N71-28821

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HIGH SPEED IMPACT TESTS OF A MODEL NUCLEAR REACTOR CONTAINMENT SYSTEM

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TECHNICAL PAPER proposed for presentation at
American Nuclear Society National Meeting
Boston, Massachusetts, June 13-17, 1971

E-6361

HIGH SPEED IMPACT TESTS OF A MODEL NUCLEAR REACTOR CONTAINMENT SYSTEM

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SUMMARY

In a mobile nuclear reactor, fission products must be contained even in the event of a severe impact such as would occur in the crash of an aircraft powered by a nuclear engine or a suborbital abort of a nuclear power supply launched by a rocket. In both cases impact against a hard surface may occur with velocities up to 1000 ft/sec.

Five impact tests have been conducted on models of reactor containment systems. These models mock-up the impact energy absorbing characteristics of the reactor, shield and containment vessel. The reactor was simulated by a 12 inch solid steel ball. The gamma shielding was simulated by steel saddles and the neutron shielding was simulated by either water or wood (simulating LiH). The stainless steel containment vessel was 2 feet in diameter. The models weighed from 350 lbs to 1305 lbs. Their impact velocities varied from 241 to 580 ft/sec. Impact occurred against a 15,000 lb reinforced concrete block.

Results of the tests are as follows:

1. No leaks were detected nor cracks observed on any of the models.

2. Even though the deformation (expressed as a function of sphere radius) of the 2 foot diameter hollow sphere was slightly higher than predicted the test did verify that the deformations are not significantly affected by vessel diameter.

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3. The model with the radiation shield/energy absorber outside the containment vessel had a diametral strain of only 5% at an impact velocity of 580 ft/sec.

4. The highest deformations and diametral strains occurred in the model which had water inside the vessel mocking up a neutron shield.

The deformations and diametral strains recorded on all models indicated that the models should be able to sustain impact velocities of 800 to 1000 ft/sec without containment vessel rupture.

INTRODUCTION

Future applications of nuclear energy will require the use of mobile nuclear reactors. Mobile reactors can be classified in two ways. First, those that supply power to large low speed earth surface vehicles and second, those that supply power to high speed, high altitude vehicles. Examples of the first category are ships, submarines and air cushion vehicles. Airplanes and launch vehicles would be in the second category.

In all mobile reactors, fission products must be contained with the same level of confidence as in stationary powerplants. This is true not only in their normal modes of operation but in the event of a crash impact accident. The most severe impact would occur in accidents involving the high speed, high altitude vehicles. Both a suborbital abort of a nuclear power supply launched by a rocket and a nuclear powered airplane accident can result in impact velocities of 800 to 1000 ft/sec. Also, in both cases, direction of impact and type of impact surfaces are unknown prior to impact.

One method for containing fission products under these severe conditions is to put the reactor in a containment vessel and design the containment vessel and its contents to absorb the impact energy without rupturing the containment vessel. The energy of impact would be absorbed by deformation of the vessel and internal components such as the shielding and reactor parts.

Work is being performed at LeRC to answer the following questions: What design principles can be used to permit containment vessels to survive high speed impacts without leaking? How much containment vessel deformation will a given velocity produce? How much deformation can a containment vessel tolerate before it ruptures? How do the contents of the containment vessel affect deformation?

Morris correlated experimental deformation and failure data on 3/4 inch to 4 inch o.d. hollow spheres (refs. 1 and 2) which had been impact tested as part of an isotope space power program (ref. 3). Some of these spheres were impacted to 700 ft/sec without rupture. The deformation correlation equation when extrapolated to large diameter containment vessels, for example a 15 foot diameter vessel, indicated that the deformation of large vessels should be similar to that for small vessels. The failure correlation equations suggested that failure was a function of the wall thickness of the vessel and that larger vessels should be made of several layers. These correlations did not consider the effects of internal components. Experimental tests were necessary to evaluate these effects.

Five mock-up models of a reactor containment system have been designed and tested. The designs represent a reactor surrounded by radiation shielding and a containment vessel, both of which were designed to absorb impact energy. The reactor containment vessel models mock-up a reactor system that would be used to power a three million pound gross weight air cushion vehicle or a $1\frac{1}{2}$ million pound nuclear airplane. The containment vessel for these applications would be about 15 feet in diameter and the reactor shield containment vessel package would weigh about 450,000 pounds.

Tests were conducted at the Sandia Sled Track in Albuquerque, New Mexico. They were impacted at speeds from 241 to 580 ft/sec. This report describes the models, test set-up, and presents preliminary results of the tests.

DESCRIPTION OF TESTS

The impact tests were conducted on a two rail rocket sled track 5000 feet long. The model remained stationary and was impacted by a concrete block. A typical test set-up is shown in figure 1. The model to be tested is placed between the track rails on a styrofoam plastic pedestal. The sled is shown at the point of impact. It consists of a cage and a 15,000 pound reinforced concrete block cube $4\frac{1}{2}$ feet on a side and is accelerated by an array of surplus HVAR rockets to the desired impact speed. The cage in front of the concrete block catches the model after impact to prevent damage to the track and model. A door in front of the cage closes within 0.2 second after impact. It is released by explosive bolts triggered by the initial contact of the model with the concrete. The concrete block, cage and model are decelerated after the impact by a water brake system.

Two movie cameras were mounted at the impact point (see fig. 2). They operated at a speed of 7000 frames/sec. One had two exposures per frame providing 14,000 exposures per second. Three additional camera were mounted further down the track. These cameras operate at 2000 frames/sec. Their purpose is to record second impacts within the cage. Also, a 400 frame/sec and a real time movie was taken from a tower showing the sled at ignition, accelerating to impact, impact and subsequent braking.

Instrumentation on the model was limited to the high speed movies. The impact velocity was measured by two sensors on the track.

TEST MODEL MOCK-UP AND SIMULATION

The test models were designed to mock-up a 6 foot diameter 300 Mw reactor surrounded by shielding which in turn is surrounded by a 15 foot diameter containment vessel. Piping, valves etc. were not mocked-up. This reactor containment vessel system is capable of powering a $1\frac{1}{2}$ million pound aircraft.

The containment vessel diameter was 2 feet. Standard hemispheres were available at this size thus minimizing fabrication costs. Its material was 304 stainless steel. This material provides good properties for impact survival, i.e., high strength, high ductility, good notch toughness, and good weldability. The wall thickness was selected at 5/8 inches. This thickness maintained about the same diameter to wall thickness ratio desired for the 15 foot diameter full scale design.

An 11 inch diameter spherical steel ball inside the containment vessel was intended to simulate the effect a nuclear core would have on the containment vessel at impact due to internally impacting the shielding and containment vessel. The ratio of the model core to containment vessel diameter was about the same as in the full scale design. The reactor model material simulated the equivalent density of the full scale core. Some conservatism resulted from simulation of a reactor core because of the incompressibility of the steel ball. Since the ball did not deform, all of its impact energy contributed to other impact effects.

Between the solid steel ball and the containment vessel various materials were placed to simulate gamma and neutron shielding. The gamma shielding was simulated by steel saddles and the neutron shielding was simulated by either water or wood (simulating LiH).

Test Model Description

A total of five models were built and tested. These models are shown schematically in figure 3. They are described in the following paragraphs.

1 - Hollow Sphere Model

The first unit to be tested was a hollow sphere 2 foot in diameter with a wall thickness of 5/8 inches (ref. 4). It was fabricated from two 304 stainless steel hemispheres welded together and weighed 350 pounds.

2 - Metal Shield Model

The second unit to be tested contained an 11 inch diameter steel ball, simulating the reactor core, surrrounded by steel saddles (ref. fig. 4) which simulated a heavy metal shielding material. This was then surrounded by the containment vessel of the same size used for the hollow sphere model. The total weight of this model was 980 pounds.

The saddles in the containment vessel have a 78% void fraction.. This model simulated a metal-water shield with the water removed.

3 - Lithium Shield Model

This model contained an 11 inch diameter steel ball for core simulation surrounded by mahogany wood for simulating the strength properties of lithium hydride. Since the wood is anisotropic the wood grains were oriented in the radial direction. Surrounding the wood was a 2 foot diameter containment vessel fabricated in the same manner as the hollow sphere model. The total weight of this model was 705 pounds.

4 - Metal Water Shield Model

The fourth unit that was tested was identical to unit no 2 - Metal Shield Model - except the void spaces in the saddles were filled with water. A 7% void was left in the containment vessel to simulate the void of helium coolant lines that exist in the full scale design. The unit weighed 1110 pounds. This test was run to study the case where the water shielding was not removed prior to impact.

5 - Inner and Outer Lithium Shield Model

The final unit impacted contained a steel ball simulating the core surrounded by wood which simulated lithium hydride as in test model no. 3. This was then surrounded by a 2 foot diameter containment vessel. Outside the containment vessel a 6 inch spherical layer of wood was placed to simulate additional lithium hydride shielding. Then a layer of 1 inch fiber glass layup plastic was wrapped around the wood to provide some impact resistance and constraint for the wood on the exterior. The model was 3 foot in diameter and weighed 1305 pounds.

TEST RESULTS

The five models were impacted at speeds from 241 to 580 ft/sec against a 15,000 lb concrete block. They all were impacted by the concrete in a similar manner and were captured in the cage except model no. 3, the "Lithium Shield Model." This model will be discussed separately.

Impact Sequence

A typical sequence of the high speed motion pictures taken during the impact of model no. 2 is shown in figure 5. The film speed was 7000 frames/sec. The impact velocity was 413 ft/sec. The vertical lines are the bars of the catcher box. The white surface is the concrete block. At impact the debris shown are concrete chips and dust. The straining of the sphere at the impact surface of the concrete block can be seen in figures 5(e) to 5(j). Models no. 1, 4, and 5 performed in similar manner. Model no. 4 which was water filled endured the most deformation and diametral strain. Model no. 5 was partially obscured on the high speed film by splinters and debris from the wood and plastic outer layers and from dust and fragments of the concrete block.

Post Impact

Figure 6 shows the post impact condition of the models. The "Hollow Sphere Model" shown in figure 6(a) was impacted at a velocity of 392 ft/sec.

It had an impacted face as expected. The concave surface was characteristic of the 3/4 to 4 inch diameter spheres in reference 3.

The "Metal Shield Model" shown in figure 6(b) is the model shown in the sequence shots. The impact face in this case was flat with the exception of the center of the face. Here the steel ball on the inside caused some deformation. This model was sectioned to look at the arrangement of the components on the inside. Figure 7 shows the sectioned unit. Thermowax was poured into the unit prior to sectioning so that the saw blade would not disturb the interior components. The saddles are at the impact face leaving a void at the top of the unit. (The model was filled completely with saddles prior to impact.) The steel ball crushed the saddles between it and the impacted face. The deformation on the impacted face and the integrity of the containment vessel wall can be seen in this photograph.

The "Metal Water Shield Model," figure 6(d) was impacted at 467 ft/sec. This model suffered the most strain. In the other models the bulk of the deformation occurred in the hemisphere that received the impact. In this case deformation occurred in both hemispheres. The reason for the equal deformation was that the impact caused the water to generate a hydraulic pressure and thus transmitted the forces throughout the sphere. When the hydraulic pressure reached about 8000 psi pressure forces caused the containment vessel stress to exceed its yield strength and permanent deformation occurred throughout. The diametral increase that occurred was 21%.

The highest impact velocity, 580 ft/sec, occurred on the fifth unit - the "Inner and Outer Lithium Shield Model." Its post impact picture is shown in figure 6(e). Part of the wood covering the outside is still on the top of the containment vessel. None of the plastic surrounding the wood remains. The deformation was limited primarily to the hemisphere in the impact direction. The outer layer of wood absorbed part of the impact energy.

Model 3 - Lithium Shield Model

This model was set to be impacted at 500 ft/sec. However, an error in the wiring of the rockets resulted in an impact velocity of 241 ft/sec. In addition, the model bounced out of the cage, and along the ground adjacent to the track. It finally came to rest after impacting a ground electrical station.

Figures 8 and 9 show this electrical station before and after impact. The important part of this impact was the deflection of a 4 × 4 inch angle iron 3/8 inch thick. It can be seen in figure 9 and is shown closer in figure 10. It was hypothesized prior to this test, that an impact against a sharp object of this type could result in a "spear type" penetration. The speed at impact was 160 ft/sec. An examination of the containment vessel showed no penetration, or tendency to penetrate at this speed. In addition, the impacts from bouncing along the ground resulted in only superficial scratches.

Concrete Block - Post Impact

The impacts also caused damage to the rocket sled cage and concrete block. This damage results in a form of energy absorption. Excepting models no. 1 and 3 all concrete blocks were cracked after each test thus requiring new blocks. Figure 11 shows the concrete block and cage after the test of model no. 5 which impacted at 580 ft/sec.

Leak Check on Models

Leak checks were performed on all the models before and after impact. This check was as follows:

Helium pressurize containment vessel to 200 psig.

Plastic bag entire assembly.

Check for helium leak by probing interior of plastic bag for 2 hours.

No leaks were detected nor cracks observed on any of the models after impact.

TEST MODEL DEFORMATION

The test models were measured after impact. The two deformation parameters of primary interest are δ/r and $\Delta D/D$ (ref. fig. 12). δ is the amount of permanent deflection that occurred and is defined for each model. The ratio of δ/r was one of the parameters used in the study of references 1 and 2.

The parameter $\Delta D/D$ is the diametral strain. It was measured at the location of maximum diameter. With the exception of model no. 4, the "Water Lithium Shield Model," this maximum diameter occurred in the hemisphere in the impacted direction as shown schematically for each unit in figure 12. In the case of model no. 4 the maximum diameter occurred at the equator (see fig. 6(d)).

Figure 12 contains a table listing δ/r and $\Delta D/D$ values for each of the models tested. Their values increase with increasing velocities with the exception of model no. 5. In this case, wood was placed around the o.d. of the containment vessel to simulate lithium hydride shielding. The resultant diametral strain on the containment vessel was only 5% even though the model was impacted at a high velocity.

The large differences in the design of the models together with the limited number of test points makes it difficult to compare each model on the basis of δ/r and $\Delta D/D$. For example, the wood surrounding model no. 5 absorbs energy. This is apparent when comparing the δ/r and $\Delta D/D$ values of model no. 5 with the values of models 1, 2, and 3. A second example is the water filled model (no. 4). In this case the deformation was transmitted throughout both hemispheres by the hydrostatic pressure of the water thus making its values of δ/r and $\Delta D/D$ different from those whose deformations occurred largely in the impacted hemisphere.

As designs are generated and tested the values of δ/r and $\Delta D/D$ should contribute substantially to the indication as to whether the model is close to the point of failure and to what magnitude various shielding materials absorb the impacted energy. In the meantime, the impacted models are being studied to determine the maximum strain in the vessel wall, estimate how near this strain is to an impact rupture strain, estimate the velocity that could produce a ruptured vessel and design a method for reducing localized points of high strain.

CONCLUDING REMARKS

Five impact tests have been conducted on models of a reactor shield containment system. The models were 2 and 3 feet in diameter and weighed from 350 to 1305 lbs. Their impact velocities varied from 241 to 580 ft/sec. Impact occurred against a 15,000 lb reinforced concrete block.

Results of the tests are as follows:

1. No leaks were detected nor cracks observed on any of the models.

2. The deformation (the ratio of deflection to radius) of the 2 foot diameter hollow sphere was slightly higher than predicted by the correlating equation obtained from 3/4 to 2 inch hollow sphere impact data. But it verified one of the major predictions of the correlation - that the deformations are not significantly affected by vessel diameter.

3. The model with the radiation shield/energy absorber outside the containment vessel had a diametral strain of only 5% at an impact velocity of 580 ft/sec.

4. The highest deformations and diametral strains occurred in the model which had water inside the vessel mocking up a neutron shield. The model was impacted at 467 ft/sec and the surface of the sphere was deflected towards its center a distance equal to 76% of the original mean radius of the sphere. The diameter of the sphere (measured parallel to the impact surface) increased by 21%.

5. The model which had wood inside the vessel mocking up a lithium hydride shield, escaped from the catcher cage, bounced across the desert, and struck a power cabinet. The secondary impacts that occurred resulted in only superficial scratches even though a 4 × 4 × 3/8 inch angle iron was impacted directly on the end at 160 ft/sec.

6. The higher speed impact tests caused the concrete block to crack with a resultant damage to the model catcher cage.

The deformations and diametral strains recorded on all models indicated that the models should be able to sustain impact velocities of 800 to 1000 ft/sec without containment vessel rupture or leak.

REFERENCES

1. R. E. MORRIS, "Correlation of Small Sphere Impact Deformation Data and Extrapolation to Larger Spheres," TM X-2067, NASA (1970).
2. R. E. MORRIS, "Empirical Correlation of Small Hollow Sphere Impact Failure Data Using Dimensional Analysis," Tm X-52874, NASA (1970).
3. J. C. SIMONIS and C. E. STONEKING, "A Study of Impact Effects of Spherical Shells. Part II: A Theoretical and Experimental Study of the Response of Spherical Shells to Impact Loads," SC-CR-67-2540, Sandia Labs. (December 1966).
4. R. L. PUTHOFF and T. DALLAS, "Preliminary Results on 400 ft/sec Impact Tests of Two 2-Foot Diameter Containment Models For Mobile Nuclear Reactors," TM X-52915, NASA (1970).

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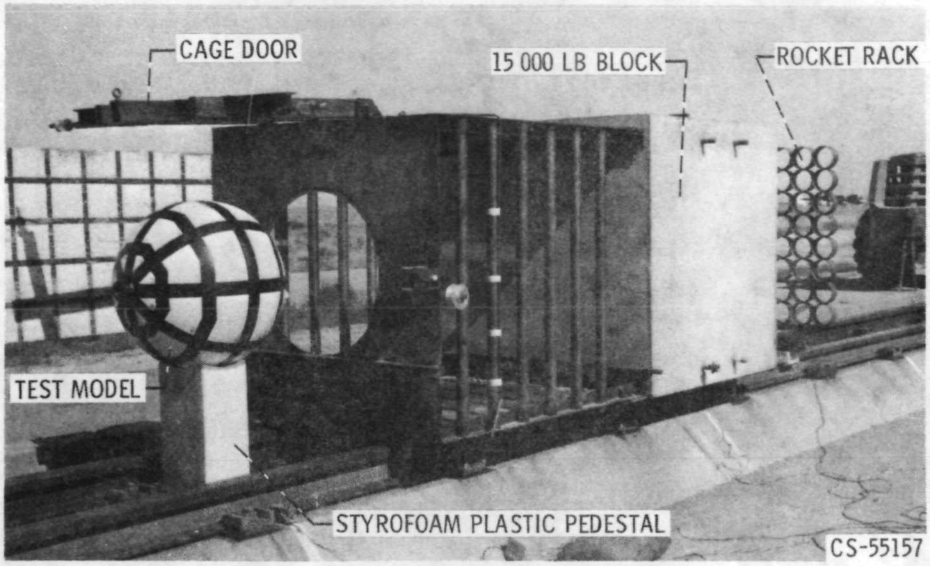

Figure 1. - Sled at point of impact.

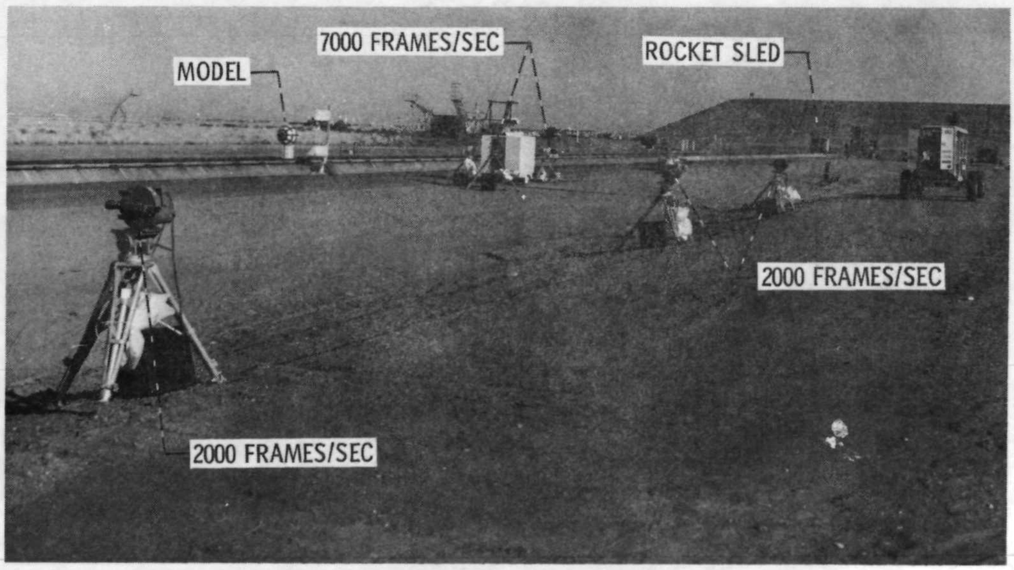

Figure 2. - High speed movie cameras at point of impact.

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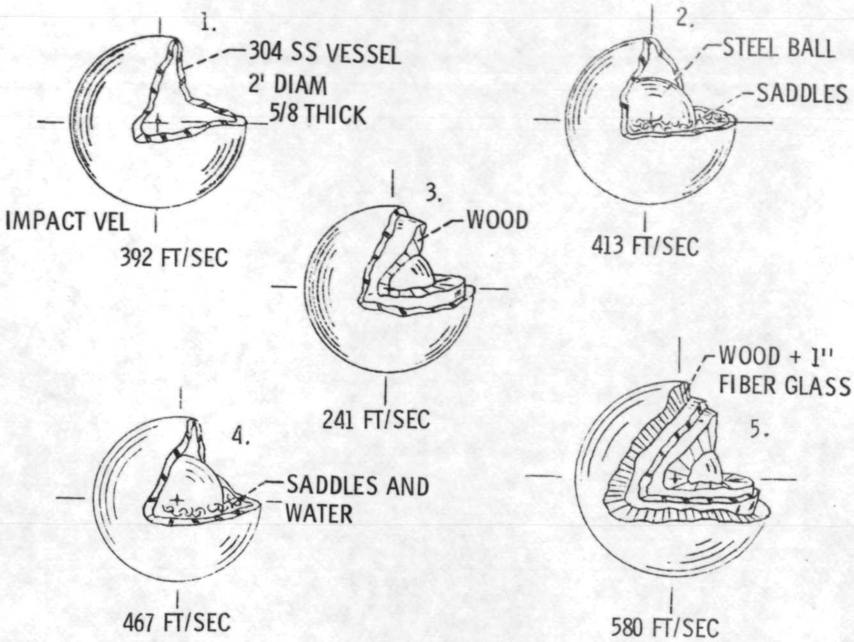

Figure 3 - Impact models

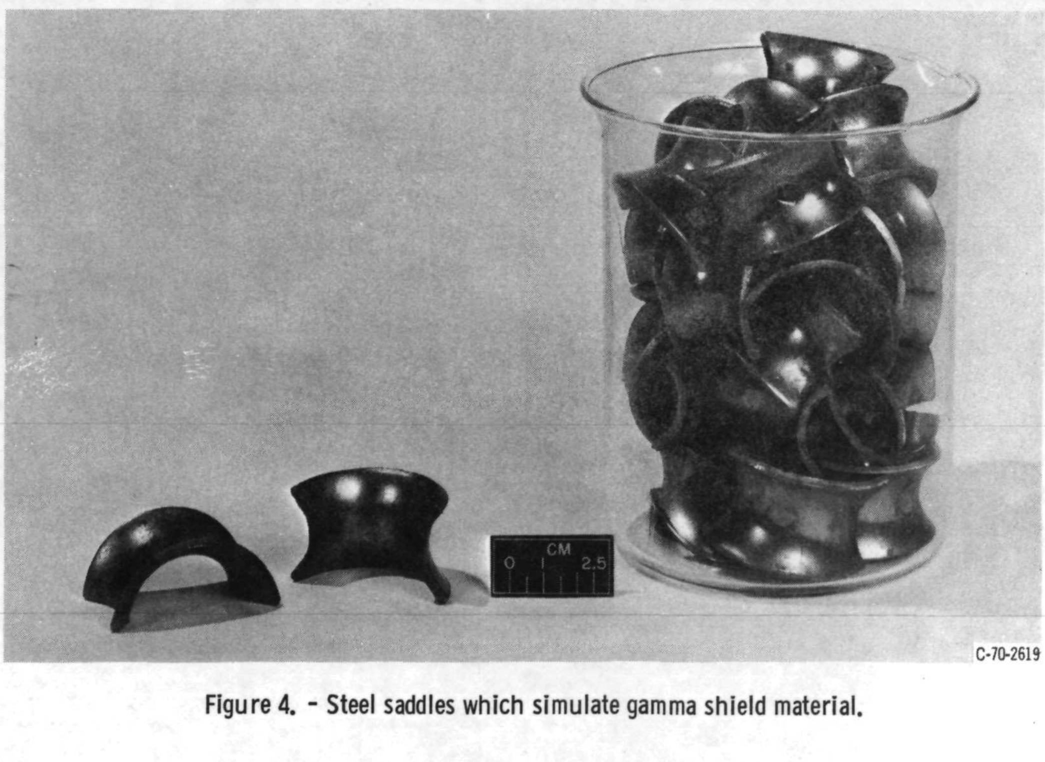

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Figure 4. - Steel saddles which simulate gamma shield material.

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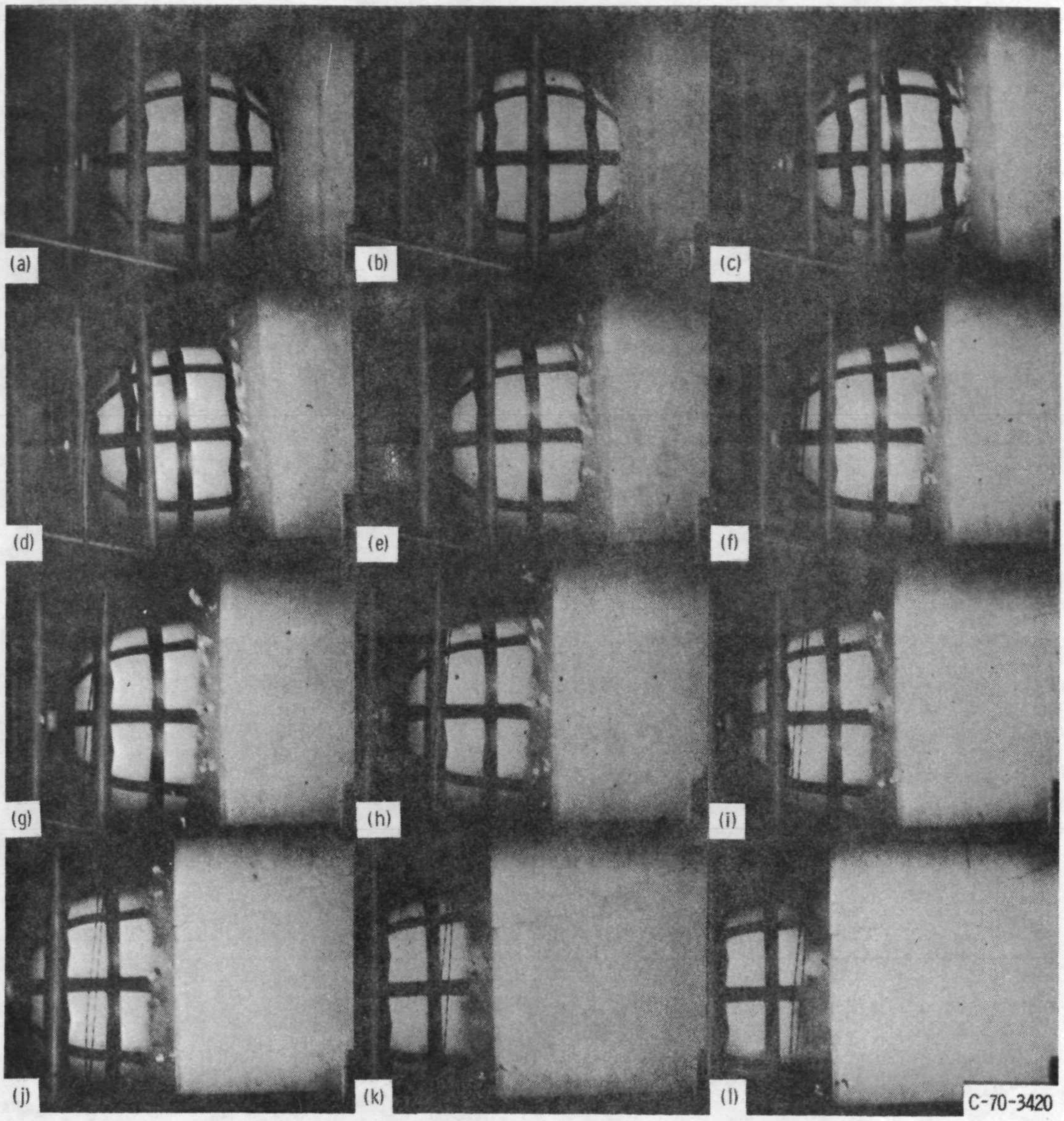

Figure 5. - Sequence photographs at impact of containment system model No. 2. Time between frames = 1.3×10^{-4} sec.

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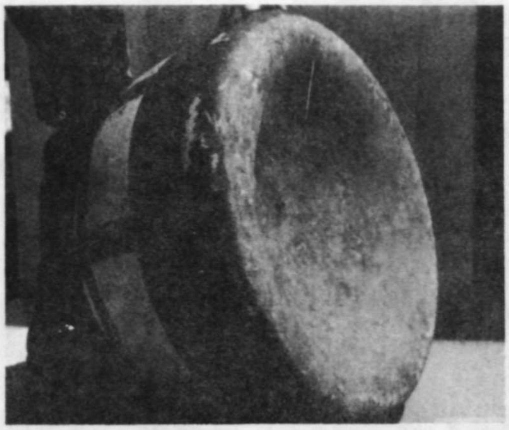
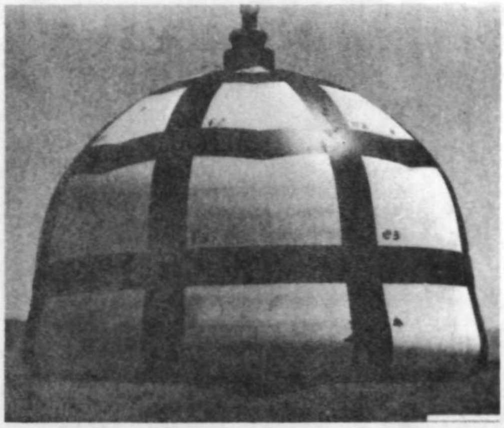
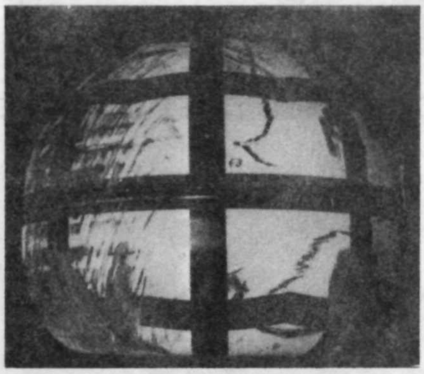


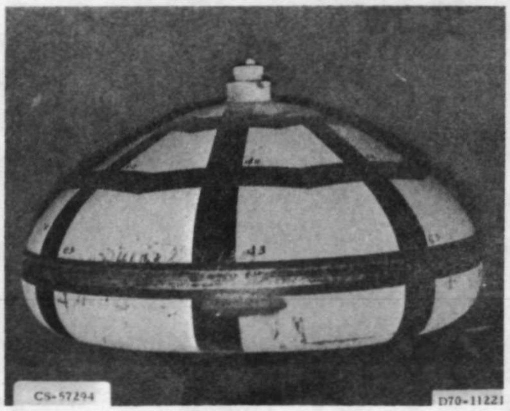
(A) HOLLOW SPHERE MODEL.



(B) METAL SHIELD MODEL.



(C) LITHIUM SHIELD MODEL.



(D) METAL-WATER SHIELD MODEL.

(E) INNER AND OUTER LITHIUM SHIELD MODEL.

Figure 6. - Post impact photographs of models.

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Figure 7. - Sectioned photograph - No. 2 metal shield model.

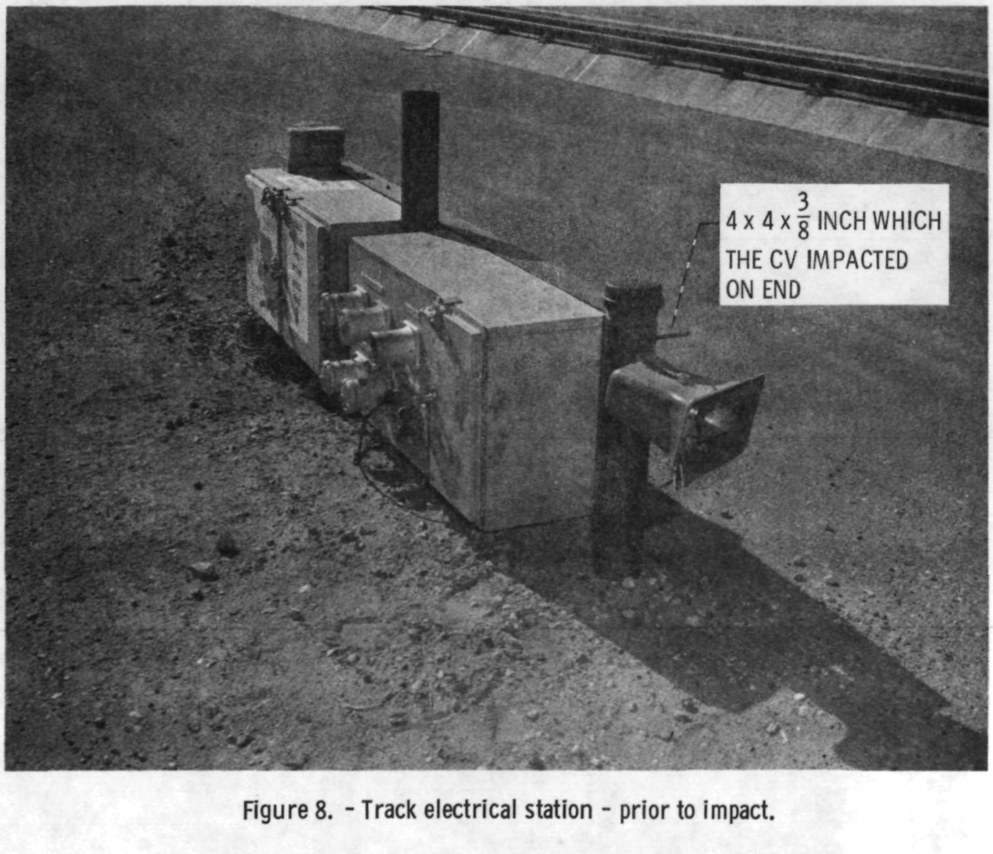

Figure 8. - Track electrical station - prior to impact.

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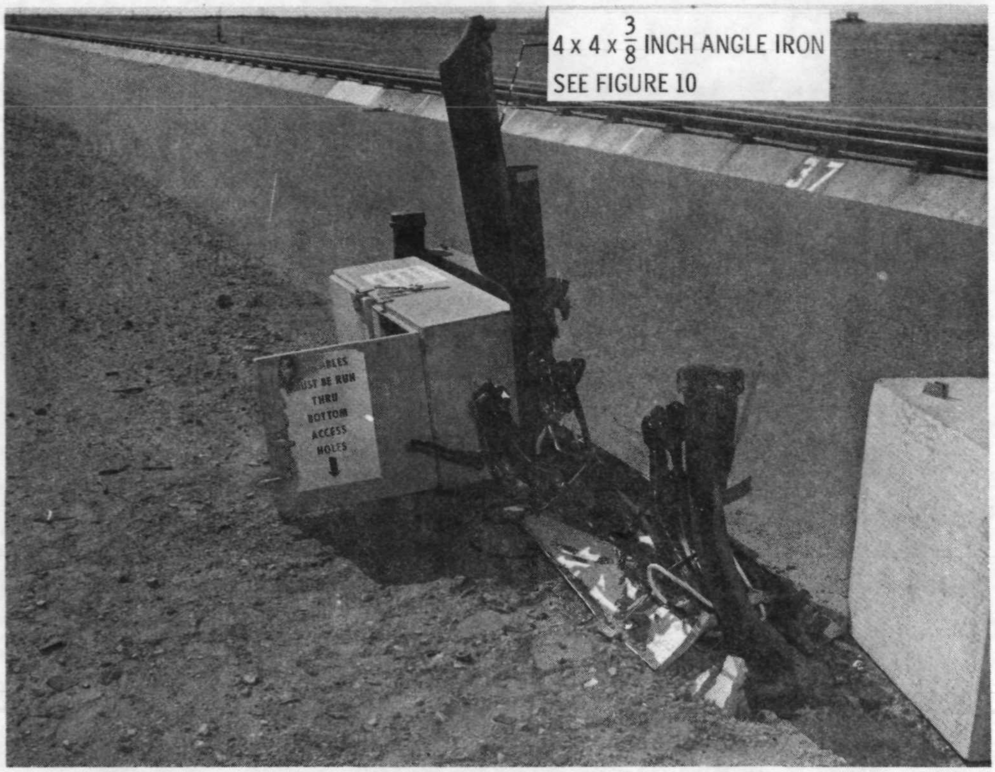

Figure 9. - Track electrical station - post impact.

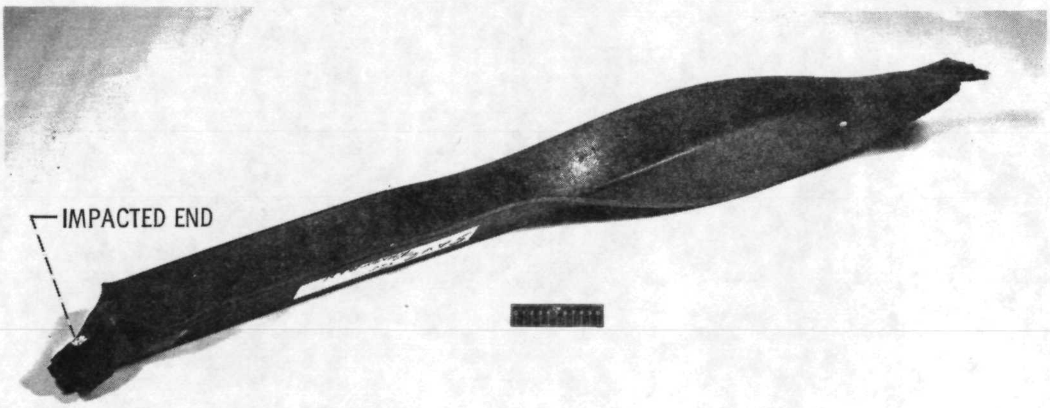

Figure 10. - 4 x 4 x $\frac{3}{8}$ inch angle iron.

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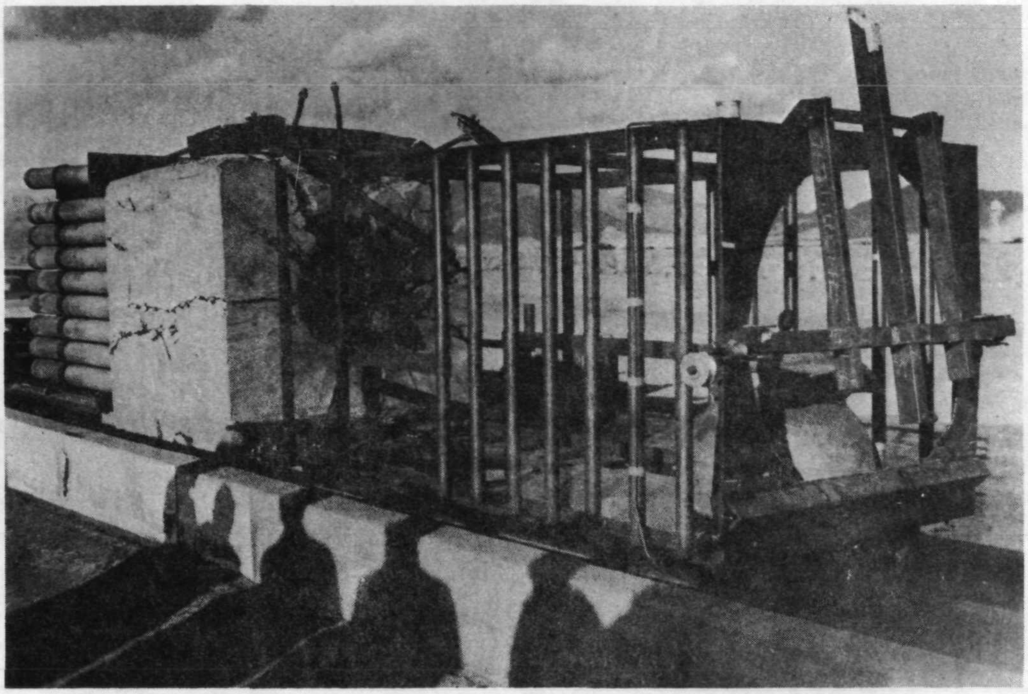
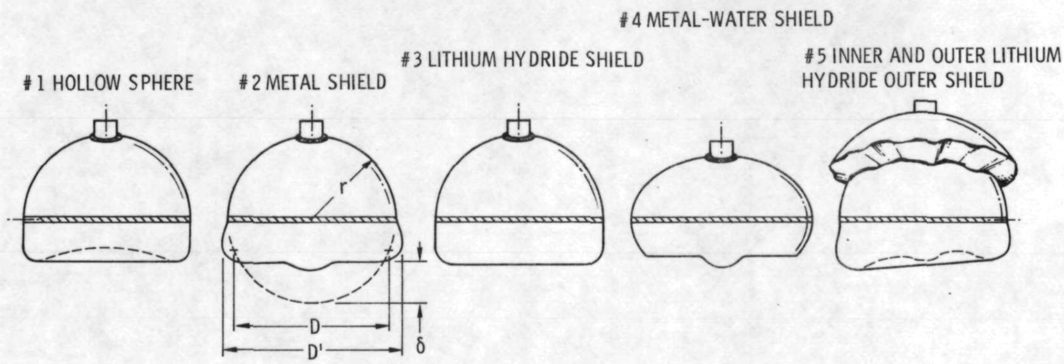


Figure 11. - 15 000 pound concrete block - post impact, Model No. 8.



$$\frac{D' - D}{D} = \Delta D/D$$

MODEL	VELOCITY, FT/SEC	WEIGHT OF MODEL PARTS - POUNDS							IMPACT ENERGY		δ/r	ΔD/D, %
		REACTOR MOCK-UP	SHIELD WOOD OR SADDLES	SHIELD WATER	C. V.	RSCV TOTAL	SHIELD/ EN. ABS.	TOTAL	RSCV $x10^6$ FT-LB	TOTAL $x10^6$ FT-LB		
HOLLOW SPHERE	392				350			350	0.84	0.84	0.63	13.2
METAL SHIELD	413	195	435		350	980		980	2.61	2.61	.55	18.0
LITHIUM HYDRIDE SHIELD	241	195	160		350	705		705	.64	.64	.29	2.5
METAL-WATER SHIELD	467	195	440	170	350	1110		1110	3.76	3.76	.76	21.0
INNER AND OUTER LITHIUM HYDRIDE SHIELD	580	195	160		350	705	600	1305	3.68	6.6	.53	5.0

Figure 12. - Deformation parameters.

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