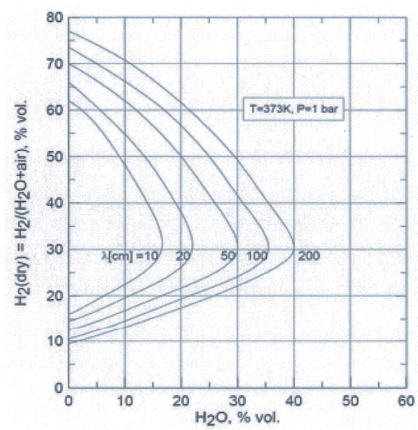
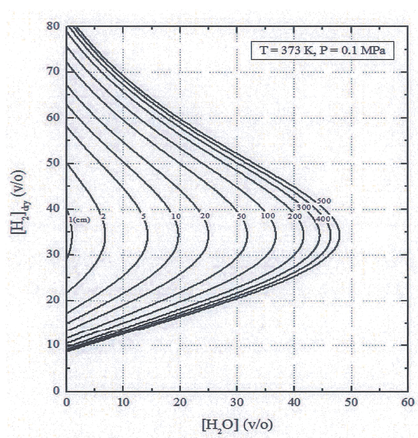


(a) Cell Width Calculated with Gavrikov Correlation



(b) Cell Width Calculated with Eq. 3-15

Figure 3-5 Comparison of Detonation Cell Width given by Eq. 3-15 and Gavrikov Method

3.3.2.4 Characteristic Length of Compartments

The characteristic length of a compartment is an important input parameter required in the 7λ criterion of Eq. 3-12. Characteristic length in the context of the 7λ criterion refers to the distance available while the 7λ length refers to the minimum distance required for DDT formation.

Determining characteristic length of the compartments or containment nodes of a nuclear plant can be very ambiguous because of the complex geometry of the plant.

In this analysis, the rules for determination of characteristic size in a lumped-parameter approach given in Appendix F of the SOAR [Reference 6] are utilized. In these rules, 4 simple shapes of rectangular boxes including long box, flat box, tall box and cubic box as shown in Figure 3-6 are used to characterize the compartments found in the containment. The characteristic length is determined according to the formula shown next to individual compartment shapes shown in Figure 3-6.

For compartment nodes that can be flooded with water, actual compartment height is determined by taking into consideration the water height in the compartment. Due to the complexity of the containment geometry, rather than deciding the shape to individual compartment and calculating the characteristic length, a conservative approach can be taken such that the characteristic lengths of all 4 shapes are first calculated and the maximum is selected as the characteristic length. The calculated characteristic length cannot be longer than the longest dimension of the compartment.

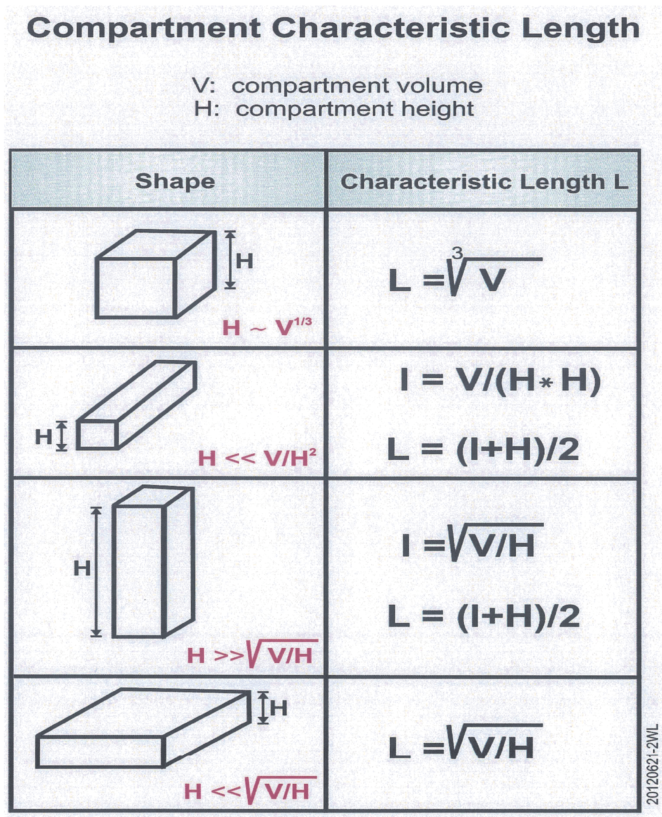


Figure 3-6 Guidelines for Determination of Compartment Characteristic Length [Reference 6]

4.0 Evaluation and Results Summary

Evaluations of (1) AICC pressure, (2) hydrogen distribution and (3) potential of DDT for APR 1400 containment have been performed in three separate calculation notes, respectively. The results of each evaluation are summarized here.

4.1 AICC Pressure Evaluation and Summary

The evaluation of AICC pressure has been performed. The upper bound value for the pressure load as a result of slow deflagrations of hydrogen produced from 100% metal-water reaction and uniformly distributed in the containment is determined to be 85.14 psig. The upper bound AICC pressure load was determined based on the maximum-steam-concentration pre-burn condition allowed by the flammability limit curve. At this maximum-steam-concentration pre-burn condition, the steam volume fraction is 44.02%, and the volume fraction of hydrogen produced from 100% metal-water reaction is just 6.31%. As discussed in section 2.4, the combustion would not be a complete burn if hydrogen concentration is below 8%. Hence, the calculated value of 85.14 psig for the upper bound AICC pressure load is also conservatively underlined by the complete combustion assumption. This value is compared favorably to the Factored Load Category (FLC), 109 psig.

4.2 Local Hydrogen Accumulation Evaluation and Summary

The evaluation of local hydrogen accumulation has been performed using MAAP4.0.8 [Reference 17]. This evaluation identifies local conditions within the containment with hydrogen exceeding 10%. The 10% hydrogen volume fraction is taken as a criterion for determining whether the accumulation should be further considered for DDT evaluation.

The analyzed accident sequences include 5 initiator types with a base case defined for each initiator type. For each initiator type, variations in the availability of accident mitigation systems are made such that their impact, if any, can be observed. Here, severe accident mitigation features refer to containment spray system, cavity flooding system, hydrogen mitigation system, and manual opening of Pilot Operated Safety Relief Valve (POSRV) for rapid RCS depressurization. The five initiator types are as follows:

- Large break LOCA (LBLOCA)
- Medium break LOCA (MBLOCA)
- Small break LOCA (SBLOCA)
- Station Blackout (SBO)
- Total loss of feedwater (TLOFW) that also represents total loss of essential service water (TLOESW) and loss of offsite power (LOOP)

These sequences represent the entire spectrum of severe accident conditions important to hydrogen accumulation and distribution in the containment. Other PRA accident sequences can be either represented or bounded by these analyzed sequences such that analysis of that specific sequence is not necessary.

All analyzed sequences have hydrogen generated in-vessel equivalent to 100% Metal Water Reaction (MWR) assuming minimum generation rate of 0.045 kg/s. The total amount of hydrogen

generated during the analyzed sequences exceeded the equivalent of 100% MWR for sequences with MCCI.
It was predicted the release of hydrogen at various containment compartments under severe accident scenarios. The possible hydrogen release points considered in the analysis include the hot-leg break (for LOCAs), IRWST spargers, failed reactor vessel lower head, and POSRV three way valves. For LOCAs prior to vessel failure, hydrogen is released from the break in the hot leg into SG compartment. For non-LOCA sequences like SBO and TLOFW, hydrogen is first released to the In-containment Refueling Water Storage Tank (IRWST) through the pressure-lifted POSRVs. When three way valve manual alignment is actuated, hydrogen is also released to SG compartment via the three way valve. For high pressure sequences including SBO, TLOFW and SLOCA, additional release point could come from the hot leg failure due to creep. After vessel failure, the failed lower head provides another hydrogen release point to the cavity area.
Figure 4-1 ~ Figure 4-4 show the hydrogen distribution in the dome region when applying all severe accident mitigation features. With all severe accident mitigation features available, the hydrogen concentration is less than 10 percent.

In the screening of 10% hydrogen limit exceedance for various accident scenarios, it was found that

(1) if the POSRV via the three way valve is available, there is no limit exceedance anywhere in the containment except in the IRWST quarters and in the SG compartment for high pressure sequences (such as TLOFW, LOOP , and TLOESW for delayed actuation timing of POSRV and three way valve).

(2) If the Containment Hydrogen Control System (HG, i.e. igniters and PARs) is available and no containment sprays are actuated, there is no limit exceedance anywhere in the containment for all LOCA sequences.

Four locations during various accident scenarios were identified to exceed the 10% hydrogen limit. The 10% limit conditions for each of these locations are summarized as follows.

10% Limit Condition in the Reactor Annulus for LOCAs with Cavity Flooding System (CFS):

The 10% limit condition is exceeded in the reactor annulus when molten corium pours from the failed vessel to the flooded cavity for a very brief duration of about 20 to 40 seconds.

10% Limit Conditions in Lower Containment Regions: In-Core Instrument (ICI) chase, Corium Chamber room, and Reactor Cavity Access Area for LOCAs without CFS

The 10% hydrogen limit is exceeded in the cavity and its vicinity such as ICI chase, corium chamber room, and reactor cavity access area for cases where igniters are unavailable and the cavity is not flooded. Such conditions occur right after vessel failure when artificial hydrogen generation is still ongoing. At the time, the high hydrogen concentration is resulted from both the ex-vessel hydrogen generation from MCCI in a dry cavity and the artificial in-vessel hydrogen generation intended to meet the 100% MWR requirement. The 10% limit condition in lower containment regions is not detected for cases with CFS actuated.

10% Limit Conditions in IRWST and Regions above IRWST:

The appearance of the 10% limit conditions in the IRWST is commonly found in non-LOCA accident sequences (such as SBO, TLOFW, and TLOESW) when POSRV fails to depressurize the RCS through realigned three way valve. This leads to accumulation of hydrogen in the pressurizer which is released into the IRWST through the intermittent POSRV opening.

In TLOFW sequence, the actuation of POSRV via three way valve reduces the number of locations with 10% limit exceedance significantly. With the POSRV via the three way valve, the 10% limit conditions are eliminated in the IRWST quarters without spargers and in most areas above the entire IRWST quarters. However, the actuation of POSRV via three way valve does not entirely eliminate the 10% limit conditions in the IRWST quarters with spargers.

In contrast, for SBO sequences, the actuation of three way valve (without POSRV) entirely eliminates the 10% limit conditions in the IRWST.

The major difference in the 10% limit conditions between the analyzed SBO and TLOFW sequences is in the timing of POSRV actuation. In TLOFW sequences, POSRV is actuated 30 minutes after core damage. This actuation time is much later compared to the one used in the analyzed SBO sequences (which is 30 minutes after the first POSRV lifting). Variations in the availability of igniters, PARs, CFS, and containment spray make no differences.

10% Limit Condition in Steam Generator Compartment at Time of Hot Leg Creep Rupture

The 10% limit condition is detected in the steam generator compartment at the time of hot leg creep rupture for a high-pressure sequence. The 10% limit is also exceeded in the steam generator compartment when the three way valve is aligned to it. This 10% limit condition is caused by the assumption of the well-mixed condition (an intrinsic assumption of the MAAP code) in the steam generator compartment following the blowdown of the high-temperature, hydrogen-rich gases out of the hot leg break at the time of creep rupture failure. However, a well-mixed condition is unlikely achieved in the steam generator compartment. A more likely scenario is a hydrogen burn as a diffusion flame emanating from the pipe rupture location. A diffusion flame is considered a threat to nearby equipment rather than to the containment integrity.

4.3 DDT Evaluation and Summary

The evaluation of the potential of DDT has been performed using MAAP4.0.8. Based on the screening results of 10% hydrogen limit exceedance discussed in section 4.2, DDT index conditions as discussed in section 3.3.2 were further evaluated for the potential of DDT.

Here the DDT index condition refers to the gaseous mixture that has compositions that meet the criteria of flame acceleration (FA) and the detonation cell size that allow DDT to develop within the characteristic length of the compartment. When the DDT index condition is detected in the accident simulation, it means that all necessary conditions for DDT are present. Whether or not the condition is sufficient for DDT is beyond the capability of the criteria. However, as a conservative approach, one may assume that the presence of DDT index condition locally or globally in the containment means DDT will occur if ignited.

It was found that there is no DDT potential anywhere in the containment if the POSRV via the three way valve is available.

Four locations during various accident scenarios were identified to meet the DDT index conditions (criteria) when the POSRV via the three way valve is unavailable. The DDT potential for each of these locations and required conditions to meet the DDT index conditions are summarized in Table 4-1 and are discussed as follows.

DDT Index Conditions in the Reactor Annulus:

There is no potential of DDT in the reactor annulus.

DDT Index Conditions in Lower Containment Regions: ICI Chase, Corium Chamber room, and Reactor Cavity Access Area:

This DDT index condition is detected in the nodes around the cavity such as the ICI chase, corium chamber room, and reactor cavity access area. The conditions meet the 7λ criterion and the σ criterion (i.e., the DDT index ≥ 1) for extremely low probability cases in which igniters are unavailable and the cavity is not flooded. The timing of such conditions is after vessel failure with MCCI as a major source of ex-vessel hydrogen production and artificial hydrogen generation as a major source of in-vessel hydrogen production for cases in which the 100% MWR requirement has not been met at the time of vessel failure.

DDT Index Conditions in the IRWST and Areas above the IRWST:

The appearance of the DDT index condition in the IRWST is found commonly in non-LOCA accident sequences (such as SBO, TLOFW, LOOP, and TLOESW) when there is failure to depressurize the RCS through the POSRV via the three way valve early enough to avoid high accumulation of hydrogen in the pressurizer that can be released into the IRWST.

In TLOFW sequence, the actuation of the POSRV via the three way valve reduces the number of locations with DDT index conditions significantly. With the success of POSRV via the three way valve, the DDT index conditions are eliminated in the IRWST quarters without spargers and in all areas above the entire IRWST quarters. The actuation of POSRV via the three way valve does not entirely eliminate the DDT index conditions in the IRWST quarters with spargers. However, the cumulative duration for the DDT index conditions is substantially reduced. Furthermore, the detonation cell widths calculated at these conditions are larger than 4 m. No detonations have ever been observed in mixtures with detonation cell width greater than 2 m [Reference 6]. Therefore, the potential of DDT is very unlikely in this case.

For SBO sequences, the actuation of the three way valve entirely eliminates the DDT index conditions in the IRWST.

The major difference in the DDT index conditions between the analyzed SBO and TLOFW sequences is in the timing of POSRV actuation. In TLOFW sequences, POSRV is actuated 30 minutes after core damage. This actuation time is much later in time compared to the one used in the analyzed SBO sequences (which is 30 minutes after the first POSRV lifting). Variations in the availability of igniters, PARs, CFS, and containment spray make no differences.

DDT Index Conditions in the Steam Generator Compartment at the Time of Hot Leg Creep Rupture

The DDT index condition is also detected in the steam generator compartment at the time of hot leg creep rupture for a high-pressure sequence with a failure of POSRV and failure to align the three way valve. However, if the three way valve is aligned to the steam generator compartment the DDT index condition disappears. This DDT index condition is caused by the assumption of the well-mixed condition (an intrinsic assumption of the MAAP code) in the steam generator compartment following the blowdown of the high-temperature, hydrogen-rich gases out of the hot leg break at the time of creep rupture failure. Under this situation a well-mixed condition is unlikely achieved yet, and if the gas mixture is ignited a much more likely scenario would be the burning of hydrogen gas as a diffusion flame emanating from the pipe rupture location. The duration of the DDT index condition is also very short (less than 10 seconds). An ignition during Thus DDT in this mode is very unlikely.

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Table 4-1 Summary of Locations with DDT Potential and Required Conditions

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Figure 4-1 Mole Fraction of Hydrogen in the Dome Region for LLOCA

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Figure 4-2 Mole Fraction of Hydrogen in the Dome Region for SLOCA

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Figure 4-3 Mole Fraction of Hydrogen in the Dome Region for SBO-3way valve

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Figure 4-4 Mole Fraction of Hydrogen in the Dome Region for TLOFW-3way valve

5.0 Conclusions

Based on the AICC pressure evaluation, the upper bound value for the pressure load as a result of slow deflagrations of hydrogen produced from 100% metal-water reaction and uniformly distributed in the containment is determined to be 85.14 psig. This value is compared favorably to the FLC, 109 psig. Hence, containment failure due to slow deflagration is highly unlikely.

Based on the evaluation of local hydrogen accumulation of a wide spectrum of accident sequences, it was found that:

(1) If the POSRV via a three way valve is available, there is no 10% hydrogen limit exceedance anywhere in the containment except in the IRWST quarters and in the SG compartment for high pressure sequences (such as TLOFW, LOOP , and TLOESW for delayed actuation timing of POSRV and three way valve).

(2) If the HG (Igniters and PARs) is available and no containment sprays are actuated, there is no 10% hydrogen limit exceedance anywhere in the containment for all LOCA sequences.

Based on the evaluation of DDT potential due to local hydrogen accumulation, it was found that:

(1) There is no DDT potential anywhere in the containment if the POSRV via a three way valve is available.
(2) If the POSRV via a three way valve is not available in high pressure sequences, the IRWST and areas above it have the potential of DDT.
(3) DDT potential exists in the lower containment areas for any sequences with igniter failure and dry cavity (due to CFS failure).

With severe accident mitigation features available, there is no potential for DDT anywhere in the containment. The mitigation features include HG, CFS, and manual opening of POSRVs with alignment of the three way valve.

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