Energy of the Explosion of Unit 3 Reactor Building of Fukushima Daiichi

Takashi Tsuruda
Akita Prefectural University
Yurihonjo, Akita, Japan

1 Introduction

Three reactor buildings of the Fukushima Daiichi Nuclear Power Plant exploded following the Great East Japan Earthquake in March 2011, owing to core overheating after the station blackout. The two explosions of units 1 and 3 were recorded by a camera. Expanding flame, gas, and fragments are observed in these recorded images [1, 3–5]. Based on the fragment trajectories, the estimated explosion pressures of units 1 and 3 are 27 kPa and 193 kPa, respectively [1]. It is known that a pressure buildup of 50 kPa results in major structural damage to a concrete building [2]. The estimated explosion pressure of 27 kPa for unit 1 is within this pressure limit for major structural damage, while the estimated explosion pressure of 193 kPa for unit 3 is significantly higher than the pressure limit.

To understand the explosion of the unit 3 reactor building, a detailed investigation of the reactor building is required. Owing to the high radiation level of the unit 3 reactor building, a limited investigation has been carried out. Recently, Tepco released a series of images from within the unit 3 building. These images show the first, second, and third floors of the reactor building. The images of the first and second floors show cases of damage caused by the external pressure buildup.

These images show that a uniform pressure buildup occurred in the unit 3 reactor building, which indicates that a space of constant volume experienced pressure buildup resulting from temperature increase or the injection of fluid from a source. One of the causes of this is the combustion of hydrogen, and another is the leakage of high-pressure fluid from the containment vessel in the reactor building.

If the normal pressure is assumed to be sufficiently small compared with the pressure in the containment vessel, then the strong shock-wave propagation model may be applicable [6]. By assuming a similarity solution and measuring the expanding gas front over time [7], [8], the explosion energy of the unit 3 reactor can be calculated [9].

2 Picture Record

The expanding gas from the unit 3 reactor building is shown in figures in a previous study [1]. By plotting the height H above ground level of the expanding gas from the unit 3 reactor building against time to the

Correspondence TTsuruda@akita-pu.ac.jp

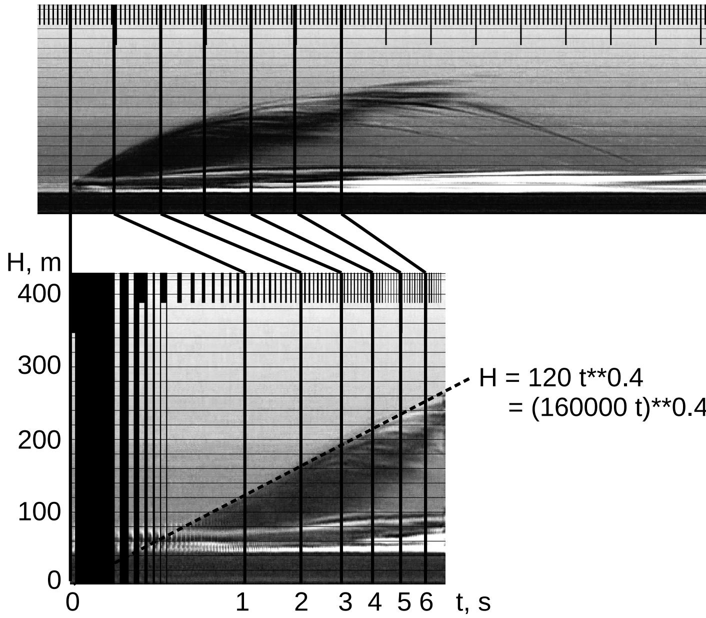

Figure 1: H–t diagrams of expanding gas from the unit 3 reactor building.

power of two fifths $t^{\frac{2}{5}}$, a line appears along the expanding gas front following the explosion near the unit 3 reactor building in Figure 1. The height H of the expanding gas front is shown in Table 1.

Table 1: Height of expanding gas front over time

Time, t, s	Height, H, m	$t^{\frac{2}{5}}$	$H/t^{\frac{2}{5}}$
1	120	1	120
2	160	1.31	122
3	190	1.55	123

This line indicates that the explosion pressure is considerably higher than the normal pressure, and thus, it is possible to obtain the explosion energy with appropriate similarity assumptions for an expanding blast wave of constant total energy [6].

This line crosses the ground level H = 0 at t = 0. This crossing point indicates that the explosion source for unit 3 is located at H = 0 at t = 0.

Now, a radially expanding shock wave is assumed, and the following similarity scaling is employed:

$$pressure, \frac{p}{p_0} = y \tag{1}$$

$$density, \frac{\rho}{\rho_0} = \Psi \tag{2}$$

$$radial\ velocity, u = R^{-\frac{3}{2}}\phi_1 \tag{3}$$

where R is the radius of the shock wave forming the outer edge of the disturbance, and p_0 and ρ_0 are the pressure and density of the undisturbed atmosphere, respectively. If r is the radial coordinate; $\eta = r/R$; and f_1, ϕ_1, and Ψ are functions of η, then

$$The\ equation\ of\ continuity, \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r} + \rho(\frac{\partial u}{\partial r} + \frac{2u}{r}) = 0 \tag{4}$$

$$The\ equation\ of\ motion, \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{p_0}{\rho}\frac{\partial y}{\partial r} \tag{5}$$

$$The\ equation\ of\ state\ for\ a\ perfect\ gas, (\frac{\partial}{\partial t} + u\frac{\partial}{\partial r})(p\rho^{-\gamma}) = 0 \tag{6}$$

where γ is the ratio of specific heats.
The conditions at the shock wave $\eta = 1$ are given by the Rankine–Hugoniot conditions as follows:

$$\frac{\rho_1}{\rho_0} = \frac{\gamma - 1 + (\gamma + 1)y_1}{\gamma + 1 + (\gamma - 1)y_1} \tag{7}$$

$$\frac{U^2}{a^2} = \frac{1}{2\gamma}(\gamma - 1 + (\gamma + 1)y_1) \tag{8}$$

$$\frac{u_1}{U} = \frac{2(y_1 - 1)}{\gamma - 1 + (\gamma + 1)y_1} \tag{9}$$

where ρ_1, u_1, and y_1 represent the values of ρ, u, and y immediately behind the shock wave, and $U = dR/dt$ is the radial velocity of the shock wave. For large y_1, u_1 represents 83 % of the radial velocity of the shock wave for $\gamma = 1.4$, as shown in Eq. (10). The expanding gas front after the shock wave may be traced instead of the invisible shock wave in the images. In this case, the velocity of the shock wave is 1.2 times u_1.

$$\frac{u_1}{U} = \frac{2}{(\gamma + 1)} \tag{10}$$

The resulting equations are

$$\frac{\partial R}{\partial t} = AR^{-\frac{3}{2}} \tag{11}$$

$$E = B\rho_0 A^2 \tag{12}$$

$$B = 2\pi \int_0^1 \psi\phi^2\eta^2 d\eta + \frac{4\pi}{\gamma(\gamma - 1)}\int_0^1 f\eta^2 d\eta \tag{13}$$

where E is the total energy of the disturbance of the kinetic energy, and B is a function of γ. In the case that $\gamma = 1.4$, $B = 5.36$. By determining A from the line appearing along the expanding gas front after the

explosion, the total energy E can be estimated.
By integrating Eq. (11) with respect to time, $R^{\frac{5}{2}}$ is found to be proportional to the time t, as shown in Eq. (14).

$$\frac{2}{5}\,R^{\frac{5}{2}} = A\,t \tag{14}$$

The height of the expanding gas H after the explosion is shown in meters in Eq. (15), with the time in seconds.

$$H = 120\,t^{\frac{2}{5}} = (160000\,t)^{\frac{2}{5}} \tag{15}$$

Assuming that the height of the expanding gas H is equal to the radius of the expanding shock wave R, it follows that

$$A = \frac{2}{5}\,160000 = 64000 \tag{16}$$

With the density of non-disturbed air being $\rho_0 = 1.25$ kg/m^3, the total energy E_0 in Jules is

$$E_0 = 5.36 \times 1.25 \times 64000^2 = 2.74 \times 10^{10} \tag{17}$$

Recalling that the velocity of the shock wave is 1.2 times u_1, the total energy is 2.49 times this value.

Considering the presence of the five reactor walls of the building, namely the bottom, south, east, north, and west walls, the expansion gas is directed only in the upward direction. The contributed energy E_1 is more than $\frac{1}{6}$ of the total energy E_0, owing to the confinement walls.

$$E_1 = 2.74 \times 10^{10} \times 2.49/6 = 1.14 \times 10^{10} \tag{18}$$

3 Energy Sources

There are two energy sources for the unit 3 explosion. One is hydrogen in the reactor building, and the other is the heated fluid in the suppression pool. The five systems in the reactor building are described in Table 2. Systems 1, 2, 4, and 5 are in single phases, while system 3 is in two phases: gas and liquid.
The released energies during the adiabatic expansion of gas for systems 1 and 5 are estimated using Eq. (19):

$$E_a = \frac{p_1 V_1}{\gamma - 1}[1 - (\frac{p_0}{p_1})^{\frac{\gamma-1}{\gamma}}] \tag{19}$$

where p_1, V_1, and p_0 denote the pressure, volume of the system, and ambient pressure. For system 1, a maximum pressure of 0.15 MPa (abs) is assumed for the reactor building. The net volume of system 1 is smaller than this volume with the volumes of systems 2 and 3 and other components subtracted.
The estimated energy quantities are shown in Table 3. These quantities are the maximum available energies.

These energies are smaller than the contributed energy E_1.
The energy E_w in the water in the suppression chamber is estimated using the enthalpy values of $h_l(423K) = 632.19$ kJ/kg and $h_l(373K) = 419.17$ kJ/kg for saturated water, the enthalpy of $h_v(373K) = 2675.6$ kJ/kg for water vapor [10], and the mass of water 2.98×10^6 kg [11]. Assuming a leakage of 1 kg of water at 423 K into the environment with $p_0 = 101$ kPa(abs), a fractionχ of the water remains after $(1-\chi)$ of the water vaporizes owing to excess enthalpy [12]. The conservation of energy is expressed as

$$h_l(423K) = \chi\, h_l(373K) + (1-\chi)\, h_v(373K) \tag{20}$$

$$\chi = \frac{h_l(423K) - h_v(373K)}{h_l(373K) - h_v(373K)} = 0.906 \tag{21}$$

The volume of the expanded water vapor V_v is

$$V_v = (1-\chi)\frac{2.98 \times 10^6}{18 \times 10^{-3}} \times 22.4 \times 10^{-3} \times \frac{373}{273} = 4.76 \times 10^5 \tag{22}$$

The energy E_w of the water vapor expansion at p_0 is

$$E_w = p_0\, V_v = 4.81 \times 10^{10} \tag{23}$$

The energy E_w is four times larger than the contributed energy E_1.

Table 2: Volumes, pressures, and temperatures of systems in the reactor building

System	Volume, V_1, m^3	Pressure, p_1,MPa(abs)	Temperature, T,K
1 Reactor building	87,584($46 \times 34 \times 56$)	0.1	300(typical)
2 Dry well	4,240	0.5	433
3 Suppression chamber	3,160	0.5	423
4 *Water in suppression chamber	2,980	0.5	423
5 *Gas in systems 2 and 3	4,420	0.5	423

Table 3: Accumulated energies of systems

System	Accumulated Energy, E_a, J
1 Reactor building	$\leq 3.60 \times 10^9$
5 *Gas in systems 2 and 3	$\leq 2.04 \times 10^9$

4 Conclusions

The explosion of the unit 3 reactor building was examined in terms of a similarity solution. Plotting the height of the expanding gas from the unit 3 reactor building against the two-fifth power of time shows a line along the expanding gas front following the explosion near the reactor building. This line indicates the presence of a strong blast wave. The gradient of the line along the expanding gas front gives a constant that depends on the energy of the explosion, the air density, and a non-dimensional parameter that depends only on the ratio of specific heats. The obtained total energy is larger than the accumulated energies of the gas-phase systems in the reactor building. The accumulated energy in the liquid-phase system in the reactor building is considerably larger than the energy of the observed explosion of the unit 3 reactor building. The observed explosion of the unit 3 reactor building is a result of the release of the accumulated energy in the liquid-phase system. The observed flame close to the unit 3 reactor building appears to result from the burning of released hydrogen.

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