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**REACTIVITY CHANGE IN A FAST-SPECTRUM
SPACE POWER REACTOR DUE TO A 328-METER-
PER-SECOND (1075-FT/SEC) IMPACT**

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16. Abstract Application of nuclear reactors in space will present operational problems. One such problem is the possibility of an Earth impact at velocities in excess of 305 m/sec (1000 ft/sec). This report shows the results of an impact against concrete at 328 m/sec (1075 ft/sec) and examines the deformed core to estimate the range of activity inserted as a result of the impact. The results of this examination is that the deformation of the reactor core within the containment vessel left only an estimated 2.7 percent void in the core and that the reactivity inserted due to this impact deformation could be from 4.0 to 10.25 dollars.					
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REACTIVITY CHANGE IN A FAST-SPECTRUM SPACE POWER REACTOR DUE TO A 328-METER-PER-SECOND (1075-FT/SEC) IMPACT

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SUMMARY

Application of nuclear reactors in space will present operational problems unique to this form of power generation. One such operational problem is the possibility of high-velocity Earth impact of a fast-spectrum reactor. These reactors, because of their high densities, can return to Earth and impact at speeds in excess of 305 meters per second (1000 ft/sec).

This report examines the consequences of impacting a simulated fast reactor against concrete at 328 meters per second (1075 ft/sec). The purpose of the study was twofold; to experimentally determine the postimpact integrity of the spherical containment vessel surrounding the reactor model and to analytically examine the deformed core to estimate the range of reactivity inserted as a result of the impact.

The results of the impact experiment and analytical analysis of the core show the following: (1) Postimpact analysis of the steel containment vessel showed no leaks and no observable cracks. (2) Deformation of the reactor core within the containment vessel was extensive. Only an estimated 2.7 percent of the total core volume void remained in the core fuel pin structure. (3) The reactor pressure vessel was split open at several locations revealing the inner portions of the core. (4) The analytical analysis of the postimpact core configuration estimated the net range of reactivity inserted, due to impact, to be from about 4.00 to 10.25. (5) The larger the core eccentricity due to compaction, the lower the possibility of the reactor going prompt critical. A similar core voided of lithium with an eccentricity approaching 0.90 could be held (via control drums) below the prompt critical conditions.

INTRODUCTION

As the exploration of space and the development of the Earth's resources from space evolves through the 1980's and 1990's, the need for large amounts of electrical

power in Earth orbit will become increasingly important. Electrical power outputs one or two orders of magnitude greater than presently available are predicted for such missions. Based on current technology, only nuclear reactors can supply the energy for these large power requirements. The application of nuclear reactors in space, however, presents operational problems unique to this form of power generation. The radiological hazards associated with the use of nuclear reactors in space appear to be the prime operating constraint. For this reason it is essential that these hazards be identified and evaluated.

The objective of this study is to identify and evaluate one such potential hazard - the high velocity Earth impact of a fast-spectrum reactor core. This type of accident can arise as the result of several operational malfunctions: (1) a launch phase abort, (2) guidance malfunction prior to orbital insertion, or (3) random Earth re-entry from orbit. When the mass to frontal area ratio of these reactors exceeds 3.5 newtons per square centimeter (5 psi), impact velocities in excess of 305 meters per second (1000 ft/sec) are possible as a result of the malfunction.

The consequences of such a high-speed impact of a reactor core could be quite severe. If we assume the reactor has been operated at design power for an appreciable length of time, then a large fission product inventory has been accumulated. Safety considerations require that the fuel and fission products of the reactor be contained at all times, even during the impact event.

One method of containment under these severe conditions is to put the reactor in a containment vessel and to design the 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 containment vessel and the internal components of the vessel such as the shielding and the reactor. At impact velocities approaching 328 meters per second (1075 ft/sec) considerable deformation of the containment vessel and the reactor core result. Core deformation, to the extent discussed in this report, alters the neutronics of the system resulting in an insertion of reactivity. A ramp insertion of appreciable magnitude can cause the reactor to go prompt critical, thereby attaining a very high power level, a large fission product inventory, and high fuel temperatures with a resultant fuel meltdown and eventual rupture of the containment vessel (ref. 1). Therefore safety considerations require that the containment vessel be designed to absorb the impact energy through deformation and that the reactor core within the containment vessel not go critical as a result of this deformation.

This report will examine the deformed reactor core configuration and analytically determine the amount of reactivity change generated by the impact accident.

DESCRIPTION OF SLED TESTS AND REACTOR

Sled Tests

The impact test was conducted at the Holloman Track in Alamogordo, New Mexico. This is a dual rail track extending 10 880 meters (35 588 ft). Only 610 meters (2000 ft) of the track was used for this test. The test setup is shown schematically in figure 1. It consists of a pusher sled, payload sled, culvert, and target.

The model is placed on a payload sled (fig. 2). It is attached by nylon straps that provide the support during sled operation. A pusher sled, containing four Genie motors for its propulsion thrust, pushes the payload sled down the track (fig. 3). Having reached predesigned speed, the pusher sled is stopped by water braking and momentum exchange. The payload sled continues down the track propelled by 12 Zuni motors.

A culvert placed at the end of the track (fig. 4) is designed to separate the impact model from the payload sled. This massive 10 000-kilogram (22 000-lb) structure is welded from 7.6- and 15.2-centimeter (3- and 6-in.) armor plate. Knives are positioned on the sled splitter to cut the nylon support straps and allow the impact model to pass through. The payload sled is destroyed with each test by the culvert. Small shape charges are also placed on the payload sled to initiate its destruction.

15.3 meters (50 ft) beyond the culvert is a concrete block (fig. 5), 1.5 meters (5 ft) on a side weighing approximately 8150 kilograms (18 000 lb). The impact model having been separated from the payload sled continues a free-flight impacting against the concrete block. For this particular test, a rock was mounted on the concrete (not shown in photograph). It measured about 15.2 centimeters (6 in.) in diameter by 10.2 centimeters (4 in.) high.

Movie cameras were mounted at the impact point (fig. 6). They operated at speeds of 4545 and 9090 frames per second. Additional movies were taken from a helicopter in real time and 250 frames per second showing the entire test sequence.

Reactor Model

The impact reactor model used for this test was a carbon steel, one-third scale model of a conceptual uranium nitride fast-spectrum space-power reactor. A cross-sectional view of the reactor model is shown in figure 7. One-hundred-and-ninety-three carbon steel tubes with a 6.35-millimeter (1/4-in.) outside diameter and a 0.89-millimeter (35-mil) wall thickness and a 12.1-centimeter (4.75-in.) length were used to represent the reactor fuel pins. These pins were held in place by a cylindrical can with a wall thickness of 1.14 millimeter (49 mil). Outside the fuel can, twelve 2.54-

centimeter (1-in.) diameter carbon steel cylinders were used to represent the peripheral control-drum elements. Steel bar stock was used in the interstices of the control drums to simulate the remaining reflector and provide a snug fit for all the components. The remainder of the reflector was represented by a 7.1-millimeter (280-mil) thick steel cylinder. The pressure vessel was 4.75-millimeter (188-mil) thick, 17.8-centimeter (7-in.) outside-diameter carbon steel tubing cut to a 17.8-centimeter (7-in.) length. Top and bottom end plates 32-millimeter (1/8-in.) thick were welded into place. The reactor model was then placed in the containment vessel as shown in figure 8. Sand and salt with steel saddles were used to represent shielding material and to fill in the remaining void within the containment vessel.

The containment sphere consisted of two stainless steel 0.62-meter (2-ft) diameter hemispheres. The total weight of the impact model was 522 kilograms (1150 lb).

TEST RESULTS

The impact model was slung on the payload sled by nylon straps. It was oriented such that the filler plug was up range from the impact point at about 45° to the horizontal. In this position the impact occurred on the weld. This orientation also caused the impact forces to be applied to the reactor core mockup perpendicular to its longitudinal axis.

The rocket ignition point was at the 10 000-meter (32 850-ft) track station. Impact of the sled with the culvert and subsequent release of the model occurred at the 10 600-meter (34 790-ft) track station. The last speed recorded by the track sensors was 314 meters per second (1035 ft/sec).

On impact of the sled with the culvert, the model separated from the nylon sling and passed through the culvert impacting with the concrete block 15.2 meters (50 ft) beyond. Figure 5 shows the culvert and concrete block before impact. Shape charges on the payload sled initiated destruction of the sled with the culvert before impact. The position of the culvert after the test is shown in figure 9. Little damage resulted to the culvert, and it can be used for additional tests.

Impact velocity of the model with the concrete block, as measured by the high-speed film was 328 meters per second (1075 ft/sec). This is an increase in velocity of 12.2 meters per second (40 ft/sec) over that recorded just before impact of the sled with the culvert. This increased velocity is due to the sling shot effect of the nylon strapping. The model is retained in the sled by two sets of straps. Just before the impact of the culvert with the payload sled, the cutter on the culvert severs the first set of straps leaving the model momentarily suspended in the sled by the second set of straps, which are still under tension.

Figure 9 also shows the concrete block and the containment vessel after impact.

The concrete block has been totally destroyed. The reinforcing bars are clearly shown. The model came to rest at the base of the destroyed block indicating that after impact the model dropped directly down. The high-speed motion pictures also showed that the model penetrated the concrete block at impact.

Photographs of the impacted model are shown in figure 10. Deformation occurred in both the impacted hemisphere and the hemisphere opposite from the direction of impact. The weld is approximately 45° to the impacted face cutting across the impacted face. The impacted face shows the impression of the rock that was mounted on the concrete. No traces of the rock could be found after the test due to the total destruction of the concrete. No cracks were observed in the containment vessel both along the weld and at the rock indentation.

A leak test was performed on the model. This test consists of pressurizing the containment vessel to 34.5 newtons per square centimeter (50 psig) with helium gas. The entire assembly is then encapsulated in a plastic bag; the interior of the bag is probed for leaks using a mass spectrometer type of leak detector. No leaks were detected.

Measurements were taken of the containment vessel. These measurements indicate how much strain occurred. The maximum diameter occurred at the impacted face. It was measured as 73.5 centimeters (29 in.), which is 12.7 centimeters (5 in.) greater than the preimpact diameter. This is a diametral strain of 16 percent. It is of the same magnitude as similar impacted models (refs. 2 to 5). The amount of deformation of δ/R was measured as 0.74 (where δ is defined as the diameter of the vessel before impact minus the height of the vessel after impact and R is the vessel radius before impact).

Containment Vessel Sectioning

The containment vessel was cut with a carbon arc torch around its perimeter to lift part of it away for the examination of the interior. Figure 11 shows the model after the cut. The saddles and salt have been left undisturbed. Figure 12 shows the core after the removal of the saddles and salt. It shows that impact occurred at less than 90° to the longitudinal axis. Figure 13 shows the core removed from the containment vessel. The physical dimensions of this core in the preimpacted condition are shown in figure 14.

The core takes on an odd shape because of the impact forces. The end reflectors are solid and thick and do not deform when impacted longitudinally. The core of the reactor model has some void in it and deforms into a flatter shape. The overall impacted model then takes on a cylindrical geometry in the end reflectors and more of a flat shape in the core region where void fraction exists. Sectioning of the core is shown in figure 15. The core's hollow tubes have been compressed or collapsed to where there

is little void fraction. The control drums remain cylindrical since they are solid. The outer walls of the core have split because of the large impact forces.

ANALYTICAL DISCUSSION AND RESULTS

The analytical analysis of the experimental results shown in the preceding sections of this report were complicated because of (1) the extent of deformation of the reactor configuration and (2) the material makeup of the original test model (fig. 14). Since the original test model used in the experiment exhibited a 67-percent void fraction, the final core compaction was more than would be experienced by a more realistic reactor model with only about a 37-percent void fraction (27 percent void due to loss of lithium coolant plus about 10 percent for fission product void). Therefore, the relative dimensions of the postimpact test model shown in figure 15 could not be used. However, these experimental results did give valuable data as to (1) the general elliptic shape of the postimpact reactor core and (2) the postimpact core void fraction that could be expected from a 328 meter-per-second (1075 ft/sec) impact (about 2.7 percent). Based on these data, the following analytical approach was taken to determine the range of reactivity increases that could be expected from this type of accident.

The first step was to establish a base case reactor configuration with dimensions approximately three times that of the impact test model used at Holloman Air Force Base and a fuel loading such that the final eigenvalue is about equal to 0.985. This value corresponds to a core voided of lithium coolant. The calculations were made using the two-dimensional transport DOT computer program (ref. 6). An r - z S_4P_0 , four-group transport calculation was assumed to yield sufficient accuracy for these calculations. The GAM computer program (ref. 7) was used to generate the four-group cross sections used in the transport calculations.

With the base case fuel loading and dimensions established, the next step was to determine the maximum amount of reactivity gained by squeezing down the core void fraction to the experimental postimpact void fraction of 2.7 percent. This was accomplished by conserving the core masses for each region of the reactor and then reducing the cylindrical radius of each region to the appropriate volume. A transport calculation for this compacted cylinder then gave the maximum reactivity change that could be experienced for a 2.7-percent core void fraction. The transport calculation showed that a 21.62-dollar (\$) increase in reactivity was associated with the radially compacted cylindrical core.

The actual postimpact experimental model revealed an elliptic shape rather than cylindrical. Therefore, the next step in the analysis was to deform the basic compacted cylinder case into ellipses of increasing eccentricities and calculate the resulting eigen-

value. This approach would then enable a separate determination of the neutron leakage and related decrease in reactivity associated with the change in geometry. The results of these calculations are shown in figure 16. The general characteristics of this curve is about what one would expect. The low to intermediate values of eccentricity (0 to 0.70) show a relatively small change in reactivity. Beyond 0.70 eccentricity the slope of the curve changes rapidly showing the strong leakage influence. The experimental postimpact reactor model (fig. 15) exhibited an approximate elliptic eccentricity of 0.84. Since the reactor model experimentally compacted to a much flatter configuration (because of the preimpact void fraction of 62 percent) one could say that an eccentricity of 0.84 would represent the upper limit for core compaction. The reactivity change associated with this eccentricity is about 13.00 \$ (from fig. 16). Since the original base core cylindrical reactor started with a radius of about 14.40 centimeters (5.66 in.); ($K = 0.985$), the family of ellipses applicable must initially have the semimajor axis equal to or greater than 14.40 centimeters (5.66 in.). Therefore, the lower bound on eccentricity (upper bound on reactivity) is an ellipse with a semimajor axis of 14.40 centimeters (5.66 in.) and a simiminor axis of 9.31 centimeters (367 in.). The elliptical eccentricity for this case was calculated to be 0.595. This value of eccentricity corresponds to a reactivity change of about 19.20 \$. Thus, the total reactivity range for this core compaction accident would certainly be less than 19.20 \$ and more than 13.00 \$. If the basic reactor is subcritical by the worth of the lithium coolant (voided core) or about 2.30 \$ then the net positive range is 16.90 to 10.70 \$. Since the effect of the control drums was not considered in these calculations, the range of reactivity change is still further reduced. Calculations made in reference 9 indicate that a shut-down margin on the order of 6.65 \$ could be expected for a reactor of this general nature. Thus, the net excess reactivity change for this accident could be from 10.25 to 4.05 \$. From the data shown in figure 16 it would appear that it would be acceptable to have the reactor core deform to eccentricities approaching 0.90. Cores voided of lithium with eccentricities close to 0.90 would have the possibility of remaining below the prompt critical condition.

CONCLUDING REMARKS

A boiler plate model of a uranium nitride fast-spectrum reactor was impacted against a concrete block at approximately 328 meters per second (1075 ft/sec), and the resulting information used to analytically examine the total change in reactivity associated with this event. The results of the impact experiment and the analytical analysis of the core show the following:

1. Postimpact analysis of the steel containment vessel showed no leaks and no observable cracks.

2. Deformation of the reactor core within the containment vessel was extensive. Only an estimated 2.7 percent of the total core volume void remained in the core fuel pin structure.

3. The reactor pressure vessel was split open at several locations revealing the inner portions of the core.

4. The analytical analysis of the postimpact core configuration estimated the net range of reactivity inserted, as a result of impact, to be from about 4.00 to 10.25 \$.

5. The larger the core eccentricity due to compaction, the lower the possibility of the reactor going prompt critical. A similar core voided of lithium coolant, with an eccentricity approaching 0.90 could be held (by the control drums) below the prompt critical conditions.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, June 28, 1973,

503-25.

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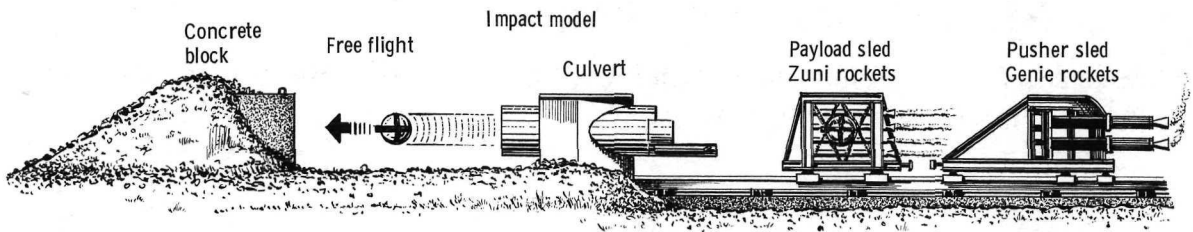


Figure 1. - Rocket sled test setup.

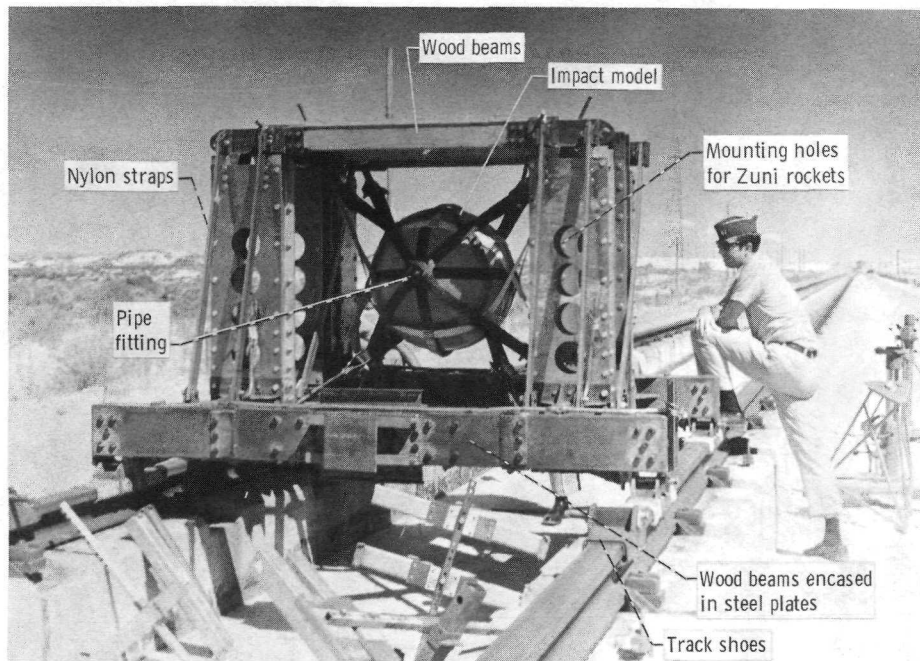


Figure 2. - Payload sled.

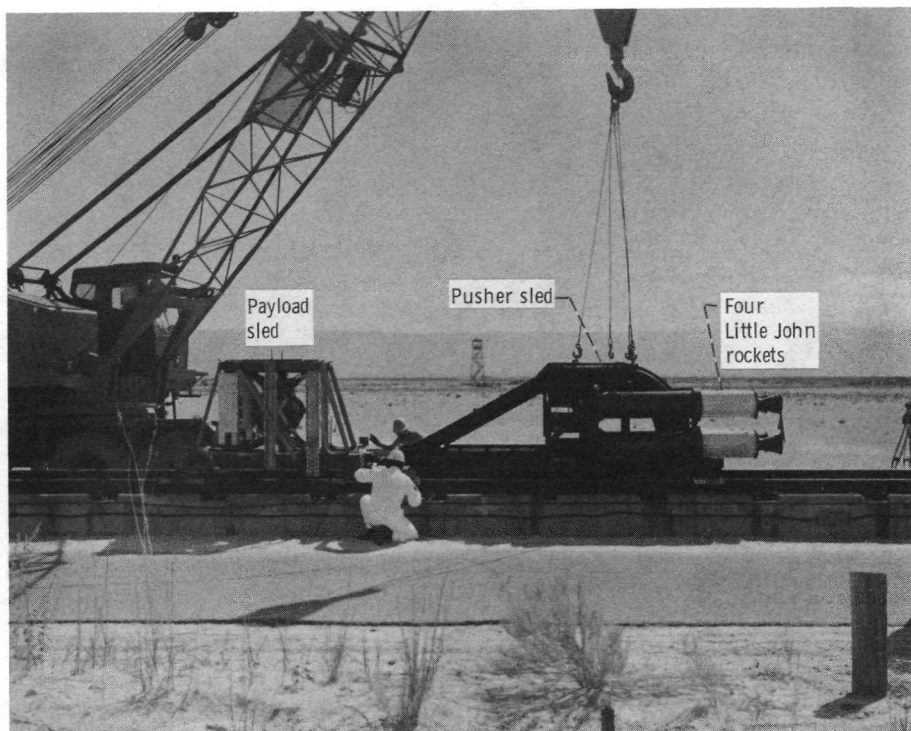


Figure 3. - Pusher sled.

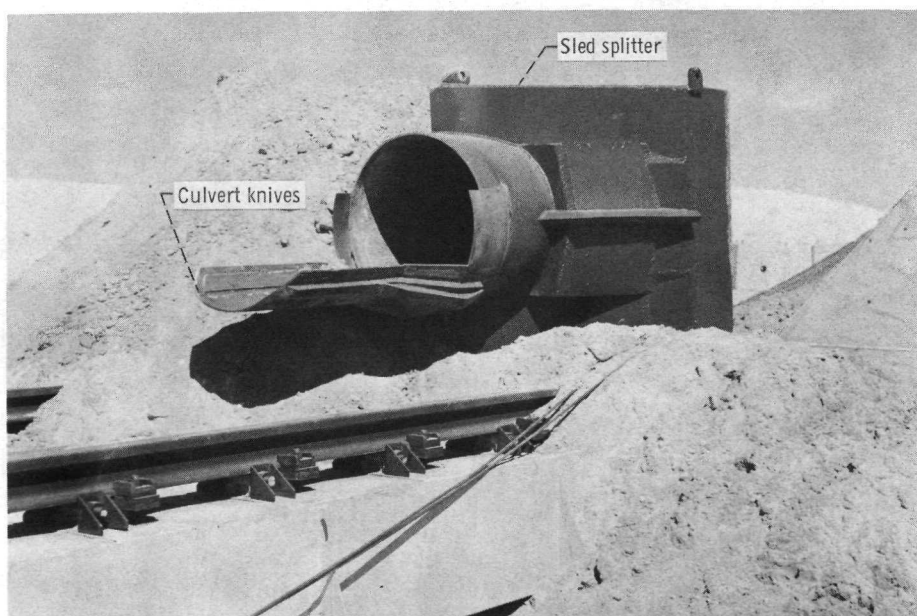


Figure 4. - Sled splitter at end of track.

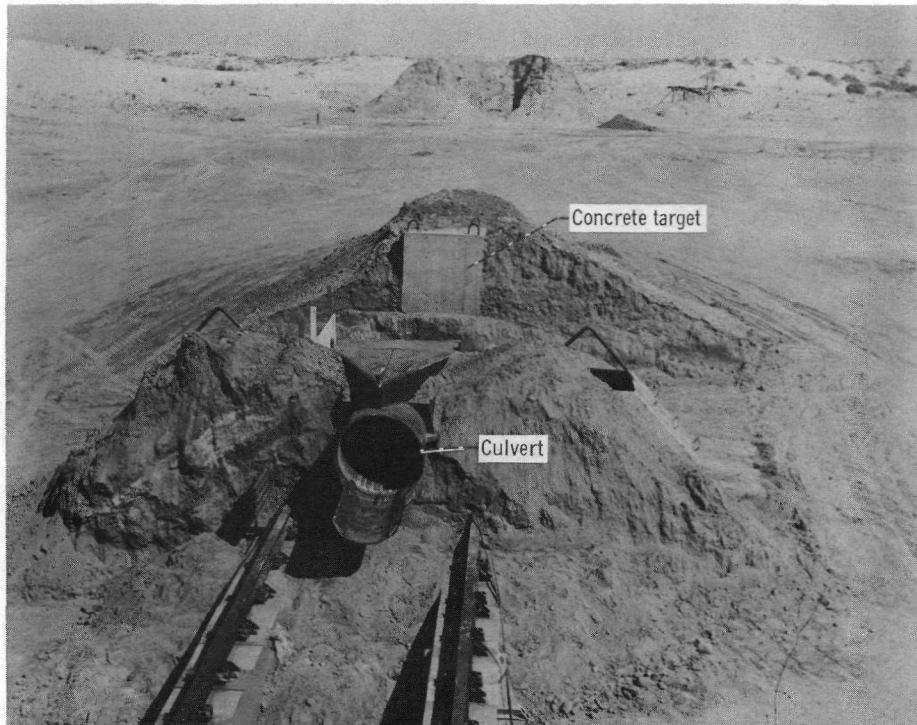


Figure 5. - Sled splitter and concrete target.

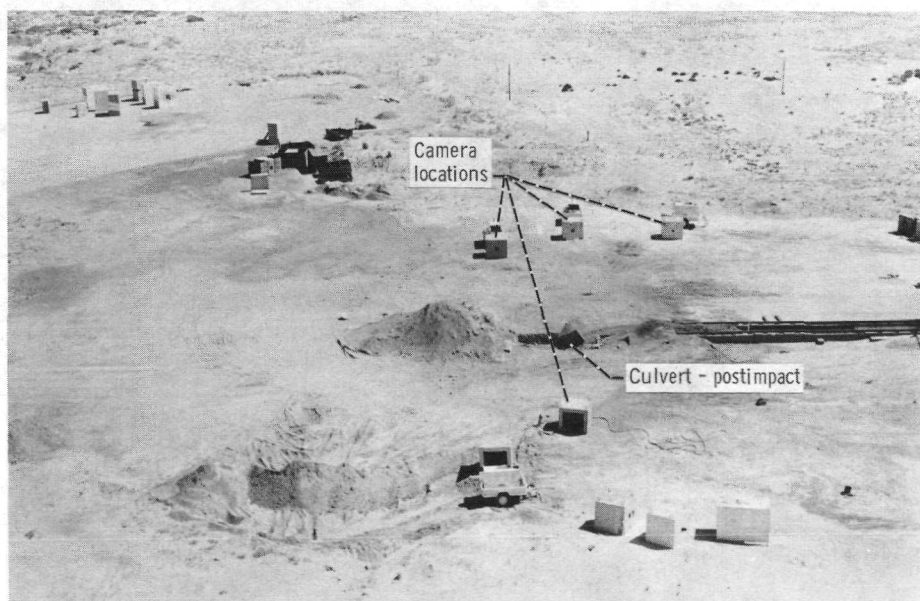


Figure 6. - Movie camera locations.

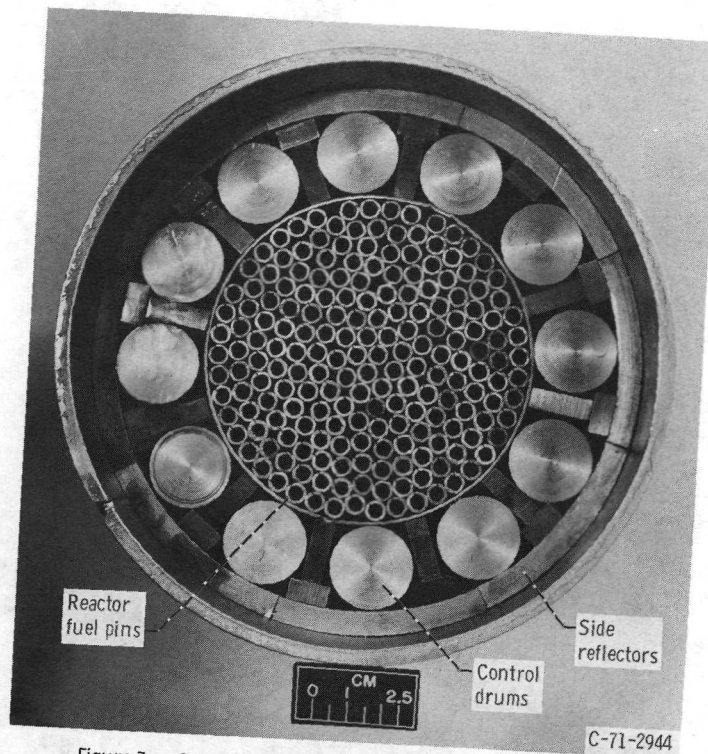


Figure 7. - Cross-sectional view of carbon steel reactor model.

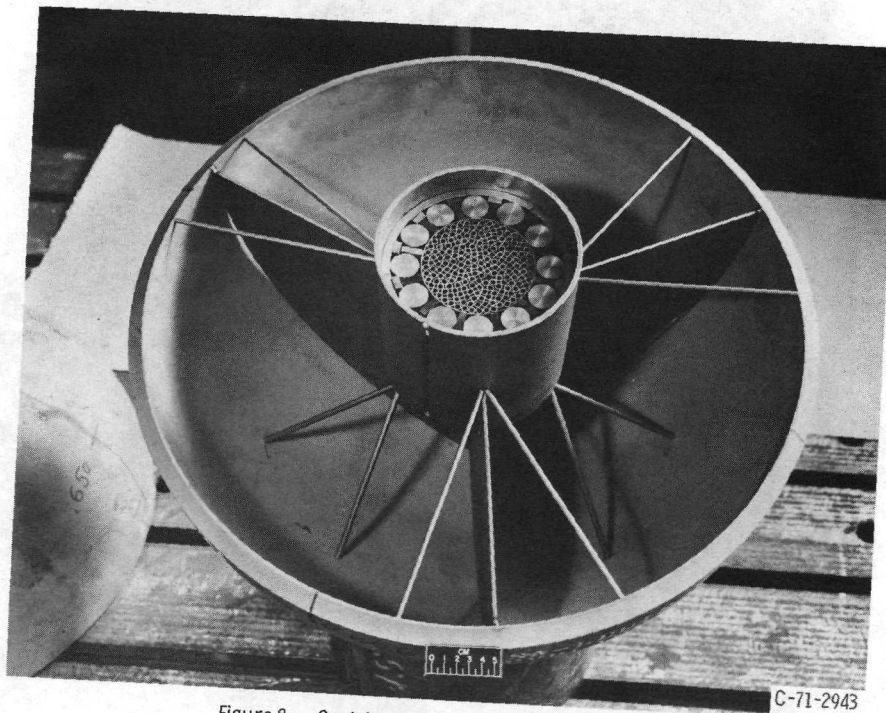


Figure 8. - Containment sphere and reactor model.

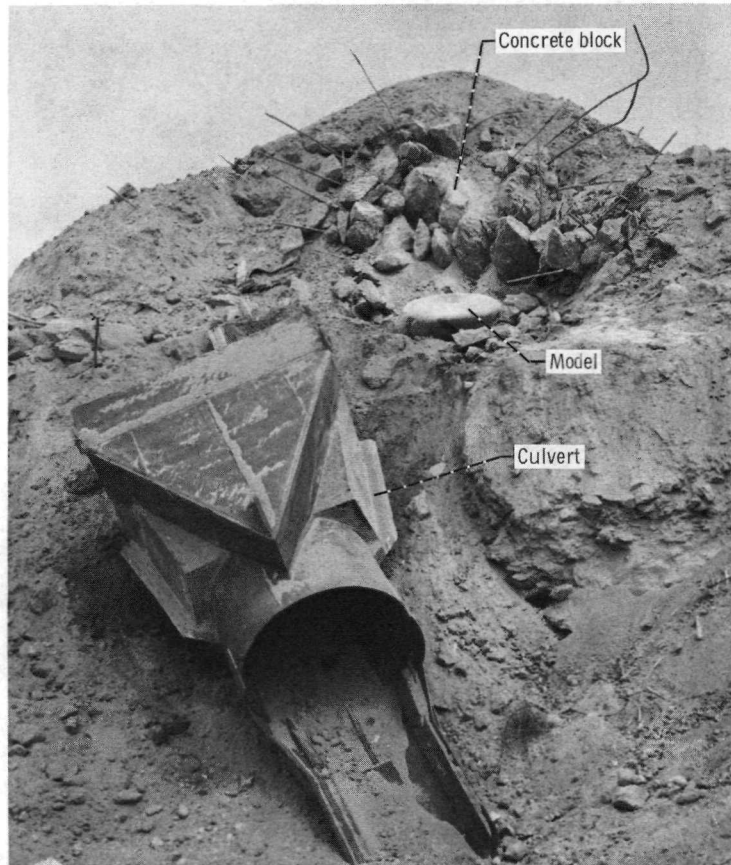


Figure 9. - Culvert, concrete block, and model - postimpact.



Figure 10. - Model - postimpact.

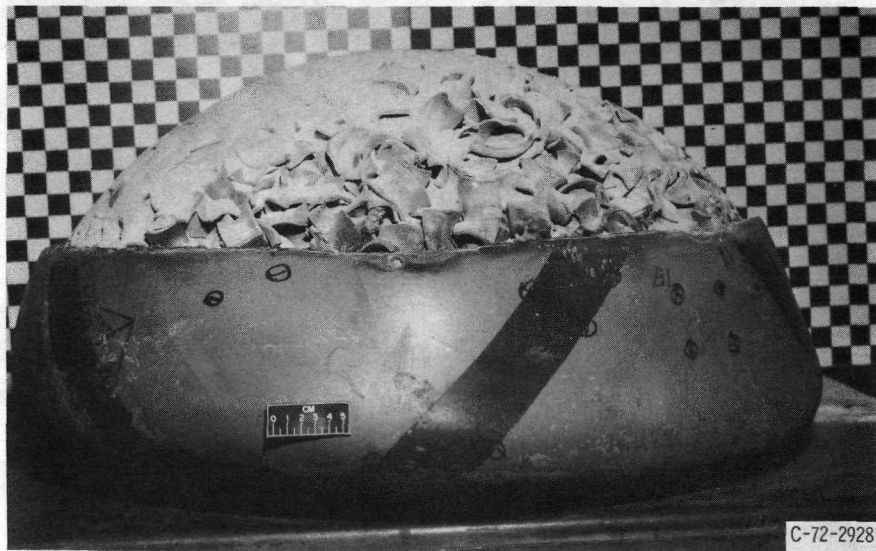
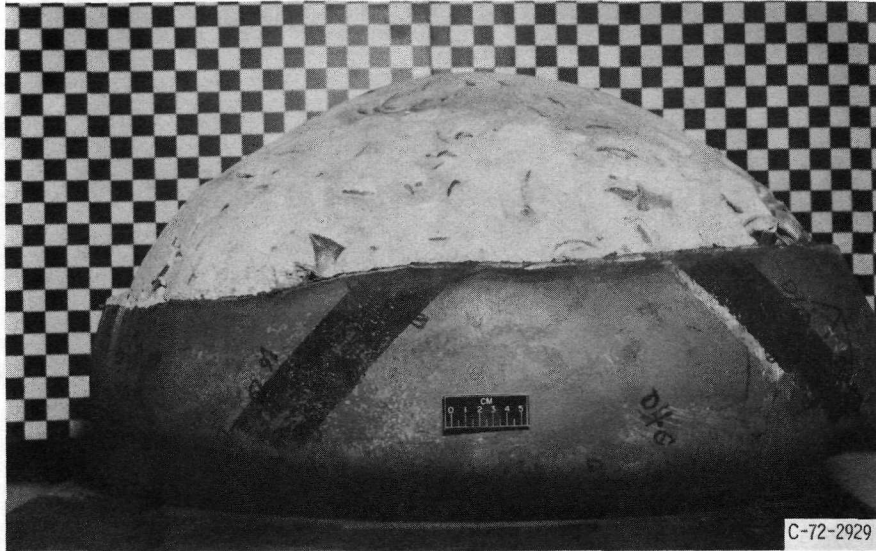


Figure 11. - Cut of containment vessel.



Figure 12. - Core in containment vessel - postimpact.

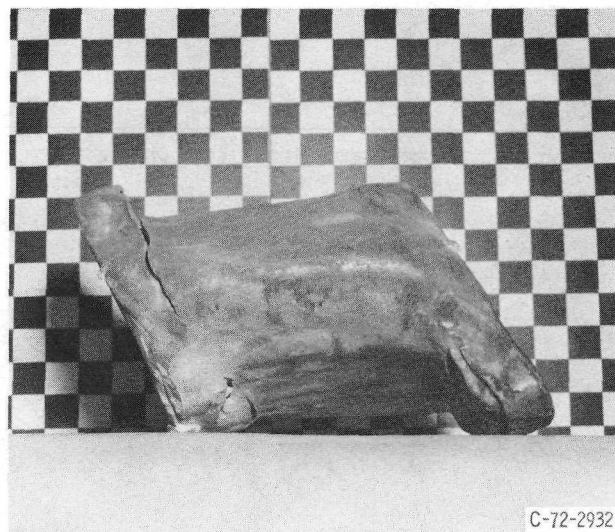


Figure 13. - Core removed from containment vessel - postimpact.

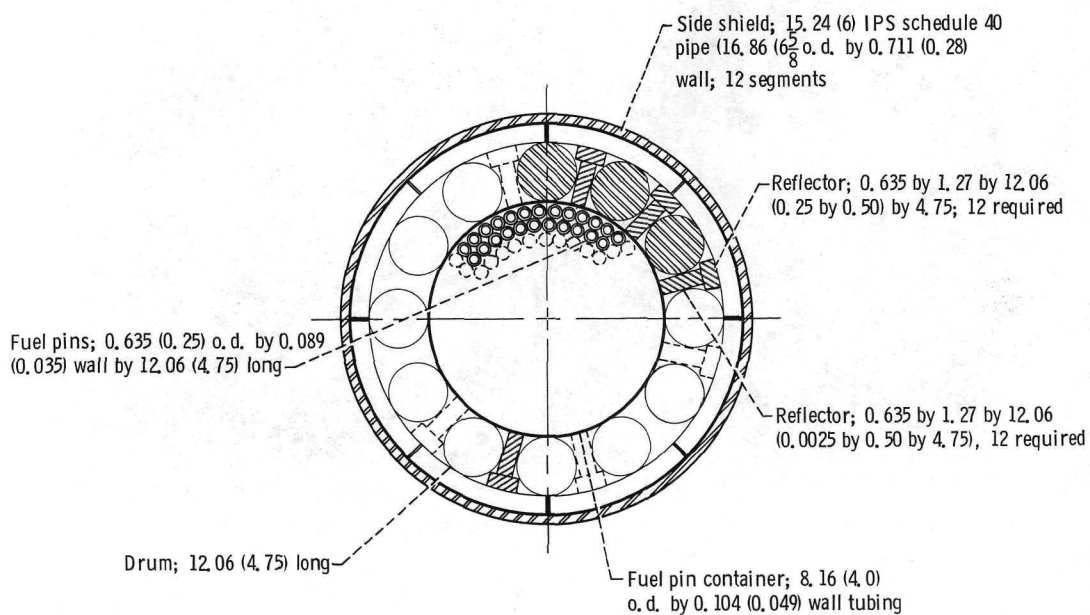


Figure 14. - Physical dimensions of core - preimpact. (All dimensions are in centimeters (in.).)

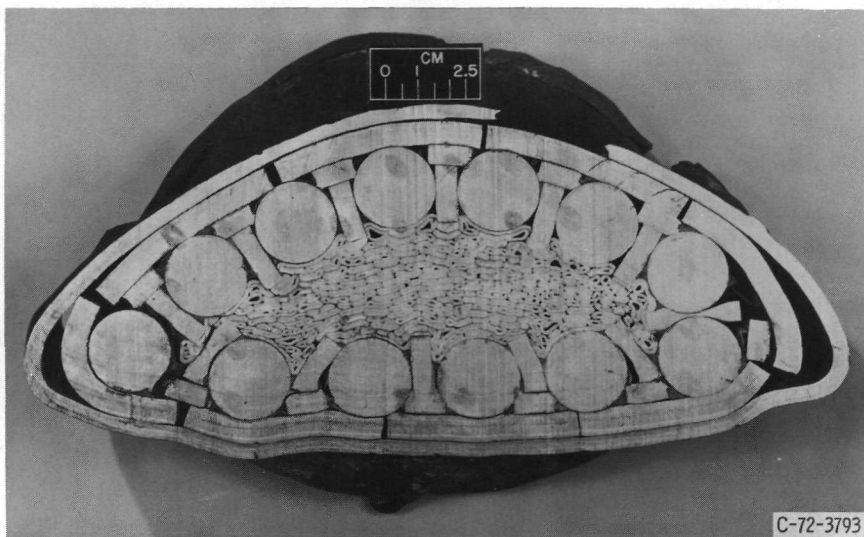


Figure 15. - Cross section of deformed reactor model.

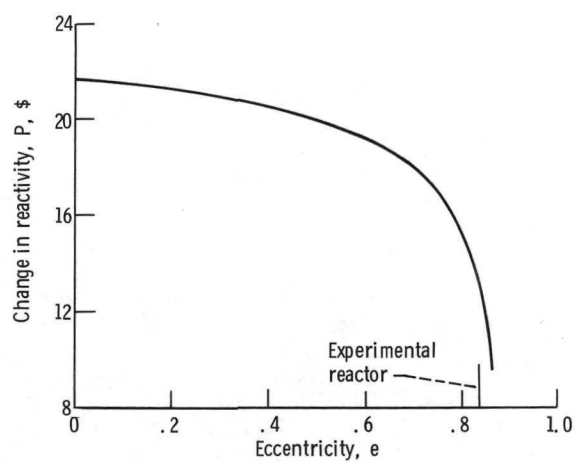


Figure 16. - Change in reactivity as function of core eccentricity.



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