CONF-720906--4

INTERACTION OF THE STRUCTURE OF A SELECTED REACTOR CONTAINMENT
WITH NEAR KILOBAR NUCLEAR WEAPON SHOCKWAVES IN AIR

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Civil Defense Research Project

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March 1972

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In the course of a program to estimate the effects of nuclear weapons on nuclear power reactors,¹ it was desired to determine the magnitude of an incident external air shock required to subject the core of a selected reactor to a pressure pulse exceeding 300 atm.

Structurally Important Elements of the Reactor Containment

In the reactor design chosen for investigation the core is immersed in a cylindrical tank of liquid coolant (sodium in the prototype, water in the model). The reactor and primary loop consist of a 14.5 m diameter, 12 m deep tank of sodium in which are immersed the core, primary coolant pumps, intermediate heat exchangers, and associated flow baffling and support structures (see Fig. 1). The insulated tank is suspended in a steel-lined concrete cavity below grade in the reactor building. An argon-filled gap of about 30 cm separates the tank from the wall of the cavity. The sodium level above the core is 2 m below the bottom of a 2 m thick reinforced concrete deck whose top is at grade. The deck is penetrated by plugs

Figure 1. Reactor and Sodium Tank, Vertical Section

supporting the intermediate heat exchangers (IHX), primary pumps, and the reactor shield plug. The structural design criterion of the shield plug and deck is to withstand 7 atm under the plug.

The deck area, containing the shield plug, the six IHX's, and some refueling equipment and facilities, is enclosed in the refueling cell (Fig. 2). This cell is about 12 x 30 x 20 m high inside and has 120 cm thick walls and roof. It is designed to withstand 1/3 atm internally. The refueling cell, the primary pump drives, and miscellaneous handling equipment are enclosed in a containment building shown in Fig. 2.

Chronology of Weapon-Structure Interaction at High Overpressures

We have determined that a 300 atm or greater pressure pulse in the sodium tank is produced by the weapon blast wave and overpressure deforming the reactor deck and punching it down into the sodium tank. When this deformed deck impacts the liquid sodium, a shockwave starts through the sodium and has progressed to the reactor core in a few milliseconds. The shock strength at the core is determined, in part, by the velocity of the

deck as it impacts the sodium as well as the deck shape at the point of impact.

At the maximum distance a nuclear weapon can be detonated and still subject the reactor core to a pressure pulse of 300 atm or more, the most destructive weapon effect is the blast wave. Ionizing radiation will be excluded from the core by the reactor biological shielding. For detonation close to the reactor, radiation from the thermal pulse will have diffused only a few centimeters into the outer concrete shell before the arrival

Figure 2. Reactor Containment Building, Vertical Section

of a near-kilobar shock. When detonation takes place at larger distances (<700 m for 1-MT), breakaway will have occurred and the shock wave arrives before the fireball.

It is assumed for this analysis that the attacking weapon would be ground burst and that the shock front incident on the building would be vertical, moving in a direction parallel to the ground. The first massive structure that the shock front would encounter would be the 1.2 m thick reinforced concrete walls of the refueling cell located above the sodium tank as shown in Figs. 1 and 2. At overpressures greater than 170 atm the structural strength of most of the reactor buildings can be ignored to a first approximation and the structure regarded as a collection of masses to be accelerated. A 1-MT detonated less than 300 m from the reactor will produce overpressures in this region.^{2,3} Therefore the refueling cell wall would shear at its base as the shock front impacts its face and the wall would move as a more or less intact unit.

The hypersonic flow field behind the initial weapon shock front sets up a standing shock front about two meters in front of the incident side of the refueling cell wall.⁴ The resultant high pressure region created between the standing shock and the cell wall produces pressures up to fifteen times the weapon overpressure. For example, if the incident weapon shock pressure from a surface burst 1-MT is 800 atmospheres, then the initial bow shock standoff distance is about 2 m and the reflected pressure in this region is about 12000 atmospheres.

Deformation of the concrete deck above the sodium tank takes place as the sheared-off refueling cell wall is pushed across the deck. Although the reinforced concrete deck is deformed as if its tensile and shear strengths can be neglected compared to the forces produced by the reflected overpressure, the ultimate strain of the reinforcing steel and steel deck liner (blast shield) is generally not exceeded. In fact, the deformed liner has been recovered after experiments and its shape compares well with the calculated deck deformation. The effects of this blast loading on the reactor structure were calculated using the procedures outlined by Glasstone² and weapons effects calculated by Hillendahl.³

In less than 15 msec from the time a 1-MT weapon has detonated 300 m from the reactor, the deformed deck will impact the sodium starting a pressure pulse toward the reactor core. A simplified sketch of a vertical section through the calculated position of the deformed deck and pressure

pulse shortly before the pressure pulse reaches the core is shown in Fig. 3.

The pressure pulse at the reactor core as a function of incident weapon overpressure is plotted in Fig. 4. The two curves presented in Fig. 4 represent (a) the pressure calculated at the bottom centerpoint of the full scale reactor core; and (b) the pressure calculated and measured for the scaled approximate model of the design reactor. If deck punch out does not occur, the pressure pulse at the reactor core is negligible. In this case, the sodium is pressurized relatively slowly by the high pressure gases behind the weapon shock front through breaches in the tank deck.

Experimental Verification

The object of the experiments was to stimulate the blast effects of megaton size nuclear weapons on the important structural elements of the reactor.

The technique used was to construct approximately 1/50 scale models of the important structural parts of the reactor. Plane explosive charges of the required energy per unit area (Table 1) were arranged at distances from the models to produce incident shocks at the model in the pressure range of interest. The pressure was measured in the model tank in order to estimate the pressure developed in the core of the prototype. To keep the quantity of explosive required to a minimum, the assembly was enclosed in an expendable shock tube.

Figure 5 is a drawing of three views of the experimental assembly for Shot F-3. To facilitate construction, several design parameters were scaled approximately and the pressure measuring transducer was off the line of symmetry.

The important structural elements of the reactor are the fuel cell, simulated by the flue tile, the main deck, modeled by a 5 cm thick reinforced (4%) concrete slab, the blast shield modeled by a 3 mm steel plate, and the sodium tank, modeled by a 1/50 scale sheet metal water tank.

Shock pressure near the center of the tank was measured by Kistler 607L quartz pressure transducers enclosed in a protective casing. A similar transducer measured the external shock pressure from the explosion. The concrete biological shield around the sodium tank is modeled by a 25 cm length sawed from a 30 cm ID reinforced concrete pipe. The explosive used was either 100% blasting gelatin or a commercial 75% gelatin dynamite. The explosive was removed from its wrappers and packed into a 50 x 50 x 5 cm box with masonite faces and wood frame. To ensure high-order detonation, a

Figure 3. Vertical Section Through Reactor Model Used in Calculations

Figure 4. Pressure Pulse at Reactor Core Vs Weapon Overpressure

layer of Du Pont "Detasheet-C" was laid over the explosive. The charge was initiated from the top center.

To prevent the explosion gasses from penetrating the soil under the charge and crushing the concrete pipe from the side, a 10 cm thick steel slab 50 cm long by 30 cm wide was placed under the charge. A 5 cm wood block between the explosive and the steel prevented damage to the steel.

The sides and top of the shock tube were 15 cm layers of sand enclosed in plywood boxes. The back of the tube was closed by a stack of sandbags. The space between the sandbags and the charge was filled with loose sand. This general type of construction was used to avoid injury to personnel.

The tank, water, concrete pipe, internal and external pressure transducers prior to backfill are shown in Fig. 6. The main deck and model refueling cell wall (flue tile) are on the edge of the hole.

After Shot F-1 the deck was deformed, but intact. No pressure was measured inside the tank. The incident pressure at the fuel cell wall was estimated at 130 atm in this shot. Figure 7 shows the fragments of the main deck, the deformed blast shield, and the tank after Shot F-2. The center of the main deck has been punched out. Pressure measured in the core was about 340 atm. There was not steel slab under the explosive on this shot.

From Shot F-3 pressure at the fuel cell wall was 1100 atm, and about 400 atm in the core. The blast shield was severely deformed and shoved all the way to the bottom of the tank.

Table 1 is a summary of results for Shots F-1, F-2, and F-3.

These experiments have provided indispensable check points for mathematical models. The results are compared with the calculations in Fig. 4.

Figure 5. Scale Model HE Test of Experimental Assembly

Application of Present Results to Other Reactor Designs

The qualitative results presented in this paper should apply to other designs of a sodium cooled reactors which employ a sodium tank than the design under consideration. All these designs will probably have a heavy reinforced concrete deck above the sodium tank whose purpose is, in part, to contain a possible accidental core excursion. For convenience, the fuel reloading cell would be located directly above the reactor on this deck. If the refueling cell does not cover the entire deck area, a strip of the deck above the sodium tank will be subjected to the high pressure region for a relatively long time while the refueling wall initially accelerates. Therefore, a similar weapon-structure/interaction sequence would apply to other tank type reactor designs.

The simplest design change to lessen the effects of a weapon is to make the refueling cell large enough that the deck above the sodium tank is entirely inside the cell. In this case, by the time the fuel cell wall has moved enough to uncover any appreciable section of the deck above the sodium tank, the weapon overpressure as well as the reflected overpressure has dropped below those values that punch out the deck. For example, if the incident weapon overpressure is 800 atm, by the time the fuel cell wall has moved its own width and just started to uncover the tank deck, the weapon over-

Figure 6. Experimental Layout Prior to Backfill and Explosion

pressure has dropped to 320 atm. By the time the wall has uncovered as much of the deck as the design under consideration leaves uncovered, the overpressure has dropped to 100 atm. These pressures are just barely sufficient to punch the deck out. For incident weapon overpressures less than 800 atm, by the time the deck is uncovered, the overpressures are too low to cause punch through.

Other design changes considered but proved less effective in reducing the pressure pulse at the core were (1) changing the deck thickness, (2) changing the fuel cell wall thickness, or (3) changing the sodium level in the tank.

Figure 7. Experimental Layout After Experimental Shot F-2

Summary and Conclusions

The interaction of a selected reactor containment with near kilobar nuclear shockwaves in air has been examined both experimentally and via calculations. In the reactor design chosen for investigation, the core is immersed in a cylindrical tank of liquid sodium coolant 15 meters in diameter, 10 meters deep. The tank is covered by a reinforced concrete deck 2 meters thick, with its top at ground level. On top of the deck is a rectangular refueling cell with walls 120 cm thick. We have determined that this complex structure interacts with the weapon shock in the following way:

The flow associated with the incident shock forms a high pressure stagnation region behind the bow shock developed in front of the vertical fuel cell wall. This pressure shears the deck at the edge of the concrete around the sodium tank, and accelerates the deck down into the sodium tank. Impact of the deck on the liquid produces the pressure pulse in the tank. Several 1/50 scale models of the sodium tank, deck, and fuel cell wall were subjected to near-kilobar shocks produced by explosive charges. The incident pressure on the deck and pressure produced in the center of the tank were measured.

The measured pressures, and the shapes of recovered models of the steel blast shield under the deck, were used to verify a mathematical model of the blast-structure interaction. Machine computations were used to explore the effects of variations in design parameters of the structure. It is estimated that for the original design an incident weapon shock exceeding 800 bars is required to produce a pressure pulse of 400 bars in the core.

Acknowledgments

This research was sponsored by the Division of Biology and Medicine, U. S. Atomic Energy Commission, at the Oak Ridge National Laboratory under contract to the USAEC. Opinions in this article are the authors' own and do not necessarily reflect those of the Oak Ridge National Laboratory or the U. S. Atomic Energy Commission.

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TABLE 1. EXPERIMENTAL RESULTS

Shot No.	Energy Density Kcal/cm ²	Standoff ⁽¹⁾ Inches	Calc. Pressure at cell wall (2) Atm	Pressure at core, Atm		Transit Time
				Water in tank	Sodium in tank	
F-1	1.65	22	130	Negligible		---
F-2	7.08	14	850	340	510	350μ Sec
F-3	7.45	12	1100	408	610	320μ Sec

(1) Distance from rear face of charge to cell wall.

(2) Extrapolated from measured pressure at 16-inches in F-3 of 800 Atm.