An Explanation of the Damage in the Fukushima 1F3 Explosion

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INTRODUCTION

Core melt accidents occurred in Fukushima Units 1, 2 and 3 as a result of the Tohoku earthquake and consequential tsunami but the most destructive set of consequences were those that caused the destruction of the entire reactor building above the refueling floor of Unit 3 (1F3). This extensive damage was due to the hydrogen discharged from the containment breach and burned as it mixed with the air in the reactor building.

Plant measurements show that the measured Reactor Pressure Vessel (RPV) and Primary Containment Vessel (PCV) pressures from 05:00 on March 13th through the end of day on March 14th, indicate the water injection rates were insufficient to prevent the core from being uncovered and overheated. Moreover, from 12:01 on March 13th event until the 11:00 explosion in the 1F3 reactor building on March 14th, the water level measurements indicate that there was little or no water in the reactor core over this 23 hour interval. With this extended duration, the hydrogen produced before the 11:00 explosion could be in the range of 600 to 1000 kg.

CONTAINMENT BREACH

The1F3 Mark I Primary Containment Vessel (PCV) pressure history shows that the containment experienced considerable pressurization several times during the accident. Immediately prior to the explosion, a site security video/audio camera recorded three loud metallic bangs over a period of about 4 seconds. In the video, these “bangs” occur after a bright flash is seen on the side of the reactor building at an elevation near the elevation of drywell (DW) head closure flange. This flash is immediately followed by the formation of a dark plume being discharge near the top of the reactor building, which rises vertically upward to a height of about 300 hundred meters and then begins to move off to the south. It is logical that the loud bangs are associated with the failure of the PCV boundary.

The plant data shows a PCV pressure of 5.2 bars at 10:55 and a value of 4.8 bars at 11:02 and then a value of 3.6 bars at the next data point. At this time, both the DW and Suppression Chamber (SC) pressures are considerably above the saturation pressure corresponding to the measured SC water temperatures. Since the failure location is at the top of the DW, the initial depressurization segment would have involved hydrogen, nitrogen and some steam. Since the detailed distribution of the gases is unknown and since hydrogen is the lightest gas in the containment, it is conservative to assume that essentially pure hydrogen could have accumulated in the region near the DW closure head flanges.

THE INFLUENCE OF HYDROGEN DISCHARGE

Single phase H_2 gas flowing from a DW pressure of 5.2 bars to atmospheric pressure would be choked. The initial gas discharge would have flowed into the local regions between the PCV and the reactor building with an upward flow path around the shield blocks and a downward path through the gap between the PCV and the reactor building structure surrounding the PCV.

Three shield plugs cover the DW head with the top plug having the largest diameter (about 12 m) and the bottom having a diameter of approximately 11 m. Each plug is about 1 m thick and rests on a step in the reactor building refueling floor with each having an annular gap that has been measured for the top shield plug after the accident to have a width of about 1 cm [1]. These concrete shield plugs would be levitated by the initial pressurization causing an upward movement that would open a flow path into the refueling bay. The annular gap between the top plug and the refueling floor would become the upward choked flow path. With a diameter of 12 m and a gap of 1 cm, the flow area around the shield plug would be 0.38 m^2.

The Vertical Discharge and Expansion

The critical pressure ratio for a diatomic gas is 0.528 such that a stagnation pressure (P_o) of 5.2 bars would generate a throat pressure (P_t) of 2.7 bars. Assuming that the initial stagnation gas temperature (T_o) was 800 K, an isentropic expansion to the throat would cause a decrease in the gas temperature (T_t) to 667 K. For choked flow, the throat velocity (U_t) would be the sonic velocity at the local temperature, which is:

$$U_t = [\gamma \, R \, T_t / M_{wH2}]^{1/2} \qquad (1)$$

In this equation, the isentropic coefficient γ is 1.4, R is the universal gas constant [8314 J/K/(kg-mol)], and M_{wH2} is the molecular weight of H_2, with the resulting velocity being 1970 m/s. At the throat pressure and temperature, the gas density (ρ_t) is 0.097 kg/m^3. The product [ρ_t U_t] is the critical mass flux which has a value of 191 kg/s/m^2.

This mass flux being discharged through the vertical flow path area gives a mass flow rate of 72 kg/s, or a molar flow rate (N_{H2}) of 36 kg moles/s. Since the mass flow varies with the square root of inverse of the absolute temperature, there is only a weak dependency on the gas stagnation temperature. Also, for choked flow, the discharge rate was independent of the downstream pressure (the refueling bay) unless the pressure would have increased to a 2.7 bars or greater, which is considerably greater than the building walls could withstand.

Continuing the isentropic expansion from the throat to the environment, there would be an additional expansion/acceleration to atmospheric pressure (P_{atm}) that cooled the gas to about 500 K. Moreover, the momentum equation for the expansion from (P_t) to (P_{atm}) and the final gas velocity gas (U_F) are given by:

$$(P_t - P_{atm}) A_t = W_t \{U_F - U_t\} = \rho_t A_t U_t \{U_F - U_t\} \qquad (2)$$

$$U_F = (P_t - P_{atm})/(\rho_t U_t) + U_t \qquad (3)$$

With the pressure differential of 1.7 bars the H_2 would accelerate to a final velocity of 2860 m/s with a density of 0.048 kg/m^3 and a cross-sectional flow area of 0.52 m^2, which is an annular jet with a thickness of 1.4 cm. This would immediately entrain the surrounding air and burn.

Small scale experiments by [2] demonstrate that a H_2 jet discharged into 300 K air within a rectangular channel would self-ignite with a driving pressure of 5.6 MPa The gas temperature was considerably higher for the Fukushima accident so auto-ignition likely occurred at a lower driving pressure. Also, as noted above, the onset of releases from the PCV was a flash at the corner of the Unit 3 reactor building which lasted for a fraction of a second and then disappeared. Since the DW was principally pressurized by hydrogen and steam, the initial release was the highest concentration of hydrogen which ignited with the subsequent discharge having a higher concentration of steam which extinguished the flame. From these observations it can be concluded that with air entrainment H_2 stream likely initiated the following combustion reaction:.

$$H_2 + ½ O_2 \rightarrow H_2O + Q_R \qquad (4)$$

Q_R is the heat of combustion of 2.88 x 10^8 J/(kg-mol) [3]. It is realistic and conservative to assume that the H_2 is completely consumed, which for the H_2 molar flow rate corresponds to an O_2 entrainment rate of 18 kg-moles/s that would produce 648 kg/s of steam. With the air entrainment, there would also be approximately 72 kg-moles/s of N_2 which is a mass flow rate of 2016 kg/s for the nitrogen. With the resulting jet of N_2 and H_2O, the temperature increase of the gas/vapor mixture can be estimated by:

$$\Delta T_g = Q_R N_{H2} / [W_{N2} c_{N2} + W_{st} c_{st}] \qquad (5)$$

where W_{N2} and W_{st} are the respective mass flow rates of N_2 and steam with c_{N2} and c_{st} being the constant pressure specific heats which are 1190 and 2500 J/kg/K respectively. Since the jet is burning essentially at one atmosphere, a constant pressure path is the appropriate representation. The temperature increase from combustion (Eqn. 5) is 2580 K so that the final temperature of the reaction products becomes 3080 K.

With the gaseous reaction products expanding down to essentially atmospheric pressure, the N_2 partial pressure in the jet can be related to the total pressure by:

$$PP_{N2} / P_{atm} = [1 + N_{st} / N_{N2}]^{-1} \qquad (6)$$

At a pressure of 1 bar, the N_2 exhibits a partial pressure of 0.67 bars with the steam partial pressure being 0.33 bars and the density of the high temperature jet is 0.096 kg/m^3 such that the jet with a mass flow rate of 2664 kg/s would have a volumetric flow rate of 27,750 m^3/s. Considering that the building volume above the refueling floor is only about 27,900 m^3, this suggests that the rapidly burning jet would over-pressurize the building within a fraction of a second.

As an aside, this jet burning is not one of the normal hydrogen combustion processes which are characterized as either a deflagration or detonation in which a burn front moves through a hydrogen-air mixture of a given concentration. For the case here, the process is analogous to the operation of a blow torch.

The Rise of the Vertical Plume

Comparing the vertical plume discharged from 1F3 refueling floor seen in the security camera video to the height of the 120 m vent stacks, shows that the plume rising to a height of at least 300 m. Assuming pure hydrogen flow, the jet with a mass flow rate of 72 kg/s and a velocity of 2860 m/s had a momentum of about 2.1 x 10^5 N. This high velocity annular jet emitted from the refueling floor entrained air to burn and further entrained air due to the velocity difference between the jet and the surrounding air. Hence, the jet would have continued its rapid ascent until the entrainment process slowed the plume to a velocity comparable to translational wind velocity. Assuming a wind velocity (U_{atm}) of the order of 10 m/s (22 mph) and further considering that the entrained mass flow rate (W_{ent}) was far greater than the initial jet mass flow rate (W_t) such that the plume density at the end of the rise is essentially that of the air, the mass flow rate for the vertical rise can be calculated as a constant momentum process expressed by:

$$W_t U_F = W_{ent} U_{atm} \qquad (7)$$

From this expression, W_{ent} is 2.1 x 10^4 kg/s and with a plume velocity of 10 m/s, the cross-sectional flow area at that location would be 2.1 x 10^3 m^3, or a plume radius of about 26 m. Entrainment of the surrounding air by jets of vapors and gases have a radial growth velocity that is approximately 8% of the transport velocity [4] which produces a linear increase of the jet diameter as the plume rises. The jet outer radius increased from 6 m to 26 m which would require a height of about 250 m. Adding the elevation of the refueling floor (40 m), this would be an elevation of approximately 290 m. This is consistent with the observed vertical height at which the plume began to move off to the right because the wind velocity became the dominant mode for the plume transport. If the wind velocity is taken to be 5 m/s, the radius of the entrained jet would increase to 51.5 m and the vertical height of the plume would become 569 m

THE INFLUENCE OF UNIT 3 ON UNIT 4

The security camera video shows a bright flash on the side of 1F 3 that faces 1F4. Immediately following the flash, there is an explosion in the refueling bay with the vertical expanding upward. An examination of the post-accident photographs for 1F4 shows that the upper superstructure on the reactor building north face has flattened toward the south, away from 1F3. Such damage is likely due to the shockwave that radiated from 1F3

Considering that the volumetric discharge rate of 27,750 m^3/s onto the Unit 3 refueling floor, the pressure difference required to overcome the inertia of the surrounding air can be expressed by:

$$\Delta P = 3/2\ \rho_\infty\ u_r^2 \tag{8}$$

where ρ_∞ is the density of the surrounding air (~ 1 kg/m^3) and u_r is the radial growth velocity imposed by the volumetric discharge rate. Assuming a hemispherical growth from the discharge site with a radius of 6 m, the imposed radial velocity is 123 m/s which would have required a ΔP of 2.3 x 10^4 Pa (~2 psi) to support the growth rate. Shock wave overpressures decrease approximately with the inverse radius squared [5]. Extrapolating this overpressure from the 6 m radius to the 1F4 reactor building about 85 m away shows that the peak overpressure would have decreased to 114 Pa (0.017 psi) by the time it impacted the building. With a surface area of 144 m^2 for the uppermost panel on the north face, the impact force from the shock wave would have been approximately 16,400 N (~3350 lbf). This is a non-trivial load on this architectural panel that has only minimal structural support.

CONCLUSIONS

These calculations for the discharge, combustion, spreading and the rising of the discharge plume above the 1F3 reactor building result in the following conclusions.

(1) Calculations for the critical flow rate around the shield blocks suggest a choked flow area of about 0.38 m^2. This is consistent with the post-accident observations of the shield block condition.

(2) The H_2 combustion processes would occur at essentially constant pressure. The volumetric discharge onto the refueling floor of burning hydrogen gas would overpressure the structure sufficient to cause failure of the building panels and walls above the refueling floor and blowout all of the panels between the structural members for the entire building.

(3) For the upward rising vertical plume, entrainment of the surrounding air causes the expansion and slowing of the plume, which can be represented as a constant momentum process. The initial momentum is the product of the H_2 mass flow rate and the gas velocity after it has expanded to atmospheric pressure. The rapid upward ascent continued until the plume rise velocity decreased to a value comparable to the wind velocity, about 10 m/s. Evaluating the height needed for the plume velocity to slow to10 m/s value yields a plume height of about 300 m, which is consistent with the security video observations.

(4) These observations show that the damage to the 1F3 refueling floor can be explained with the discharge and combustion of the order of 100 kg of hydrogen discharged from the PCV for a fraction of a second.

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