STEAM EXPLOSIONS

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INTRODUCTION

Steam explosions have been a concern in metal foundries when molten metal is accidentally poured into water, or water poured into molten metal. The rapid vaporization when a fluid comes into contact with another of a significantly different boiling point, leading to a high rate of heat transfer possibly leading to a detonation.

At the University of Illinois, molten lead was poured into a water bucket at a chemistry lecture to demonstrate the effect, leading to an explosion hurting some of the students in the front row; and eliminating the practice.

Liquid natural gas poured into water at room temperature can lead to a detonation followed by a fire as the cloud of gas ignites.

A related process is dust explosion occurring at grain elevators where the dust generated from handling grain at harvest time can be explosively ignited by a spark from a starting engine or a smoking cigarette, leading to destructive and fatal effects.

In the case of a nuclear reactor, the molten mixture of fuel, cladding and structural material designated as "corium" could conceivably interact with the water coolant leading to a destructive steam explosion.

PHENOMENOLOGY

A steam explosion proceeds in several steps:

1. Initially, the molten corium material and water coolant are separate.
2. Coarse mixing, with fragments about 1 cm in size, occurs upon contact with slow heat transfer resulting in heating without pressure increase. The slow heat transfer is caused by the formation of an insulating vapor layer around the fragments.
3. A trigger process occurs resulting from a localized pressure perturbation as from impact, entrapment or a small localized vapor explosion. The shock wave may start at the surface of the vessel.
4. A propagating pressure wave fragments the coarse corium and coolant material leading to an increased surface area, rapid heat transfer from the fine fragments, strengthening the shock wave and leading to the generation of a detonation.

The energy stored in the molten corium material is partially converted in to the energy in the shock wave to the extent of about 1.5 percent. If all the fuel is assumed to react simultaneously, this would result in the Pressurized Water Reactor (PWR) design of an explosion 150 lbs or 70 kgs of TNT equivalent.

It is suggested that spontaneous bubbles formation accompanies the shock formation and contributes to the high rate of heat transfer, and that the fuel gets fragmented into small pieces by the shear forces in the shock wave.

The explosion transmits an impulse into the coolant, accelerating a piston or slug that hits the upper head of the reactor vessel, possibly causing its failure. This failure may manifest itself as the ejection of a missile such as the control rod drive mechanism.

PWRs are equipped with a shield to contain such potential missile generation, preventing it from breaching the containment structure's wall; a low possibility event.

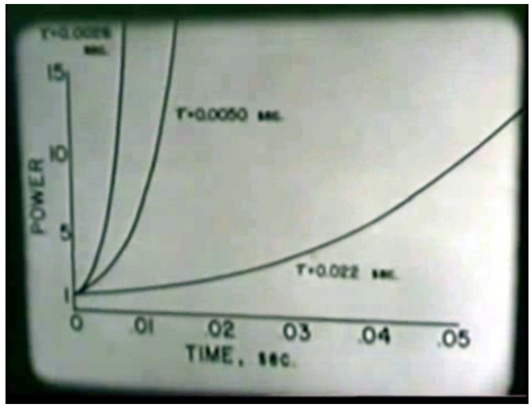

Figure 1. Increase in the power level as a function of time for different reactivity insertions and reactor periods in the Borax safety experiment on a Boiling Water reactor.

Figure 2. Progression of the Borax experiment into a steam explosion in a BWR. Notice the falling debris. Video grabs.

Figure 3. Possible steam explosion in the Unit 3 at the Fukushima accident.

Figure 4. Lava bomb steam explosion at the Kilauea Volcano, Hawaii, July 17, 2018.

ANALYSIS OF A POSTULATED STEAM EXPLOSION

Consider a hypothetical severe accident in Pressurized Water Reactor (PWR). Let us assume that m kgs of corium (molten core material) is released into a pool of water at the bottom of the reactor vessel at a temperature of 3,000 K. Let us further assume that a steam explosion ensues releasing a fraction α of the thermal energy content of the corium material.

The amount of energy released by the steam explosion can be written as:

$$E = m\alpha\beta \; [kg.\frac{J}{kg}],[J] \tag{1}$$

where:
- m is the mass of the fuel [kg]
- α is the fraction of the released thermal energy content of the corium
- β is the thermal energy of the fuel, $[\frac{J}{kg}]$

If the thermal energy is transmitted into the kinetic energy of a water piston that rises up the vessel and hits the top of the vessel, we can estimate its kinetic energy as:

$$E = \frac{1}{2}MV^2[J] \tag{2}$$

where: M is the mass of the water piston [kg]

Applying conservation of energy by equating Eqns. 1 and 2 yields:

$$E = \frac{1}{2}MV^2 = m\alpha\beta \tag{3}$$

The velocity of the water piston is thus given by:

$$V = \sqrt{2\alpha\beta\frac{m}{M}}[\frac{m}{\sec}] \tag{4}$$

After the impact of the water piston with the vessel, the vessel would begin to rise. Applying conservation of momentum yields:

$$MV = \mu\phi \tag{5}$$

where: μ is the mass of the reactor vessel [kg]

ϕ is the vertical speed acquired by the reactor vessel [$\frac{m}{\sec}$]

From Eqns. 4 and 5:

$$\begin{aligned}\phi &= \frac{M}{\mu}V \\ &= \frac{M}{\mu}\sqrt{2\alpha\beta\frac{m}{M}} \\ &= \frac{1}{\mu}\sqrt{2\alpha\beta Mm}\ [\frac{m}{\sec}]\end{aligned} \tag{6}$$

The kinetic energy acquired by the rising vessel would be:

$$\begin{aligned}E_{vessel} &= \frac{1}{2}\mu\phi^2 \\ &= \frac{1}{2}\mu\frac{M^2}{\mu^2}2\alpha\beta\frac{m}{M} \\ &= \frac{M}{\mu}\alpha\beta m[J]\end{aligned} \tag{7}$$

It must be noted that a substantial part of the water piston energy is lost in the impact. If we assume that the kinetic energy acquired by the vessel would be transformed into potential energy raising it to a height h.

Conservation of energy equating the kinetic energy to the potential energy yields:

$$E_{vessel} = \frac{1}{2}\mu\phi^2 = \mu gh = \frac{M}{\mu}\alpha\beta m[J] \tag{8}$$

where: g is the gravity acceleration constant=9.81 [$\frac{m}{\sec^2}$]

The height to which the vessel would rise in the air becomes:

$$h = \frac{Mm}{\mu^2}\frac{\alpha\beta}{g}[m] \tag{9}$$

EXAMPLE

Let us assume the following data:

$$\alpha = 0.03$$
$$\beta = 1.5[\frac{GJ}{mt}]$$
$$m = 50[mt]$$

The energy release of the steam explosion would be:

$$\begin{aligned} E &= m\alpha\beta \\ &= 50mt\frac{1{,}000}{1}\frac{kg}{mt}\times 0.03\times 1.5\frac{GJ}{mt}\frac{1}{1{,}000}\frac{mt}{kg}10^9\frac{J}{GJ} \\ &= 2.25\times 10^9[J] \\ &= 2.25[GJ] \end{aligned}$$

Let the mass of the water piston:

$$M = 10[mt]$$

The speed of the water piston will be:

$$V = \sqrt{\frac{2E}{M}} = \sqrt{\frac{2\times 2.25\times 10^9}{10\times 1{,}000}} = \sqrt{4.5\times 10^5} = 670.8[\frac{m}{\sec}]$$

Let us further take the mass of the vessel as:

$$\mu = 500[mt]$$

The vertical speed of the vessel would be:

$$\phi = \frac{M}{\mu}V = \frac{10}{500}670.8 = 2\times 6.708 = 13.42[\frac{m}{\sec}]$$

The kinetic energy carried by the vessel would be:

$$E_{vessel} = \frac{1}{2}\mu\phi^2 = \frac{1}{2}500\times 10^3\times (13.42)^2 = 4.5\times 10^7[J] = 45[MJ]$$

This kinetic energy would propel the vessel to a height of:

$$h = \frac{Mm}{\mu^2}\frac{\alpha\beta}{g} = \frac{10\times 50}{500\times 500}\frac{0.03\times 1.5\times 10^9}{1{,}000\times 9.81} = \frac{90}{9.81} = 9.17[m]$$

DISCUSSION

Steam explosions are thought to have occurred in the SL1 and Chernobyl accidents and possibly in the Fukushima accident in rector unit number 3.

EXERCISE

1. In a hypothetical steam explosion, assume the following data:

$\alpha = 0.03$

$\beta = 1.5[\frac{GJ}{mt}]$

$m = 50[mt]$

$M = 10[mt]$

1. Calculate the energy release in the steam explosion.
2. Calculate the speed of the rising water piston.
3. If the water piston rises from the reactor water sump in the air outside the pressure vessel, calculate the height to which it would rise in meters.