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A Chamber Design for Fuel/Coolant Interaction using Real Corium Material

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Abstract

A chamber design for fuel/coolant interaction experiment using real corium material in two-dimensional configuration is presented. Given the amount of material involved, the bounding value for static pressure is calculated. A maximum dynamic pressure impulse is also estimated using TNT equivalent method and Henry estimate method, in case steam explosion is observed. With a judicious choice of instrumentation locations, mainly for pressure and temperature, the chamber design is expected to provide valuable information for melt behavior during the premixing stage and energetics during the propagation and expansion phases of steam explosions.

1. Introduction

When a cold liquid is brought into contact with a molten material with a temperature significantly higher than the liquid boiling point, an explosive interaction due to sudden fragmentation of the melt and rapid evaporation of the liquid may take place. This phenomenon is referred to as a steam explosion or vapor explosion. Steam explosions have been of concern in the nuclear industry since in hypothetical severe accidents which involve fuel melt down, the extremely fast thermal interactions , and possibly some chemical reactions, between the molten fuel and coolant may cause steam explosion and subsequent containment failure.

Experimental studies of vapor explosions are usually classified into two categories, namely, small scale and intermediate/large scale. The difference depends on the amount of fuel and coolant liquid involved in the interactions. Small scale experiments which usually involve less than 20 grams of melt may not precisely represent the real propagating event and the resulting destructive phenomena. These experiments, however, have been useful for investigating some of the basic process which takes place during steam explosions, such as fuel fragmentation and pressure pulse behavior. Experimental observations indicate that small scale experiments represent a unit cell of the more realistic large scale interaction. This implies that the propagation phase of the explosion could not be observed coherently in such small scale experiments.

Intermediate or large scale experiments, on the other hand, involve more than 1 kg (up to ≈20kg) of melt. More than one unit cell is involved in such experiments. The main purpose for this type of experiments is to provide an integrated picture of all phases of the explosion, as well as investigating the initial conditions for triggering and propagation, quantifying the magnitude and time characteristics of the pressure pulses, and mechanical work produced.

The difference between small and intermediate/large scale experiments is important because a small scale test involves a single fuel drop or a few particles and spatial propagation of the interaction is not always possible.

One of the major uncertainties involved in the phenomena of steam explosion is material characteristics. In order to setup relatively simple experiment facility, materials with lower melting points, such as tin, have been frequently used. These tests were performed on the ground that the experimental observations using substitute materials would be extrapolated for the real corium material. A full understanding of experimental observation with a certain material would provide adequate models for other materials. The measurement techniques, however, in the extremely fast transient phenomena like steam explosion have been the major restrictions in obtaining full physical parameters needed to understand the complex phenomena. It is therefore generally agreed that experiment using real corium material, despite its relatively high cost and technical difficulties involved, is essential.

This study presents the furnace design for two-dimensional intermediate scale experiment using real corium material. The two-dimensionality was adopted to allow multidimensional characteristics of premixing and propagation stages. The bounding value for the static pressure, for a given furnace volume and the amount of corium material, is calculated. The dynamic pressure impulse is also estimated , using TNT equivalent method and Henry estimate. The results would be eventually used when structure analysis for the chamber design is performed.

2. Experiment

The main purposes of the experiment are to study mixing and boiling characteristics during the premixing stage and to find the elements and their degree of effects on the explosivity of steam explosions, when real corium material is used as melt. Currently, two major elements are considered; the environmental pressure and the coolant temperature. Test matrix set up is as follow.

- Corium Composition:	UO_2/ZrO_2 (80/20 w/o)
- Corium mass:	20 Kg
- Corium target temperature:	3150 K
- External trigger:	Always applied
- Delivery method:	Drop by gravity

	Pressure (1 bar)	Pressure (2 bar)	Pressure (4 bar)
Water temperature	Saturated and 70 K subcooled	Saturated and 70 K subcooled	Saturated and 70 K subcooled
Number of tests	12	4	4

Table 1. Test Matrix

Following parameters are to be measured for each test.

During the tests

- Melt temperature estimation by energy balance
- Pressures at water container side inner wall (12 locations at three different levels) and bottom (2 locations)
- Pressures at Test Chamber (12 locations)
- Temperature of coolant during premixing (12 locations)
- Temperature of Test Chamber (i.e. gas temperature : 12 locations)
- Water level swell during premix phase
- Visual observation if applicable

Post test measurement

- Debris size distribution

3. Facility

The main purpose of the experiment chamber is to contain the pressure and test debris generated during the steam explosion or steam spike. Design criteria was therefore based on a pressure vessel of sufficient size and rigidity to withstand the pressure load expected from the thermal and possibly chemical interaction between high temperature melt and water coolant. The chamber also provide several physical parameters, such as temperature and pressure, as well as means for visual observation. The chamber design schematic is shown at figure 1. As seen from the figure, the facility is composed of mainly three sections, the furnace chamber, the upper head, and the body of test section. The small chamber located at the top of the facility is a furnace chamber. The chamber is designed to hold UO_2/ZrO_2 furnace. The main design considerations here involve both thermal and mechanical aspects. Obviously, the chamber is in very close proximity to the high temperature furnace which holds over 3000K corium melt. The water jacket design is thus necessary. Mechanically, since the furnace chamber and test section below are designed to be coupled to form a sealed environment, high pressure resistance is required. Current design provide 30 bar capability for the furnace chamber. Figure 2 shows the nozzle orientation view from the top of furnace chamber. They are mainly for the instrumentation lines, but one of them might be used as a visual port if applicable. The upper head is removable to provide access to the test section. The mass of the head is approximately 3900 kg. The upper head also provide visual ports which might used for lighting as well. The body of test section has several ports. As seen in figure 1, there are two visual ports located at the upper part of the body. They are marked as N-3 and N-4 and their diameters are 6 inches. At the same level, a port for pressure relief value is provided, which is marked as N-10. The two larger ports marked as N-1 and N-2 are for both main-way usage and visual observations when applicable. They are in right angle with each other, and the dimension is 12 inches in diameter. The top view of these ports are shown in Figure 3. Again at the same level is located two 6 inch instrumentation port. All the signal lines as well as power sources are through these ports. A small port marked as N-7 is provided for pressurization. Inert gas such as Argon is currently considered for pressurization. The drain port is located at the bottom of the test chamber, marked as N-6.

The water container, where the interaction between high temperature corium and liquid water takes place is located on top of the column at the center of the chamber. The size of the water container will be such that the mass of water is 50 times that of melt. This mass ratio is necessary for adequate cooling of UO_2/ZrO_2 melt even when steam explosion is not observed. Since the mass of the melt is 20 kg, about 1 ton of liquid water is required.

Located between the furnace chamber and test chamber is a sliding gate for test section isolation. The closing time of 0.1 sec is considered necessary to provide chamber isolation before melt is in contact with water. In case the gate is not functioning, a pressure relief value will be provided for the furnace chamber as well. The threshold pressure for this value is currently under evaluation.

4. Bounding Static Pressure and Dynamic Pressure Impulse

Maximum Static Pressure Estimation

The maximum static pressure is estimated based on following assumptions in order to obtain bounding value.

1. Maximum melt mass of 25 kg
2. Water to melt mass ratio to be 50
3. entire thermal energy of mass available for vaporization
4. no condensation or heat loss from expanding steam

Thermal energy per unit mass of melt (80 w/o of UO_2 and 20 w/o of ZrO_2) is estimated by noting that specific heat for solid state, melt state, and fusion energy are 445 J/kg.K, 565J/kgK, and 0.365×10^6J/kg, respectively. Therefore,

$$\Delta U = 445\ \text{J/kgK} \times 2850\text{K} + 0.365\times10^6\text{J/kg} + 565\text{J/kgK} \times 300\ \text{K}$$

$$\cong 1.8\ \text{MJ/kg}$$

The total thermal energy of the melt is, hence, 25 Kg x 1.8MJ/kg = 45 MJ

- Total minimal volume for the step to occupy is

$$V_{steam} = V_{chamber} - V_{water} - V_{etc}$$

$$= 3.14 \times (1.0\ \text{m})^2 \times 3.0\ \text{m} - 1.25\ \text{m}^3 - 2.0\ \text{m}^3$$

$$\cong 6\ \text{m}^3$$

- The latent heat for water at 1 bar is 2250 kJ/kg. For the elevated pressure, however, the value is lower., If we take 2000 kJ/kg for bounding calculation, the thermal energy of 45MJ can evaporate about 23 kg of saturated liquid water. The specific volume of the 23 kg of resulting steam is then $6\text{m}^3/23\text{kg} = 0.26\ \text{m}^3/\text{kg}$. This value corresponds to 7.3 bar, and 170 °C, from steam table.

Dynamic pressure impulse load estimations (TNT equivalent method and R. Henry estimate)

For the impulse load arising from the steam explosion, TNT equivalent methodology was used [1]. The method assumes that the stored thermal energy within a superheated mass of corium can be related to a charge of TNT. The shock wave characteristic from the TNT explosions is known to have steeper leading edge than those from steam explosions, hence will have more impact on the surroundings of concern. The TNT equivalent analogy, therefore, would provide more conservative assessment when applied for steam explosion phenomena. The same methodology was followed for the NUREG-1150 EVSE load assessment for Grand Gulf pedestal integrity assessment [2].

For the total thermal energy of 45 MJ, and with typical conversion ratio of 0.03 [3,4], the total thermal energy for steam explosion is

E_{total}= 45 MJ x 0.03 = 1.35 MJ.

Since TNT equivalent $\cong$ 5.1 MJ/Kg [5],

W=1.35 MJ x (1Kg/5.1J) $\cong$ 0.26 Kg (=0.58 lbm).

The radial distance of test chamber is 3.28 feet. The impulse load is therefore,

$I= 1.46 (0.58)^{1/3}(0.58^{1/3}/3.28)^{0.89}$

$\cong 0.36$ (psi-sec).

The shock wave impulse by steam explosion in ALWR was estimated by R. Henry using simplified methodology [5]. The uniform peak pressure of 1450 psia is assumed in the interaction zone where high temperature melt and liquid water undergo thermal interaction. The pressure pulse is then assumed to decay by a square law. If similar approach is followed to assess pressure pulse on the test chamber, one could define the interaction zone whose radius is 0.25 meter. Considering the melt volume of about 3000 cc, the assumed interaction zone would involve more 20 times of water volume and therefore could be safely considered as a bounding size. Since the distance for the center of interaction zone to the chamber wall is 1 meter, the pressure at the chamber wall could be estimated by

P_{wall}=1450 psia x $(0.25 \text{ m} / 1.0 \text{ m})^2 \cong$ 90 psia.

Since the experimental data suggests the steam explosion has a rapid pressure rise followed by a linear time decay for a duration of 2 to 3 milliseconds, the impulse from the pressure peak of 90 psia would be about 0.15 psia-sec. This value is found to be a little lower than one obtained by TNT equivalent methodology.

5. Conclusions

A chamber design for fuel/coolant interaction using real corium material in two-dimensional configuration is presented. For the corium mass of 25 kg at 3150 K, the bounding value for static pressure is found to be 7.3 bar. A maximum dynamic pressure pulse impulse of 0.36 psi-sec is also estimated using TNT equivalent methodology. When R. Henry method is applied, the pressure impulse is lower at 0.15 psi-sec. The pressure transducers and temperature probes inside a water chamber are expected to provide valuable data for tracing melt behavior during premixing phase. The temperature of the melt and local void fraction of the premixture are, however, expected to remain unmeasurable due to the limitation of current measurement technique. During the expansion phase, the pressure measurement inside the test section would provide the expanding pressure behavior. Finally, when tests are performed with controlled melt delivery, the explosivity of steam explosion by real corium material would be elucidated.

Acknowledgement

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Fig. 1.jpg (1000x1350x256 jpeg)

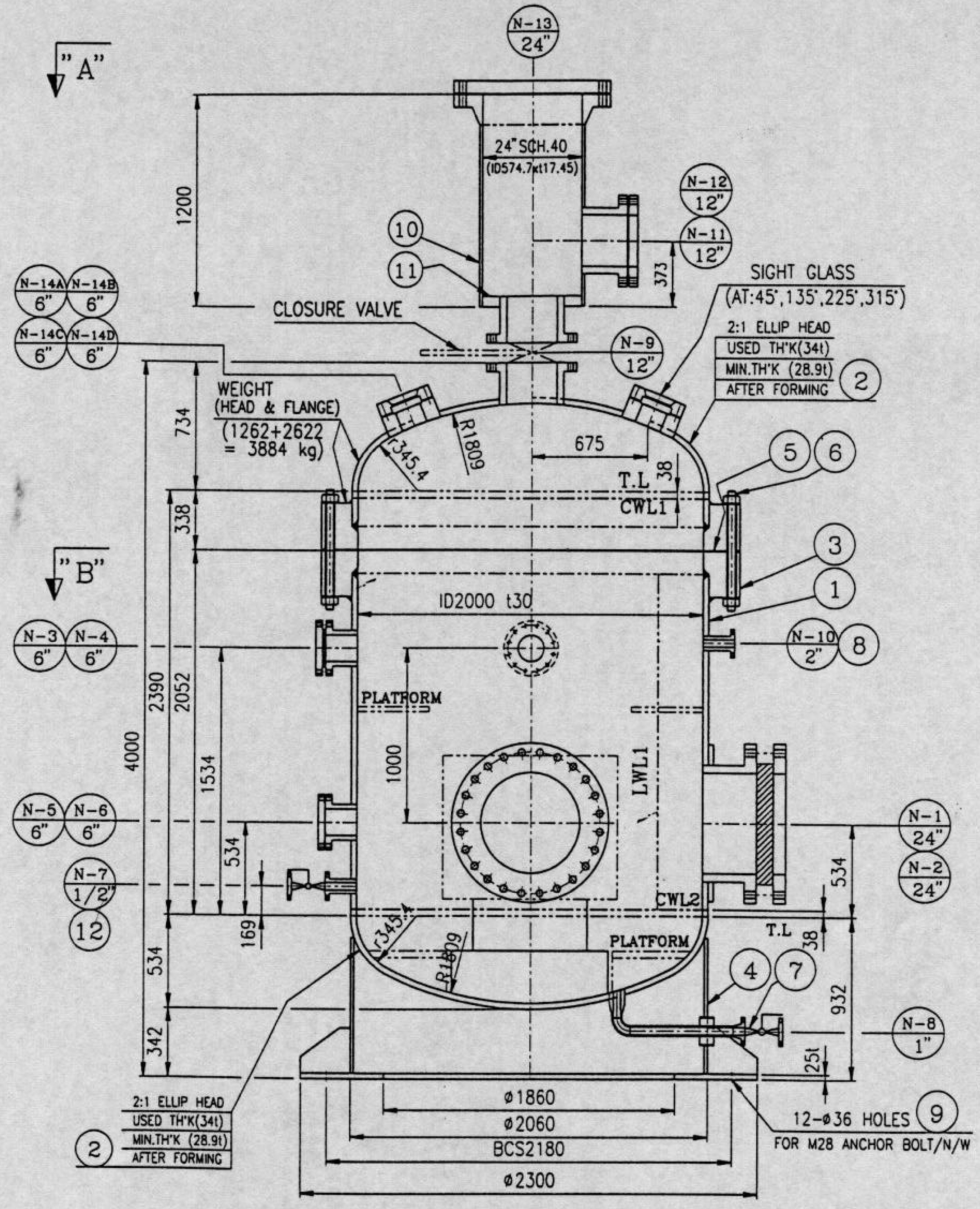
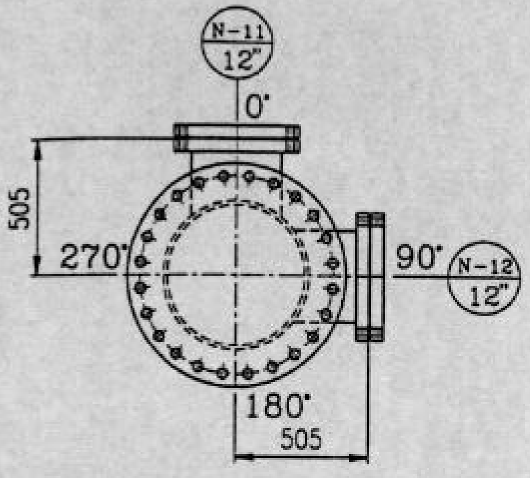
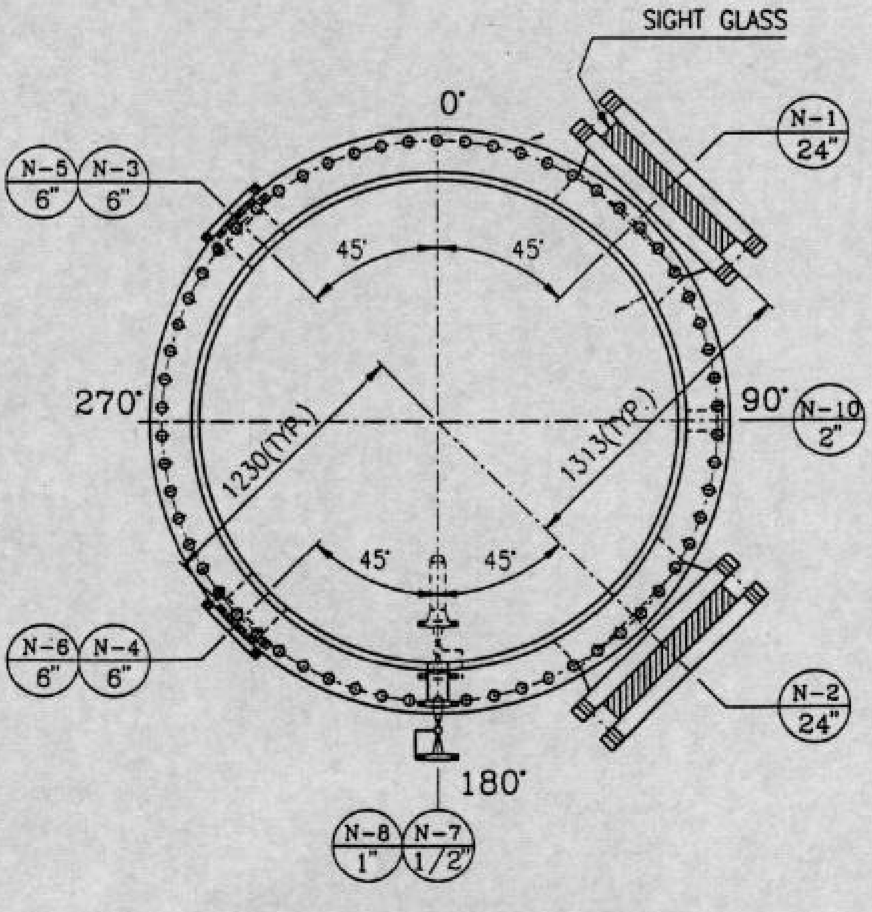


Figure 1. Facility schematic for Fuel/Coolant Interaction Experiment



NOZZLE ORIENTATION
(VIEW "A-A")

Figure 2. Nozzle Orientation for Furnace Chamber



NOZZLE ORIENTATION
(VIEW "B-B")

Figure 3. Nozzle Orientation for Test Section