is larger for lower power-to-volume ratios is explained by the effect of lower power on steam fraction in the containment, since plants with higher power level are more likely to be steam-inerted for a longer duration. However, variation of any one parameter independently does not result in a containment failure probability that is significant (i.e., higher than 0.05).

On the basis of analyses performed for essentially all U.S. Westinghouse-designed PWRs with large-dry containment, for the majority of PWRs, the challenge to containment from global hydrogen and/or carbon monoxide deflagration is insignificant (i.e., containment failure probability less than 0.01), while a significant minority may experience containment failure probabilities in the approximate range from 0.01 to 0.10.

Table 3 provides a summary of estimated conditional containment failure probabilities for Westinghouse PWRs with large-dry containment, during various phases of severe accidents. It is seen that the overall probability of early and very early containment failure is estimated to be essentially zero for all Westinghouse plants with large-dry containment. On the other hand, the likelihood of late containment failure due to combustion is estimated to range from negligibly low values for sub-atmospheric designs to as high as about 0.1 for some of the atmospheric plants. Note that the overall likelihood of late containment failure (due to all over-pressure, over-temperature processes, including combustion) for all U.S. PWRs with large-dry containment (Westinghouse and others), is shown by the results of the plant-specific IPEs [1], to range from zero (for two plants) to about 0.75 (for three plants), with the majority of plants being in the late containment failure probability range of 0.05 to 0.50.

Table 3 Summary of the estimated range of conditional containment failure probabilities for Westinghouse PWRs with large-dry containment

Conditions	Very Early	Near Time of Vessel Breach	Several Hours After Vessel Breach
Sub-atmospheric Containments			
Without Sprays	0	0	0 – 0.03
With Sprays	0	0	~ 0
Recovery of Sprays	0	0	0.01 – 0.1
Atmospheric Containments			
Without Sprays	0	0	$\leq$0.10
With Sprays	0	0	$\leq$0.10
Recovery of Sprays	0	0	0.1 – 1.0

It is noted that the scope of this study has been limited to deflagration under well-mixed conditions, and as such, the present assessment does not explicitly address the impact of flame acceleration and deflagration-to-detonation transition on the integrity of large-dry containment design, even though some qualitative discussions applicable to hydrogen detonation are provided.

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