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A4 5 Tidal energy and Thermal Runaway: Fukushima Disaster

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Abstract

This paper quantifies two energetic components of the 11 March 2011 Fukushima Daiichi disaster. First, modelling the incoming tsunami as a shallow-water gravity wave we estimate an energy transport of $\sim 1.9 \times 10^{10}$ J m^{-1} per wave cycle; over a 1 km shoreline segment this totals $\approx 1.9\times10^{13}$ J, about 4.5 kilotons of TNT. Secondly, we estimate the radioactive decay heat generated by one of the reactor cores in the immediate aftermath of its emergency shutdown. We found that even one day after shutdown, the core still produced over 8 MW of thermal energy, highlighting the critical need for continuous cooling and the catastrophic consequences of its failure.

Introduction

On March 11, 2011, the Tōhoku earthquake triggered a catastrophic tsunami that struck the coast of Japan. One of the most severely affected sites was the Fukushima Daiichi Nuclear Power Plant. While the reactors successfully performed an emergency shutdown (SCRAM) following the earthquake, the subsequent tsunami overwhelmed the sea walls of the plant, which disabled the backup diesel generators responsible for powering the vital cooling systems [1].

This paper aims to quantify the physics of this disaster from two perspectives. First, we will estimate the gravitational potential energy of the tsunami wave before its landfall at the plant. Second, we will assess the ongoing hazard within the reactor core by estimating the rate of radioactive decay heat released in the hours and days following shutdown, which ultimately resulted in the core meltdown.

Gravitational Potential Energy of the tsunami

We model the tsunami as a shallow-water gravity wave [2] of peak-to-trough height H and amplitude $A = H/2$ propagating over constant depth h. Following [3], vertically integrating the kinetic and potential energy densities through the water column yields an energy per unit horizontal area of sea surface,

$$E_{\text{area}} = \tfrac{1}{2}\rho g A^2, \tag{1}$$

where $\rho = 1{,}025$ kg m^{-3} [4] is the density of the sea-water, at standard conditions of 20 °C and 1 atm, and g is the gravitational acceleration; for linear gravity waves, the kinetic and potential contributions are equal on average. Thus, the energy conveyed past a unit length of shoreline by one wave cycle of period T is,

$$E_{\text{crest}} = E_{\text{area}}\, c\, T = \tfrac{1}{8}\rho g H^2 \sqrt{gh}\, T. \tag{2}$$

Radioactive Decay Heat

When a reactor is shut down, fission stops almost instantly, but the decay of radioactive fission products [5] continues to release energy known as *decay heat*. Although this heat decreases over time, it can still cause serious overheating or core melting without sufficient cooling.

Decay heat $P(t)$ can be approximated by the Way–Wigner formula [6] for time t (in seconds) after shutdown:

$$P(t) = 0.0622\, P_0\, t^{-0.2} \tag{3}$$

where P_0 is the reactor's steady-state thermal power before shutdown. This formula provides a good estimate of the decay heat for times ranging from a few seconds to several months after shutdown. However, this form assumes a sufficiently long reactor operating time, making corrections for finite operation negligible.

Tsunami Energy

Post-event analysis indicates the largest incident tsunami height at the plant of $H = 15$ m and reported tsunami periods span $T \approx$ 10–40 min [7]. For a representative estimate, we adopt $T = 25$ min. Adopting the general geological definition of the continental shelf, which extends to a depth of approximately 200 m [8], as the representative depth (h) for the Fukushima shelf, the shallow-water phase speed [9] is given as,

$$c = \sqrt{gh} \approx 44 \text{ m s}^{-1}.$$

Equation (2) yields,

$$E_{\text{crest}} \approx 1.9 \times 10^{10} \text{ J m}^{-1}.$$

For a shoreline frontage of width W, the energy per cycle becomes,

$$E = W E_{\text{crest}}.$$

For $W = 1$ km,

$$E \approx 1.9 \times 10^{13} \text{ J},$$

which is approximately 4.5 kilotons of TNT [10].

The presented values are based on linear, nonbreaking propagation over an assumed uniform depth. This approach omits the energy redistribution and dissipation caused by nearshore transformation and bore formation at the seawall. Therefore, these results should be interpreted as first-order offshore-to-shoreline energy budgets, not as detailed impact loads.

Decay Heat

We will base our calculation on the plant's Unit 1 reactor, a Boiling Water Reactor with a thermal capacity (P_0) of approximately 1380 MW [11]. Using Equation 3, we can estimate the decay heat at various times after shutdown: 1 minute, 1 hour, and 1 day, as shown in Table 1.

Time (s)	**Decay Heat (MW)**
60	37.8
3600	16.7
86,400	8.84

Table 1: Estimated decay heat power output from Fukushima Daiichi Unit 1 after shutdown.

This shows that even a full day after the reactor was turned off, it was still generating over 8 MW of heat, enough thermal energy to power thousands of homes continuously. This persistent internal heating, combined with the loss of cooling caused by the tsunami, made the core meltdown inevitable.

Conclusion

Our calculations highlight the immense physical scale of the Fukushima disaster. The tsunami wave carried an extraordinary amount of potential energy, sufficient to overwhelm the engineered coastal defences protecting the nuclear power plant, which triggered the uncontrolled release of the reactor's internal decay heat.

The external energy of the tsunami disabled the critical systems required to dissipate the reactor's residual heat. Although decay-heat power declined rapidly after shutdown, the sustained thermal generation within the confined core was sufficient to initiate one of the most severe nuclear accidents in history.

References

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