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Evaluation of ESBWR PCCS Detonation Analysis

Joseph E Shepherd
Explosion Dynamics Consulting

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Introduction

A potential hydrogen accumulation and explosion hazard was recently identified in the PCCS system that is part of the GE-Hitachi (GEH) ESBWR design. The US NRC requested additional information from GEH in December 2009. In March 2010, I was asked by the US NRC to review the information supplied by GEH in response to the request for additional information. I was also asked to provide my expert opinion on the approach GEH was using to evaluate detonation hazards in the PCCS. A summary of my analysis and comparison to GEH results is given below.

Independent analysis

According to the initial analysis carried out by GEH, up to 72 hours after the initiation of a loss-of-coolant accident (LOCA), the PCCS lower drum and heat exchanger tubes may have a composition of 0.50 – 0.67 H_2, 0.25 – 0.33 O_2, 0.00 – 0.25 Steam. The maximum pressure is on the order of 407 kPa and the temperature will be between 25 and 100^{o}C.

The key issues for evaluating this as a potential explosion hazard are:

1. What are the possible combustion modes, deflagration or detonation?
2. How likely is transition to detonation in these mixtures?
3. What are the estimated structural loads due to a deflagration or detonation?
4. What are the estimated structural responses to an explosion event?

I made an evaluation of each of these issues based on simplified methods of explosion analysis that have been validated by previous experimental studies and have been applied to similar problems

Estimated Explosion Properties

The combustion mode and associated structural loads can be estimated using simple thermochemical estimates of explosion properties. The *Shock and Detonation Toolbox* (Kao, Zeigler, & Shepherd, 2008) routines and realistic thermodynamic and chemical reaction properties were used to compute ideal flame volume expansion ratios, constant volume explosion pressure, Chapman-Jouguet (CJ) pressure and velocity, and the ideal (ZND) detonation reaction zone length (Kao & Shepherd, 2008). The computations were carried out as a function of steam concentration between 0 and 50% for two initial temperatures, 25 and 100^{o}C, at an initial pressure of 407 kPa. It is unrealistic to obtain atmospheres with a steam fraction greater than 0.25 at 100^oC or greater than .0075 at 25^oC but in order to make bounding estimates on the effect of steam; we have performed the computations disregarding the effects of saturation and condensation. The results are given in Table 1 and Table 2 and shown in Figures 1-5. The initial temperature effect on detonation speed is small and the decrease in CV and CJ pressure as well as expansion ratio can be explained by the lower relative energy content of mixtures at higher temperatures. The expansion ratio is the volume of combustion products divided by the volume of the reactants for a constant-pressure (deflagration) combustion situation. The expansion ratio is an important parameter in determining flame acceleration and DDT sensitivity of a mixture, see the discussion in Chapter 3 of Breitung et al, 2000 or Ciccarelli & Dorofeev, 2008.

The detonation cell width λ is a measure of detonation sensitivity that can be measured experimentally (Lee, 2008). The smaller the cell width, the more easily a detonation can be initiated and propagated in a mixture. Data on detonation cell sizes is given in the detonation database (Kaneshige & Shepherd, 1997) and for 25^oC and 0% steam can be fit to a power law correlation $\lambda = 1.55P^{-1.06}$ where λ is mm and P is bar (Breitung, et al., 2007). In this expression, P is the total pressure of the mixture; this expression is only used to compute the reference cell length λ_o. The cell sizes given in Table 1 and 2 are scaled with the reaction zone length according to the simple model $\lambda = \lambda_o \Delta/\Delta_o$ where the reaction zone length Δ is computed from the Shock and Detonation Toolbox routines (Kao & Shepherd, 2008). The reference cell width λ_o = 0.36 mm, is the value of the detonation cell width measured at 25^oC and 407 kPa with 0% steam; this was obtained from the Breitung et al. correlation. The reference reaction zone length, Δ_o = 15.2 μm, is the value computed by the ZND model at the reference initial conditions of 25^oC and 407 kPa. This scaling model and meaning of reaction zone length are discussed in detail in Shepherd, 1986.

Table 1 Computed explosion properties of stoichiometric H2-O2-Steam mixtures at 100^oC and 407 kPa.

Steam Fraction	Expansion Ratio	CV Pressure (MPa)	CJ Pressure (MPa)	CJ Speed (m/s)	Reflected CJ Pressure MPA)	Induction length Δ (μm)	cell width λ (mm)
0.00	6.99	3.26	6.34	2889.4	15.4	1.34	0.31
0.10	6.74	3.13	6.07	2754.8	14.7	5.02	1.2
0.20	6.48	2.99	5.78	2626.1	14.0	17.5	4.1
0.29	6.19	2.84	5.49	2499.8	13.2	47.5	11
0.39	5.85	2.68	5.15	2371.5	12.4	125	29
0.49	5.41	2.48	4.76	2234.6	11.3	363	85

Table 2 Computed Explosion Properties of stoichiometric H2-O2-Steam mixtures at 25°C and 407 kPa.

Steam Fraction	Expansion Ratio	CV Pressure (MPa)	CJ Pressure (MPa)	CJ Speed (m/s)	Reflected CJ Pressure MPA)	Induction length Δ (μm)	cell width λ (mm)
0.00	8.63	4.06	7.95	2923	19.6	15.2	0.36
0.10	8.32	3.89	7.59	2784	18.6	74.8	1.7
0.20	7.99	3.71	7.23	2652	17.7	227	5.3
0.29	7.62	3.52	6.87	2522	16.8	585	14
0.39	7.18	3.31	6.44	2390	15.7	1530	36
0.49	6.63	3.06	5.92	2248	14.3	4630	108

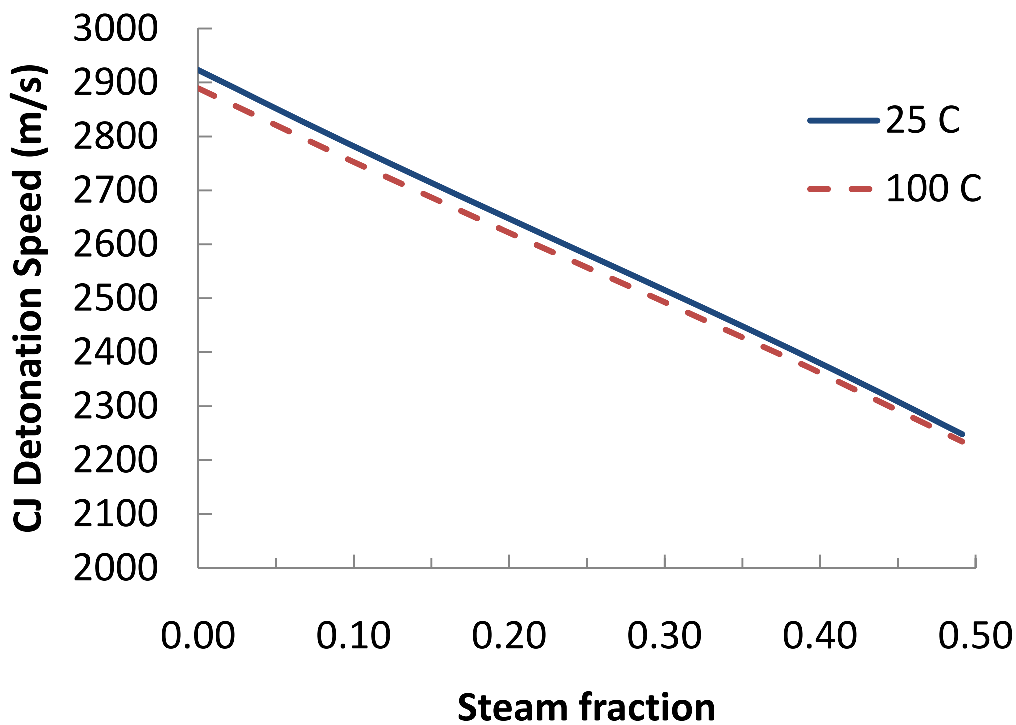

Figure 1 Computed CJ speed for stoichiometric H2-O2-steam mixtures at 407 kPa initial pressure.

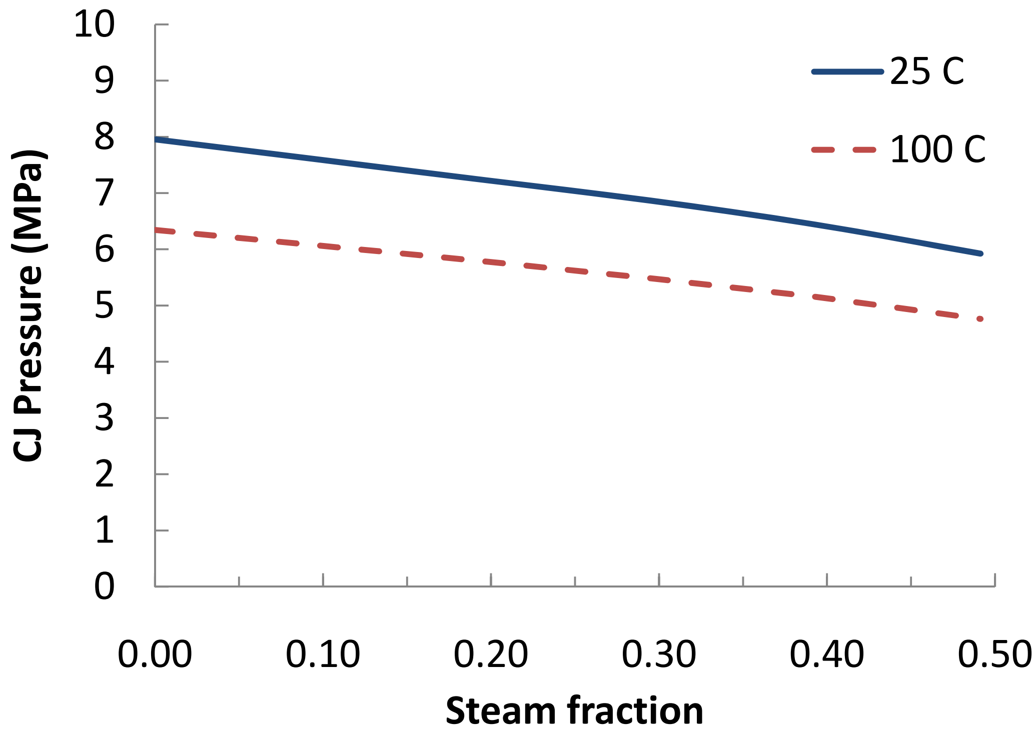

Figure 2 Computed CJ pressure for stoichiometric H2-O2-steam mixtures at 407 kPa initial pressure.

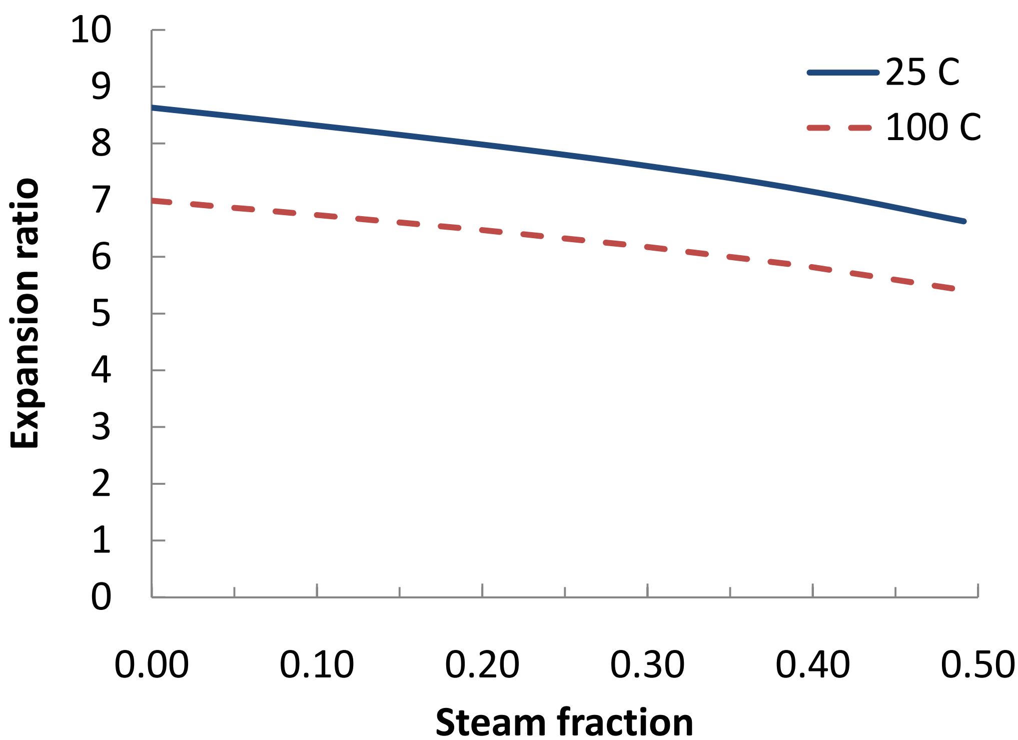

Figure 3 Computed expansion ratios for stoichiometric H2-O2-Steam mixtures at 407 kPa initial pressure.

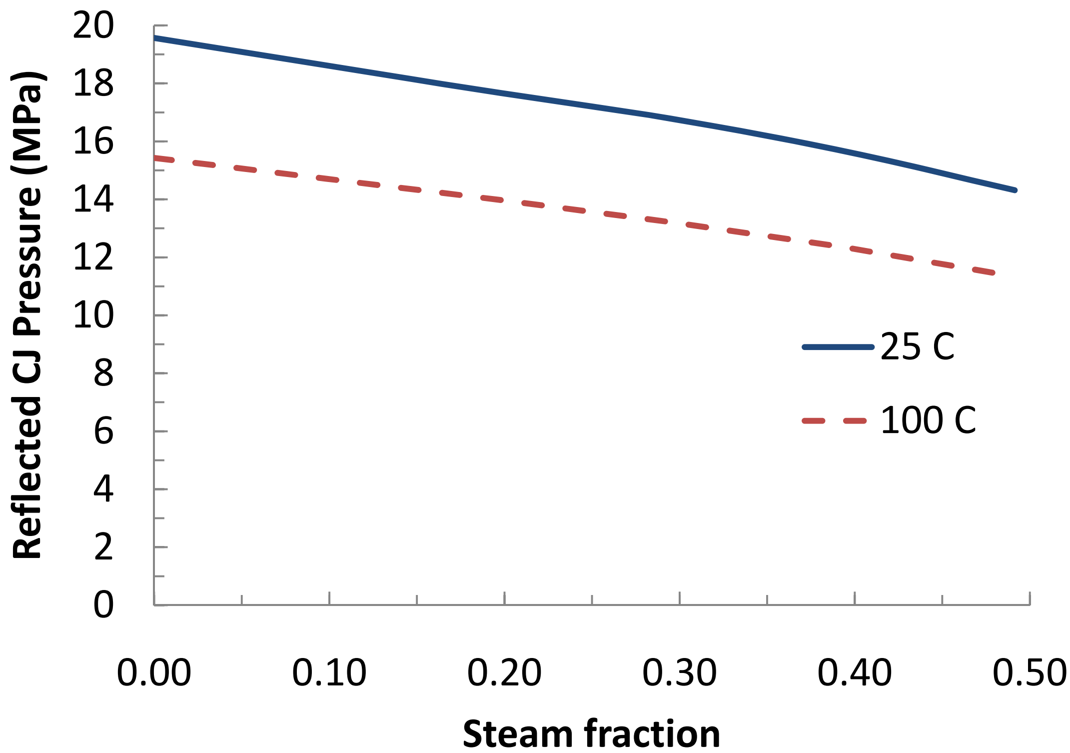

Figure 4 Computed reflected CJ detonation pressure for stoichiometric H2-O2-Steam mixtures at 407 kPa initial pressure.

Evaluation of Combustion Mode

The possible modes of combustion, deflagration vs. detonation, are determined by several factors (Lee, 2008) and specific analysis has been carried out for nuclear power plant applications (Breitung, et al., 2000). The primary consideration for propagation of detonations is the size of the pipe or vessel compared to the detonation cell width. As shown in Figure 5, as long as the steam concentration is less than 40%, the detonation cell width is smaller than the inner diameter of the PCCS condenser tubes and substantially smaller than the inner diameter (550 mm) of the PCCS lower drum. Using a realistic maximum steam fraction of 25%, the detonation cell width is less than 10 mm, which is considered a sensitive mixture. Detonation propagation in the PCCS is certainly a potential hazard.

The potential for deflagration-to-detonation transition (DDT) is determined by the expansion ratio, flame speed, and detonation cell size. Using the ideas of Dorofeev (Breitung, et al., 2000, pp. 3.1-3.41), the potential for flame acceleration has been evaluated (Breitung, et al., 2007) for a mixture similar to the one of interest and the results are shown in Figure 6. The red region indicates mixtures that have been observed in transition to detonation in 100 mm diameter tube in experimental tests. The large extent of this region in the composition space indicates that DDT is a potential hazard in the present situation. One of the main considerations is the magnitude of the expansion ratio (given in Tables 1 and 2); the values are substantially larger than 3.5 for the mixtures of interest, indicating the transition to detonation cannot be ruled out.

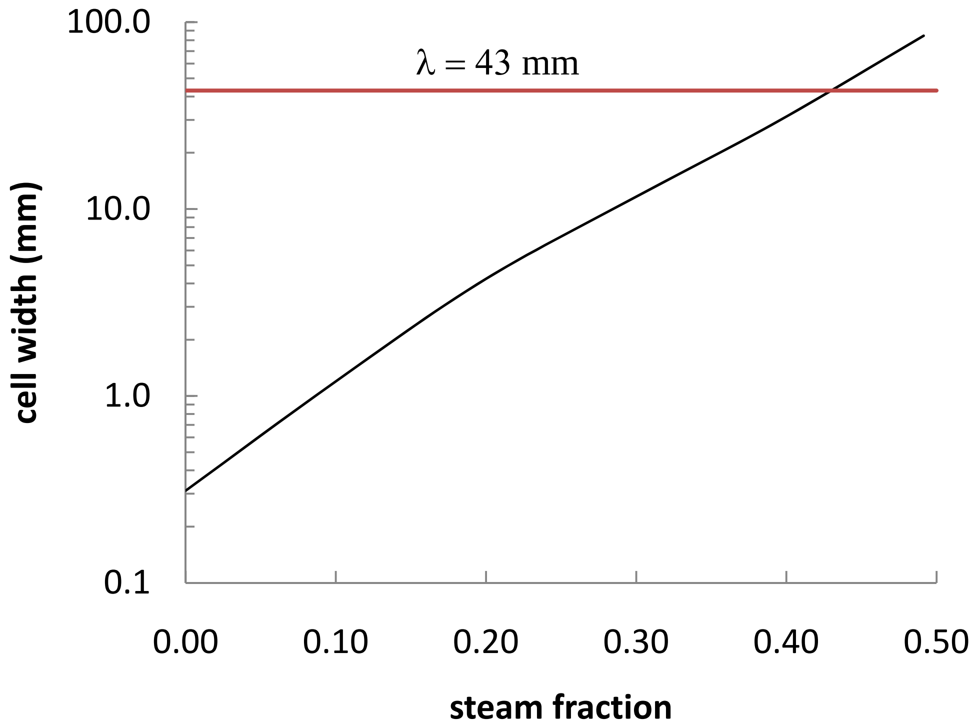

Figure 5 Estimated detonation cell widths for stoichiometric H2-O2-steam mixtures at 100^{o}C and 407 kPa initial conditions.

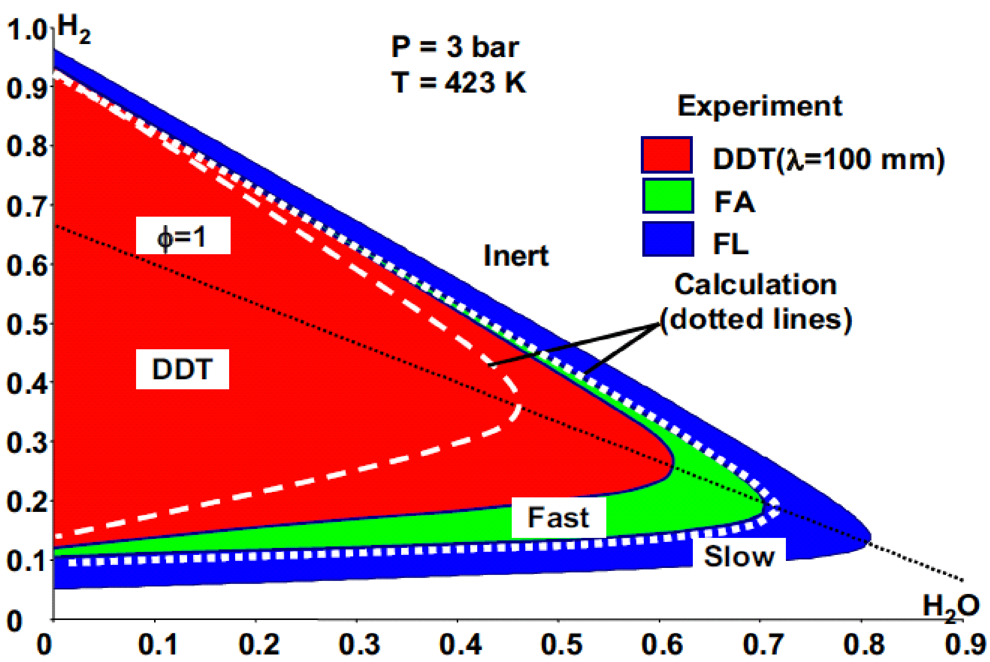

Figure 6 Explosion regimes for H2-O2-Steam mixtures (Breitung, et al., 2007).

Estimated structural response of the PCCS

The structural response to detonations depends on the details of the loading and the response time of the structure compared to the pressure-time history in the detonation (Shepherd J. E., 2009). Various situations like DDT (Liang, Karnesky, & Shepherd, 2006; Pintgen, Liang, & Shepherd, 2007), propagating detonations (Beltman & Shepherd, 2002; Shepherd, Karnseky, Pintgen, & Krok, 2008), detonation reflection (Shepherd, Teodorcyzk, Knystautas, & Thibault, 1991), and detonation propagation through tees and elbows (Liang, Curran, & Shepherd, 2008; Shepherd & Akbar, 2008; Shepherd & Akbar, 2010) have been examined at Caltech.

Direct measurements of strain in tubes with internal detonations demonstrate that the peak strains can be bounded by using an equivalent static loading pressure ΔP and a dynamic loading factor Φ in combination with a static elastic analysis. For an axisymmetric load on a thin-wall pipe, radius R and thickness h, the resulting peak strain ε (hoop direction) is

$$\varepsilon = \Phi \frac{\Delta P}{E} \frac{R}{h}$$

where E is the modulus of elasticity. For propagating detonations, the reference pressure ΔP is the CJ pressure and the dynamic load factor is 2 as long as the detonation speed is sufficiently large compared to the flexural wave resonant speed (Beltman & Shepherd, 2002). For detonations reflecting normally from a closed end or DDT away from the ends of a pipe, the reference pressure should be taken to be the reflected detonation pressure and the dynamic load factor as 2, see Figure 7.

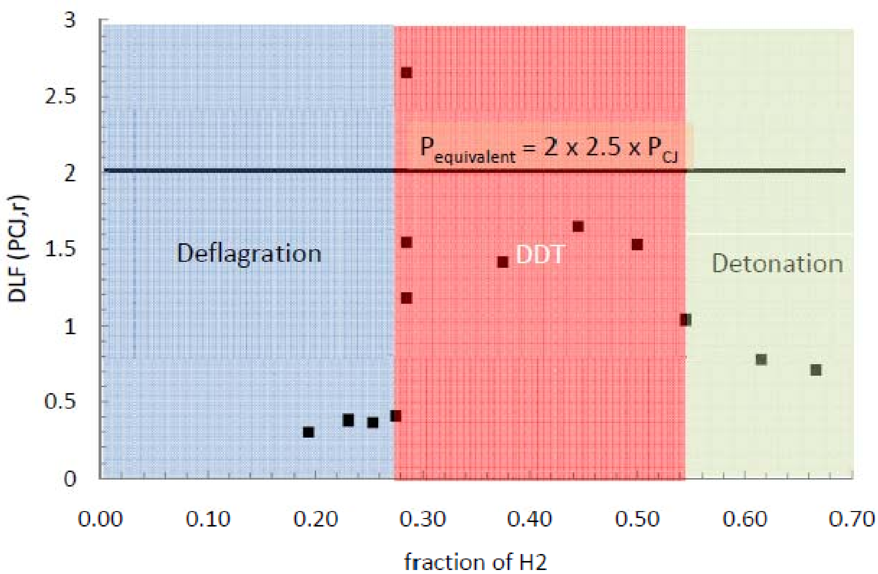

Figure 7 Dynamic load factors for deflagration, DDT and detonation in a 127 mm diameter, 1.25 m long thick-wall pipe filled with H2-O2 mixtures at 1 atm and 25°C (Pintgen, Liang, & Shepherd, 2007).

This approach is known as the single-degree-of-freedom (SDOF) structural model and for simple situations has been shown to give reasonable results for response to blast and detonation waves (Smith & Hetherington, 1994). There are some limitations in applying this method to detonation loading:

1. Neglects vibrations and wave interference effects.
2. Neglects reaction forces due to propagating waves changing directions.
3. Deflagration-to-detonation transition can result in higher loads; this requires estimating response based on experimental data.

As long as these limitations are understood and the values of Φ and ΔP are appropriately chosen, the simplicity of the SDOF is sufficiently accurate for safety analyses. It is also a very cost effective approach in comparison with detailed transient finite element analysis with unsteady loading functions that simulate explosions.

The hoop strains ε_{hoop} for a CJ static load, the dynamic load factor Φ, the flexural wave resonant frequency V_{c0}, and the hoop oscillation frequency f_{hoop} have been estimated for three of the PCCS components in Table 3. For propagating detonations, the peak strains will be $\Phi\varepsilon_{hoop}$ and for reflected detonations or DDT, the peak strains will be ~2.4 $\Phi\varepsilon_{hoop}$. We estimate that the maximum hoop stresses (strains) for DDT conditions will be 232 MPa (1250 μstrain) for the PCCS tubes and 127 MPa (685 μstrain) for the PCCS drum. All of these stresses and strains are within the elastic limit for the construction materials.

The actual peak stresses and strains computed by GEH are higher than these simple estimates. This is to be expected since the GEH computation includes all the geometric complexity and most importantly, features that result in stress concentrations in the drum and tubing.

Table 3 Estimated structural response properties to CJ detonation in stoichiometric H2-O2 at 25°C and 407 kPa.

	PCCS Tubes	PCCS Lower Drum
f_{hoop} (kHz)	34	2.5
V_{c0} (m/s)	1540	2078
σ (MPa)	44.6	24.5
ε_{hoop} (μstrain)	240	132
Φ	2	2

Comparisons to GEH results

GEH assumed (GE-Hitachi Nuclear Energy, 2010, p. 17) a detonation pressure of 19 times the initial pressure and a multiplicative factor of 2.5 for reflection and a DLF of 2 within the PCCS condenser tubes to carry out a static analysis using an equivalent internal pressure of 38.8 MPa. The results of Table 1 for 0% steam are a reflected CJ pressure of 19.6 MPa. Using a dynamic load factor of 2, this gives an equivalent static pressure of 39.2 MPa, which is within 1% of the value GEH used for their analysis.

The values that GEH chose for the DLF (2) and reference pressure (19.3 MPa) will be bounding for both a reflected CJ detonation wave and a DDT process that occurs away from the closed end of a pipe. We do not expect the exceptional situation of "pressure piling" (Shepherd J. E., 1992) to play a significant role in the PCCS since the postulated mixtures are very sensitive to detonation (small cell width and large expansion ratio) and are anticipated to quickly transition to detonation. This combined with the large size of the lower drum and the open ends of the PCCS tubing will prevent extended precompressed regions from forming.

The detonation velocities computed for all the cases in Tables 1 and 2 are significantly higher than the highest resonant flexural speed so that the excitation of large deformations by resonance will not be an issue. This means that the DLF of 2 is appropriate for all situations. The value of detonation speed assumed by GEH was 2800 m/s, appropriate for a mixture with less than 10% steam. At the highest steam concentration (25%) that is physically possible at 100^{o}C, the detonation velocity will be as low as 2500 m/s, but this is still substantially higher than the resonant speeds V_{co}. Resonance effects are not expected to be an issue for detonation propagation within the PCCS tubes or lower drum.

Interactions and Meetings

3/2/2010	Telephone conference with NRC, GEH
3/5/2010	Telephone conference with NRC, ERI
3/23/2010	Telephone conference with NRC, GEH
4/22/2010	Telephone conference with NRC, GEH
6/15/2010	Telephone conference with NRC, GEH on detonation and DDT
6/30/2010	Telephone conference with NRC/GEH on DDT
7/13/2010	ACRS meeting in Bethesda MD – participated in person and made a presentation
7/26/2010	Telephone conference with NRC-GEH re LS-DYNA
8/3/2010	Telephone conference with US NRC, DOE about Bechtel Hydrogen Explosion Guide
10/6/2010	ACRS ESBWR Subcommittee meeting - participated via telephone.

Issues and resolution

There were two main issues that were identified during the review:

1. The initial use of a non-conservative analysis for the PCCS drum. GEH originally took credit for venting through the PCCS lines and did not use the same peak pressure analysis as used for the PCCS condenser tubes. This was changed in the final version so that the same load estimates were used in the drum and tubes.

2. The LS-DYNA analysis that was initially proposed to examine transient response of the structure showed inadequate formulation and the results were not verified against standard solutions or validated against published experimental data (Beltman & Shepherd, 2002). GEH changed their approach and used a prescribed internal pressure loading to simulate the detonation effect and was able to successfully complete realistic simulations.

Both issues were resolved to my satisfaction.

Conclusions

Based on the information in revised licensing topical report (GE-Hitachi Nuclear Energy, 2010) and my discussions with GEH and US NRC, I carried out an independent analysis of the loads and estimated the structural response for the PCCS. I agree that the input and methods of computation used by GEH are based on sound engineering principles. The assumptions about the loading are bounding with a substantial factor of safety for the postulated atmospheres. More credit was taken for the steam in the atmosphere for the ICS but otherwise the methodology is the same and the loading, although lower than in the PCCS case, is also bounding. The design parameters (wall thickness of tubing, drum, and pipe schedule) chosen by GEH appear to be more than adequate to limit the response of the materials to meet the design and construction code requirements. Thermal stress, fatigue, stress risers, and discontinuities appear to have been appropriately taken into account.

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