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PHASE I MECHANICAL AND THERMOCHEMICAL TEST SERIES SNAP AEROSPACE SAFETY PROGRAM

AEC Research and Development Report

ATOMICS INTERNATIONAL

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PROPULSION SYSTEMS AND
ENERGY CONVERSION
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PHASE I MECHANICAL AND THERMOCHEMICAL TEST SERIES SNAP AEROSPACE SAFETY PROGRAM

By

S. L. PFAHLER

ATOMICS INTERNATIONAL

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ABSTRACT

This report describes the Phase I Mechanical and Thermochemical Test Series Conducted by Atomics International in conjunction with the Air Force Special Weapons Center at Holloman Air Force Base, New Mexico, as one of the projects in the SNAP Aerospace Safety Program. The principal objective of the tests was to obtain data and information which could be analyzed for evaluating the hazards that may occur before, during, and after the flight of the SNAP 10A reactor. The results of these tests will provide a means for developing criteria to guide in the design of inherently safe SNAP systems.

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I. INTRODUCTION

The SNAP 10A power unit is a small, reflector controlled, nuclear heat source utilizing thermoelectric conversion to deliver 500 watts of electrical power continuously for one year in space. NaK-78, a mixture of sodium-potassium, is used to transfer the thermal energy from the core to the thermoelectric converter. The coolant flow is produced by a direct-current conduction pump.

The reactor core vessel is thin-walled stainless steel, 9 in. in diameter and 16 in. long. Inside the vessel, there are 37 uranium-zirconium-hydride fuel elements, surrounded by beryllium (Be) reflector segments on the periphery of the fuel element cluster. In addition to fixed Be reflector blocks which enclose the outside of the reactor vessel, four moveable Be drum segments provide reactor startup and control. The outer reflector system is held in place by a stainless-steel tension band with six fusible link brazed joints. The band is designed to fail, allowing separation of the outer reflectors, when subjected to impact, overpressure, or thermal energy.

The fully assembled power system weighs 875 lb and is 10.8 ft long.

During the factory-to-orbit sequence, the SNAP 10A reactor and its related systems will be subjected to various handling, transportation, and launch conditions. As a result of these conditions, potential accidents such as impacts, chemical interactions, explosions, and fires can be postulated. In order to provide adequate nuclear safeguards, the potential hazards that could result from the postulated accidents must be analyzed. It is necessary, therefore, to evaluate the effects of possible thermochemical and mechanical incidents on the SNAP system.

To perform this evaluation a series of tests was conducted at Holloman Air Force Base, New Mexico, in which full-scale mockup reactors and systems were subjected to conditions similar to the various postulated accidents.

The selection of the individual tests was quite critical because of the large number of accident conditions, attitudes, and geometries that could be postulated.

Fourteen tests were selected which would give a statistically representative sampling of the credible conditions, and would develop the most meaningful information. Where possible, limiting conditions were selected in each test. These tests were divided into three categories: (a) chemical interaction, (b) fire and explosion, and (c) impact.

II. SUMMARY AND CONCLUSIONS

The completed Phase I Mechanical and Thermochemical Test Program was a series of tests in which mockup SNAP 10A reactor assemblies (in some cases, including the shield and converter structure) were subjected to abort environments of thermal shock, chemical interaction, overpressure, and impact.

It was noted that thermal shock due to a LOX deluge had no appreciable effect on the reactor assembly. Chemical interactions, although violent in the case of the NaK-water reaction, did not significantly damage the core vessel. Fire, explosion, 70-ft/sec impacts on concrete, and 550-ft/sec (terminal velocity) impacts on water resulted in reflector ejection with little or no damage to the core vessel. Impact on concrete at 560 ft/sec, however, did produce complete disassembly of the reactor.

Test No. 1 was planned to simulate the reactor being exposed to a LOX deluge from the Atlas fuel tank. The core vessel was not damaged as a result of the deluge.

Test No. 2 was similar to Test No. 1, except that the NaK within the core vessel was exposed to the LOX deluge. The LOX quickly froze the NaK at the point of NaK discharge, thus no chemical interaction occurred nor was there any explosion.

In Test No. 3, the reactor was immersed in water; the reactor inlet and outlet nozzles were ruptured, exposing NaK to the water. The reaction was so violent that the water tank failed. Despite the reaction, the core vessel and core were not damaged.

In Test No. 4, the test article was exposed to high thermal flux such as might be released by a missile abort fire. The reflector blocks were separated from the reactor, but the vessel suffered only very minor damages.

Test No. 5 was an explosion test. The reactor vessel with reflector assembly was placed 13 ft above 256 lb of TNT. The reflectors were ejected during the explosion, but the fuel element array remained intact.

Tests No. 6, 7, and 8 were impact tests utilizing a 100-ft tower to simulate the missile. The test articles were dropped from the tower to a concrete pad in nose-on, side-on, and tail-on impacts. In each of the tests the reflector retaining band failed, the reflectors were separated, and the core vessel had some small cracks in it, but the fuel element array remained intact.

In Test No. 9, a concrete-faced monorail sled was impacted upon a stationary test article. The velocity of the sled at impact was 560 ft/sec. The test article was completely destroyed; debris from the test article was scattered over the test area.

Test No. 10 was planned to be similar to Test No. 9, except with an impact velocity of 750 ft/sec. The test was cancelled after review of results from Test No. 9.

Tests No. 11, 12, and 13 were high-velocity water impacts. In each of the tests, the test assembly was traveling slightly in excess of the 550 ft/sec terminal velocity. In the head-on impact, Test No. 11, the article passed completely through the water tank and came to rest in a mound of earth beyond the tank. While various parts of the assembly were torn off, the core vessel was essentially intact.

Test No. 12 was a tail-on impact. The bottom of the core vessel was severed, and two fuel elements were ejected from the core can. Two other fuel elements were longitudinally displaced 10 in. The remaining 33 elements were longitudinally displaced in such a manner as to form an approximate tilted plane. Despite this damage, it was estimated that the fuel element array would be supercritical if immersed in water.

Test No. 13 was a side-on impact. Again, the reflectors came off, but there was no serious damage to the core vessel.

The last test (No. 14) was to consist of an APU impacting, nose-first, in a tank of water at 750 ft/sec. Due to a rocket stage malfunction, the impact velocity was only 428 ft/sec. The test article passed completely through the water tank. The reactor vessel came to rest on an earth mound beyond the tank, while the shield and modified converter structure were thrown farther on. Upper and lower core vessel heads were torn from the vessel and the upper grid plate was separated, but the fuel element array remained intact.

Extensive motion picture coverage was provided and many photographs were taken of the tests. The conclusions made herein are based upon analyses of the documentary films. The significant information required from the tests, in most instances, was the ultimate condition of the test assembly. This made it possible to determine whether the core configuration was capable or incapable of being made critical.

When included, both the fixed reflector blocks and rotatable control drums separated from every test article as a consequence of the imposed test conditions. During the 100-ft side-on drop test, when one control drum was seen to "rotate in," conservative calculations have shown that the reflector assembly separated before significant power generation could have occurred. However, the final condition of the reactor vessel and fuel element array after every test, except for the 560-ft/sec concrete impact, was such that the disassembly was not sufficient to prevent criticality if the reactor were immersed in water.

This test series provided valuable information about the effects of the postulated mechanical and thermochemical accidents and constitutes the foundation upon which the SNAP safety program will be based in this area.

Careful evaluation of the Phase I tests and results reveals that, although many questions have been answered, additional tests must be conducted in order to investigate tumbling impact, impact at less than 70 ft/sec, post-reentry impact, and to simulate more closely the actual condition of the reactor and its environment.

III. TESTS AND RESULTS

The Phase I Mechanical and Thermochemical Test series was performed at Holloman Air Force Base, Alamogordo, New Mexico. The tests were completed during the period of time from May 1962 to October 1962. Numerous photographs are included in this report to support the discussions presented.

A. LIQUID OXYGEN SPRAY TEST

The purpose of this test was to simulate the reactor being exposed to a liquid oxygen (LOX) spray, which could be expelled from an Atlas fuel tank. It was conducted to measure the effects of the thermal shock, created by such a LOX spray, upon the reactor vessel, grid plates, fuel element array, and to observe the general behavior of the reactor for evidence of structural failure.

The test article consisted of the reactor vessel and its internals (see Figure 1). The nose cone and reflector assembly were not a part of the test article because it was reasoned that the nose cone would be damaged or destroyed during an abort condition, and the reflector assembly would have separated. Furthermore, thermal shock to the reactor vessel would be minimized with the nose cone in position.

The test was performed on May 8, 1962. The test article was mounted on a stand with the vessel in an upright position. For 40 sec, a dense spray of LOX enveloped the reactor.

Twenty-two channels of oscillographic data were planned to be collected from 12 strain gages, 9 thermocouples and 1 event recorder. Black and white still photographs were taken before and after the spray. A 16-mm film of the test setup and the test itself was obtained. The first 5 sec of the test were recorded by three strategically placed, high-speed (1000-ft/sec) motion picture cameras.

There was no external or internal physical damage to the reactor as a result of the test. A review of the oscillographic data showed that the head temperature, as indicated by a thermocouple attached to the head, varied irregularly during the first 18 sec of the test, and then leveled off at a temperature of 54.7°F. There was no response from the other instrumentation.

Because of the thin wall construction of the reactor vessel and the good ductility of 316 stainless steel, the thermal shock effects of the LOX spray were

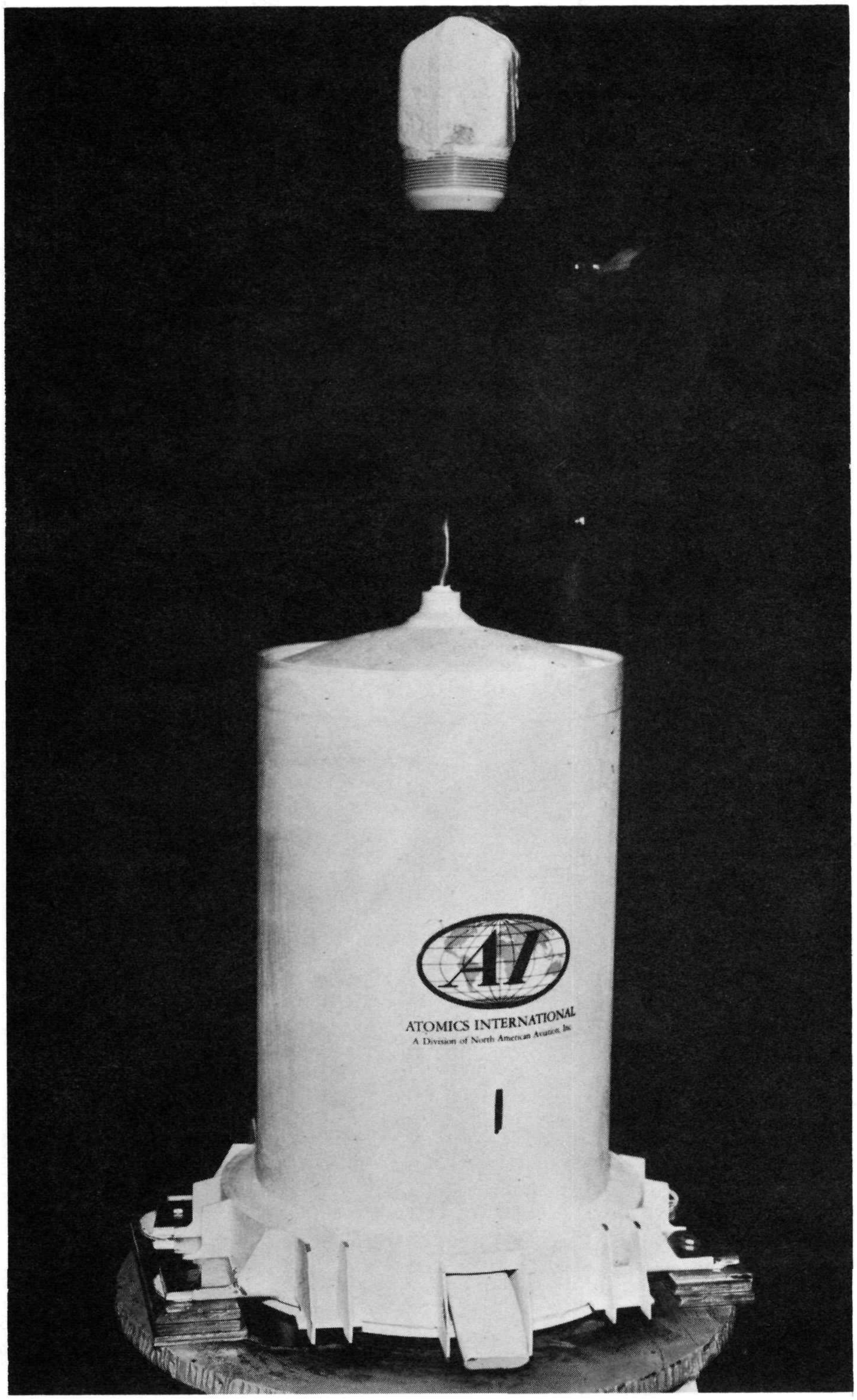

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Figure 1. Test Article Before LOX Spray Test

not damaging. It is concluded that the reactor and its internals can withstand thermal shocks resulting from a LOX spray such as might be released from an Atlas fuel tank and that no nuclear hazard exists unless the reactor is subsequently immersed in water.

B. LIQUID OXYGEN — SODIUM POTASSIUM (NaK) INTERACTION TEST

The purpose of this test was to determine the effects on the reactor assembly of the chemical reaction and any possible explosion that may be generated by the LOX-NaK interaction. The test was planned to simulate the condition where the reactor vessel or associated liquid metal coolant piping was ruptured and the NaK was exposed to a LOX spray from an Atlas fuel tank during a missile abort.

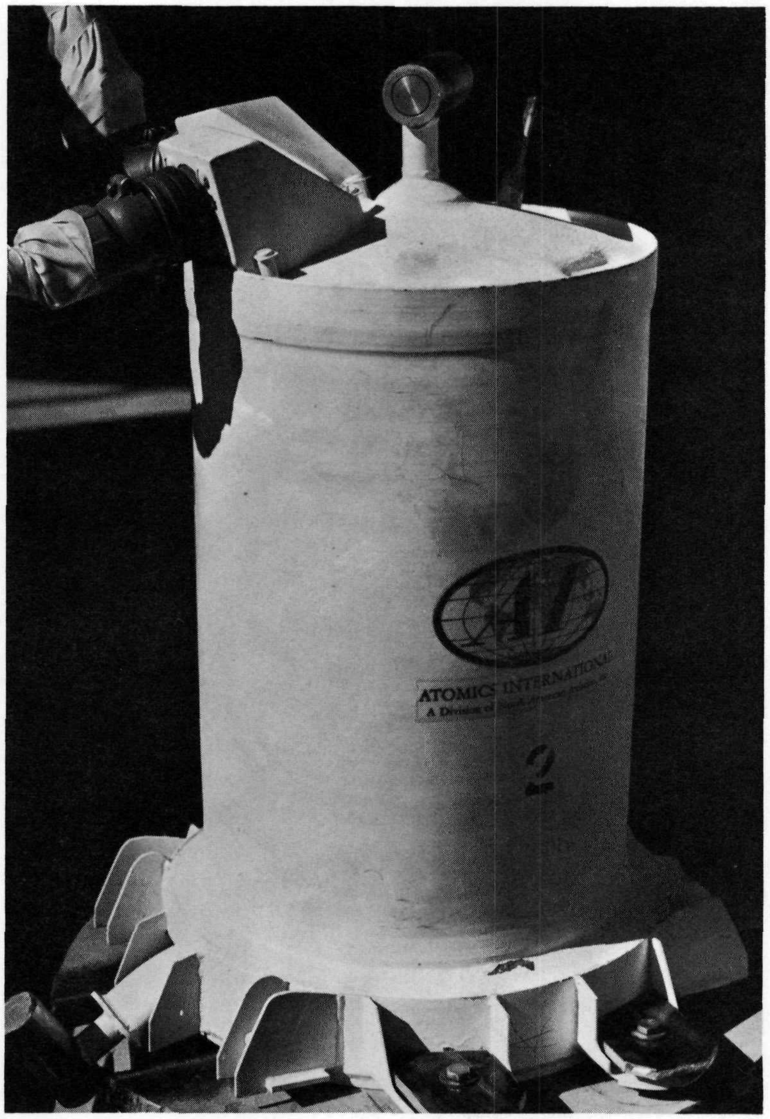

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Figure 2. Test Article Before LOX-NaK Interaction Test

The test was performed on May 17, 1962. The test article, consisting of the reactor vessel and its internals (Figure 2), was mounted in an upright position. Two seconds before the LOX spray was initiated, small explosive devices were fired to rupture the two inlet nozzles and the outlet nozzle of the reactor. The LOX spray was continued for 40 sec.

There was no explosion generated by the LOX-NaK interaction. The NaK was solidified at the nozzles and did not thaw until 8 min after the LOX spray was stopped. As shown in Figure 3, there was no external or internal damage to the reactor assembly. The internally mounted instrumentation indicated no large temperature changes.

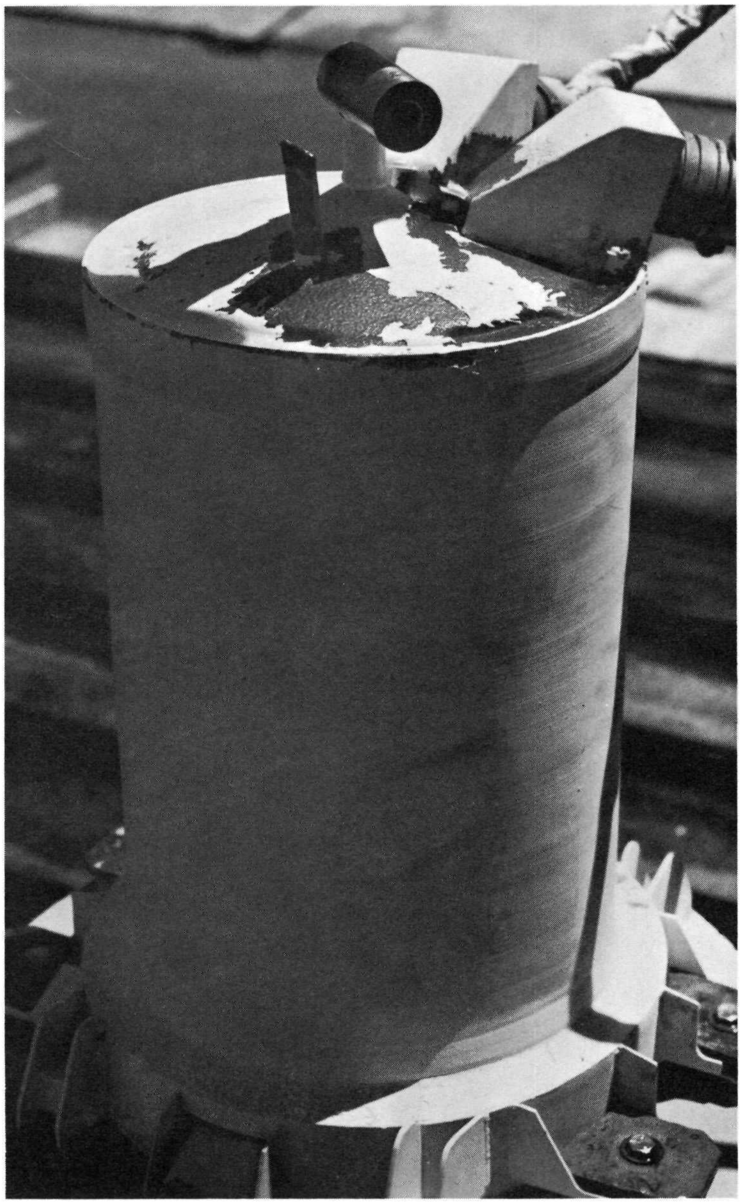

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Figure 3. Test Article After LOX-NaK Interaction Test

It is concluded, from the test, that the reactor will not be damaged if the core vessel with ruptured NaK lines is subjected to LOX spray. No nuclear hazard exists unless the reactor is subsequently immersed in water.

C. EXPLOSION TEST

The purpose of this test was to measure the geometric changes of the fuel element array and to observe structural failure of the reactor and fuel element dispersal due to an explosion. This test was planned to simulate a prelaunch or postlaunch Atlas abort and subsequent propellant explosion.

The test was performed on May 23, 1962. It consisted of exposing the test article to an overpressure in excess of 400 psi. The reactor assembly, including the reactor vessel with internals and fixed reflector blocks, was suspended on a line between two vertical poles. The explosive, 256 lb of TNT, was positioned 13 ft below the test article on a 3-ft-high table resting on the ground. Instrumentation coverage included a ground-mounted pressure transducer, high-speed color film documentary of prerun through postrun activities, and black and white still photos taken before and after the test (see Figures 4 and 5).

Simultaneously with the detonation of the TNT, the test item suspension system was severed. The force of the explosion ruptured the reflector block retaining tension band. Each of the reflector block halves came to rest 35 ft from their original position; the two halves were 70 ft apart. The reactor vessel was blackened, and its bottom was deformed inwardly by the explosion. Of the four high-speed cameras provided for film coverage, two jammed, and two recorded only the light flash from the explosion and dust. The pressure transducer did not give useful results. A positive-phase pulse duration of 2.8 msec was estimated. The calculated overpressure, at the test article, was 415 psi.

Some question remains as to how the conditions during this test would compare to an actual missile abort explosion. Some literature refers to much higher overpressures during rocket explosions. It is reasonable to assume that the damage to the reactor with a higher overpressure would be more severe; consequently, chances of a nuclear excursion would be lessened. The condition of the reactor after the above described test explosion was such that the core would not have become supercritical unless it was immersed in water.

D. SODIUM POTASSIUM (NaK) – WATER INTERACTION IMMERSION TEST

The purpose of this test was to observe the NaK – H_2O chemical reaction and its effect on the reactor.

The test article consisted of the reactor vessel and its internals. The nose cone, reflector assembly, and other components were not included since they would not have affected the final fuel element configuration. The reactor was

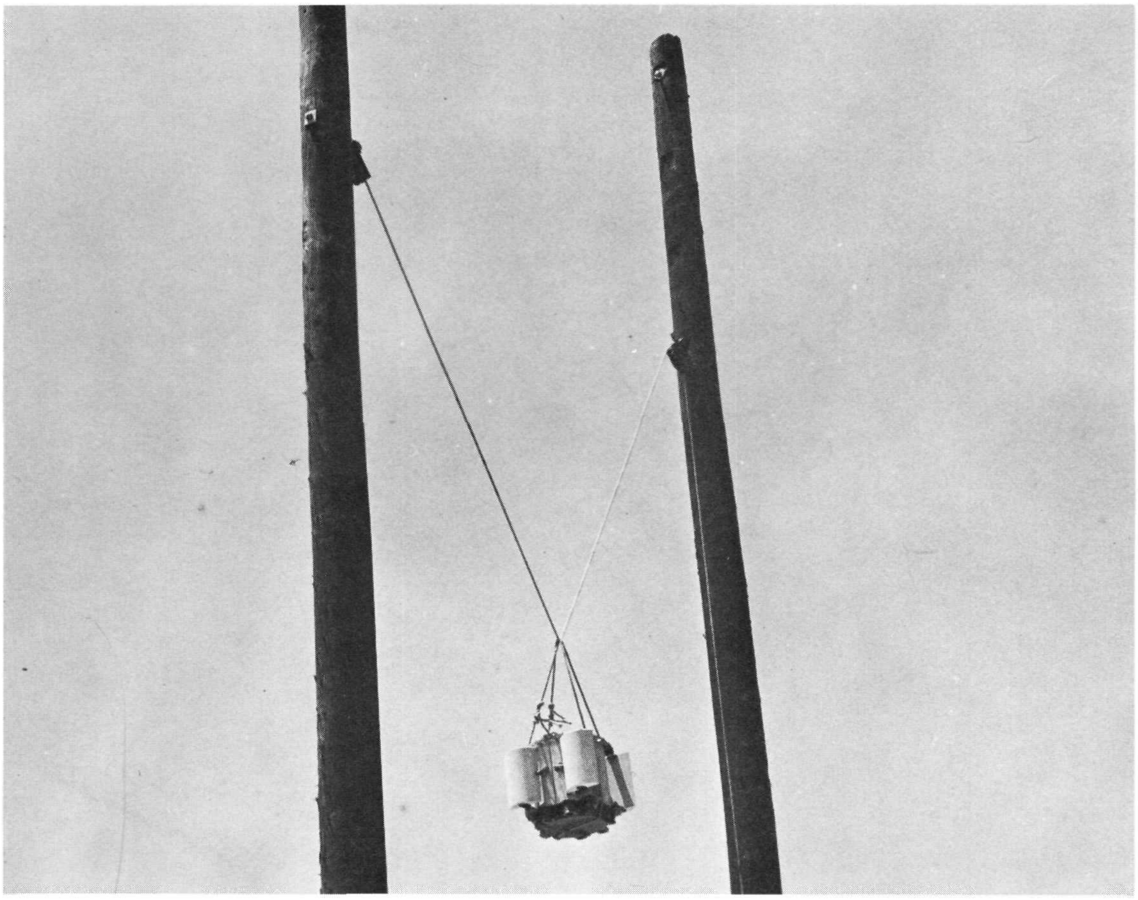

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Figure 4. Test Article Before Explosion Test

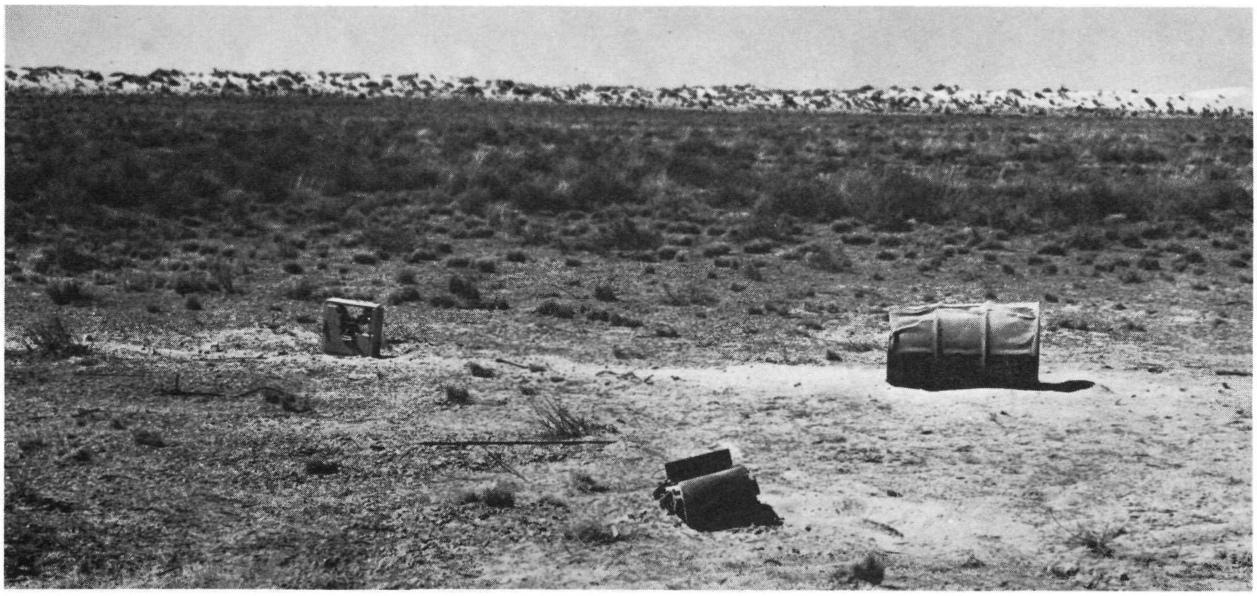

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Figure 5. Pieces of Test Article After Explosion Test

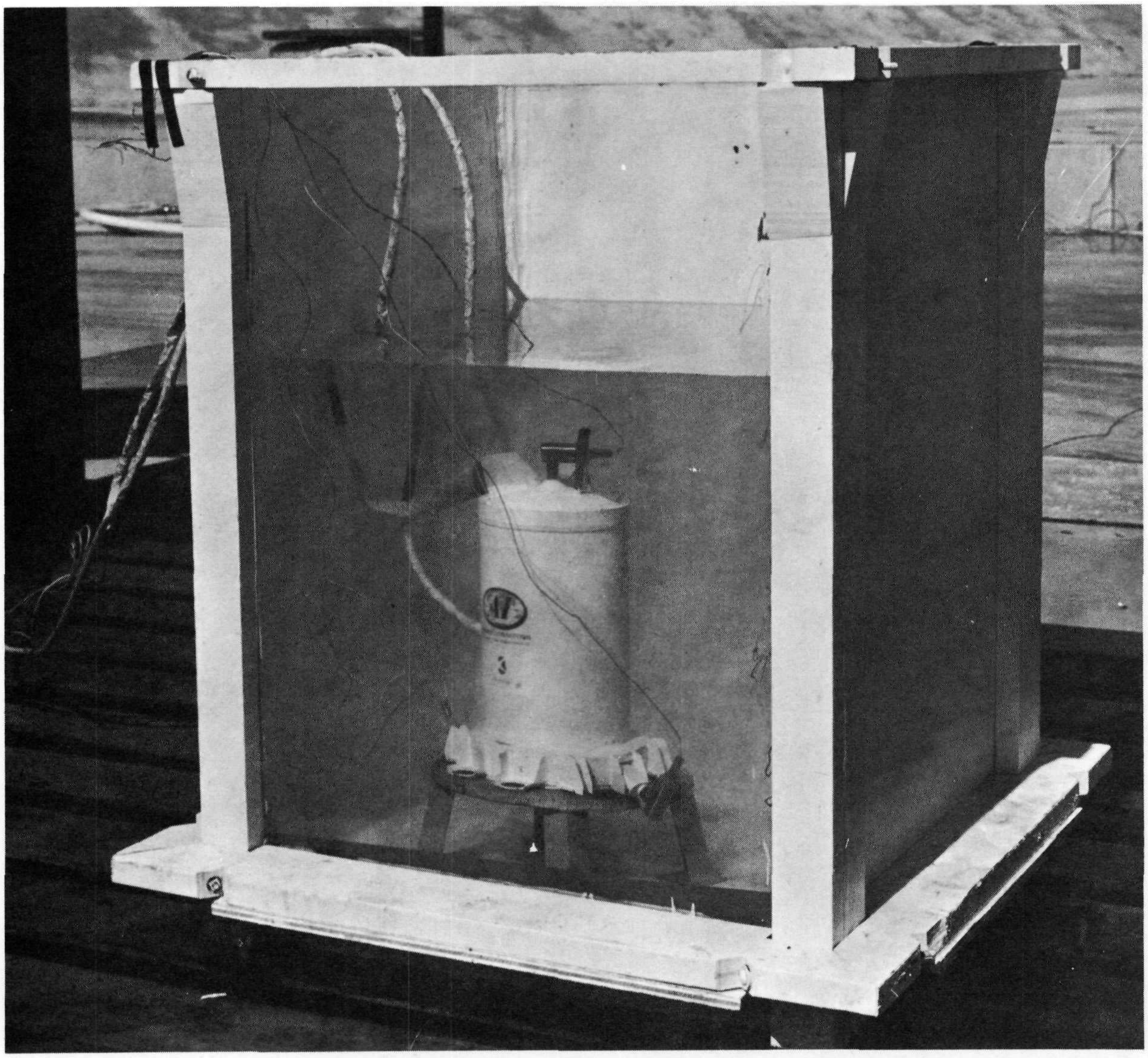

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Figure 6. Test Article in Water Tank Before NaK-H_2O Interaction Test

placed in a 36-ft^3 tank which had one plexiglas side (see Figure 6). Instrumentation similar to that for the LOX spray and LOX-NaK tests was provided. This test was performed on June 6, 1962.

After the tank was filled with clear water, squib-actuated NaK valves were opened, thereby bringing the NaK into contact with the water. The initial explosion, at one of the valves, burst one side of the water tank. This allowed the water to drain from the tank.

The core vessel was found to be slightly ballooned, with outward convexity of the bottom head. This was caused by pressure buildup in the vessel from the NaK-H_2O reaction. However, because of the water tank failure, the test is considered to have been an undertest. There was no response from the internally mounted instrumentation. Figure 7 shows the test article after the test.

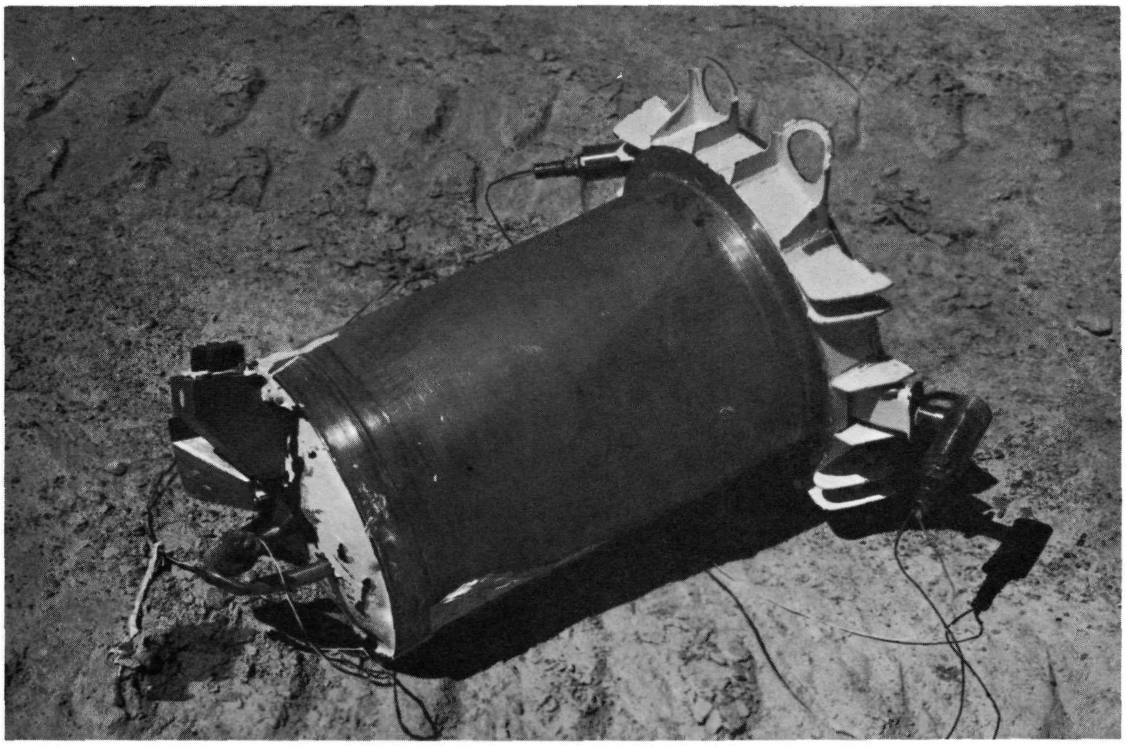

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Figure 7. Test Article After NaK-H_2O Interaction Test

E. DROP TESTS FROM 100 FEET

The purpose of these tests was to determine the mode of failure of the reactor assembly when subjected to impact with concrete at an impact velocity of 70 ft/sec. These tests were intended to simulate a reactor being dropped from the top of the launch vehicle during the mating operation.

The test articles consisted of the reactor vessel, fixed reflector blocks, reflector drums, NaK pump, shield, and converter. The nose cone was not included since it will not be installed on the Auxiliary Power Unit (APU) until after the APU has been mated to the launch vehicle. Instrumentation for these tests included three Fastex cameras, two long-range cameras, still cameras, and one accelerometer.

To simulate various modes of impact, test articles were dropped (1) side-on, (2) tail-on, and (3) nose-on. The tests were performed July 11, 1962.

For the side-on drop test, 1-in. pipe guides were placed at the center of gravity and at the end of the APU to ensure proper impact attitude. The model struck the concrete pad at 68.8 ft/sec (see Figure 8). All four reflector drums

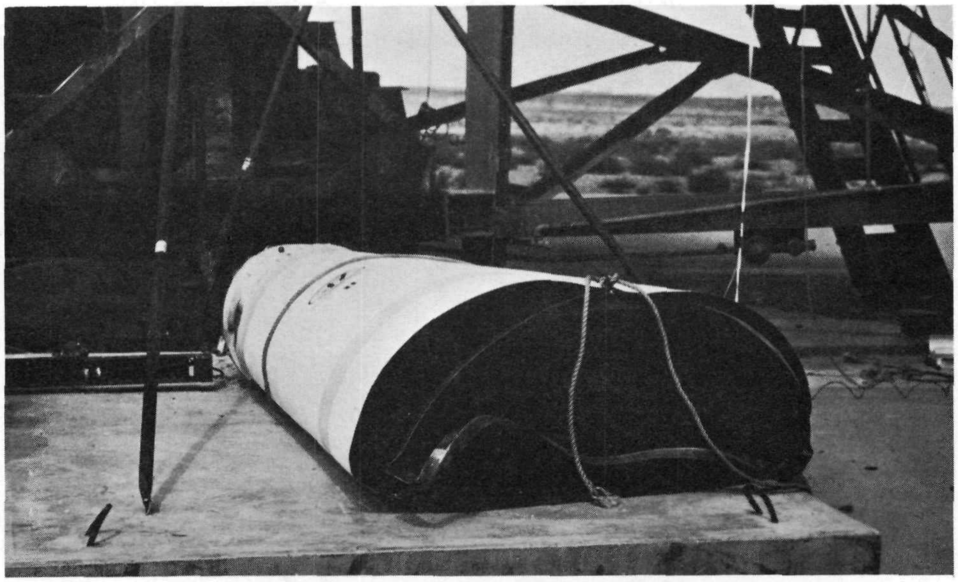

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Figure 8. Converter After 100-ft, Side-On Drop Test

appeared to be thrown into the air. The core vessel skidded 10 ft from its point of impact. After closer examination, it was found that the main reflector block was in four pieces, and that three of the four reflector drums were severed from their supports. The four ejection springs were on the ground; the core vessel was intact with only a small puncture in its side (see Figure 9). All the support legs failed, and the converter structure was completely flattened up to the shield.

Analysis of the documentary films taken during this test revealed that one drum rotated in, two drums did not rotate in, and the position of the fourth drum could not be established. It was determined that one drum started to rotate 7 msec after impact. The retaining band failed 22.5 msec after impact, and at 30 msec, the reflector blocks were well separated from the reactor. The angular velocity of the rotating drum was calculated to have been 5.5°/msec; a simplified analysis of the possible drum rotation predicted a velocity of 8.1°/msec.

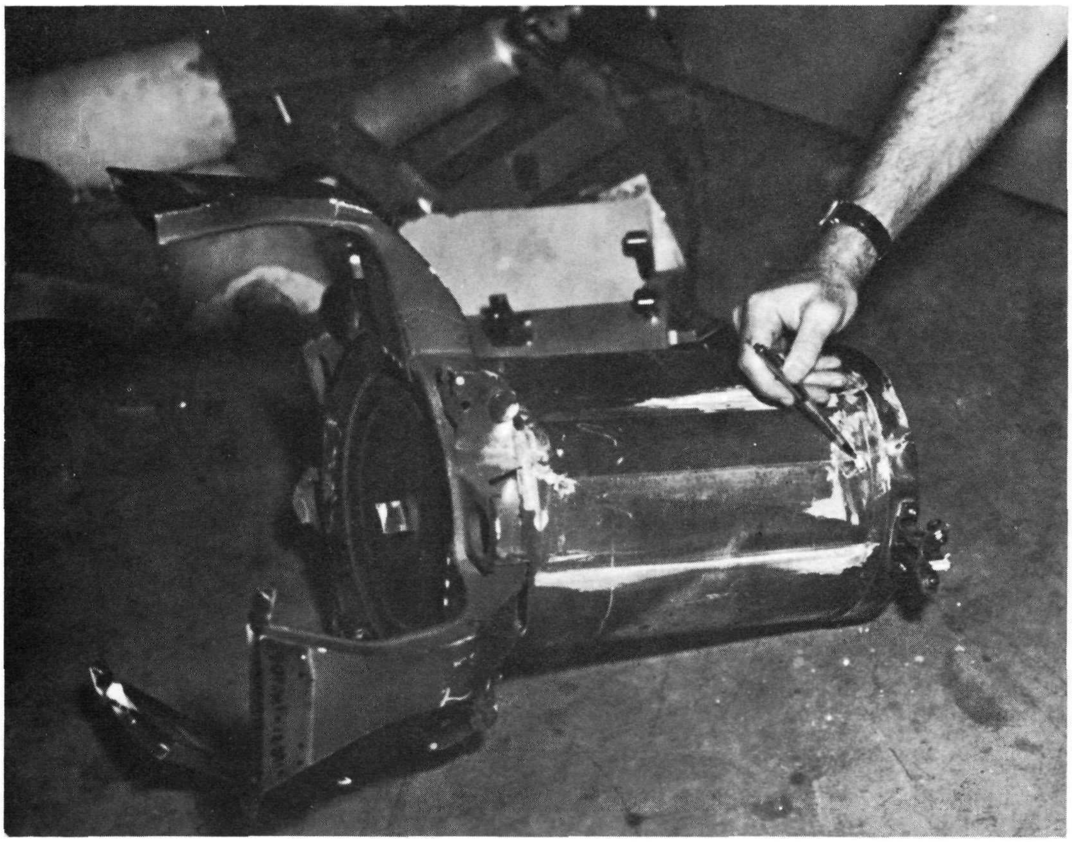

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Figure 9. Reactor Vessel After 100-ft, Side-On Drop Test

The nuclear consequences of possible reflector drum rotation, during impact, have been investigated by making four limiting calculations using the worst kind of accident assumptions. In each calculation, it was assumed that the reactor was subcritical, but the two spring-loaded drums were fully inserted, and that either one or two of the other drums rotated in at 5.5°/msec or 8.1°/msec, and further, that they remained in until reflector block separation. The energy release was calculated by applying the equation:

$$Q = 2N\tau(e^{t/\tau} - 1)$$

where

Q = energy release

N = initial power level

τ = reactor period

and t = time after reactivity input till reflector separation.

This is conservative because it describes a step input of reactivity and equal power generation during the rise and fall of reactivity. Using actual drum worth vs position and reactivity vs reactor period curves, the maximum energy release was found to be only 230 watt-sec.

Upon tail-on impact, 9 in. of the converter end rolled up as shown in Figure 10. For an instant after the impact, it appeared as if the reactor would remain in its original position, then it fell into the converter cone. All parts of the reflector assembly and reactor structure, except one reflector drum, were contained within the converter cone. All bottom drum brackets were severed, and all top pins were bent out. A circumferential buckle developed at the

7611-5509

Figure 10. Test Article After 100-ft, Tail-On Drop Test

transition region of the core vessel. In the buckle region, the vessel wall was parted almost completely around the circumference. The steel tension band was severed, but one of the two fixed reflector blocks remained with the vessel (see Figure 11).

The velocity of the test article in the nose-on impact was 64.4 ft/sec. The impact caused complete failure of the pump radiators and severed all of the reflector drums. After the vessel support legs failed, the reflector blocks were pushed into the converter structure and were held around the reactor vessel by the structure (see Figure 12). The bottom grid plate was severed, and seven fuel elements punctured the bottom head of the core vessel. The elements protruded 3 in. through the head, as shown in Figure 13. This failure is thought to have occurred because of a cutout from the shield which was made to provide room for the accelerometer. Had this cutout not been made, the vessel would not have failed in this manner because of the support provided to the head by the shield. All vessel support legs were severed.

No useful information was obtained from the onboard instrumentation during any of the drop tests. The final condition of the test article, however, indicated

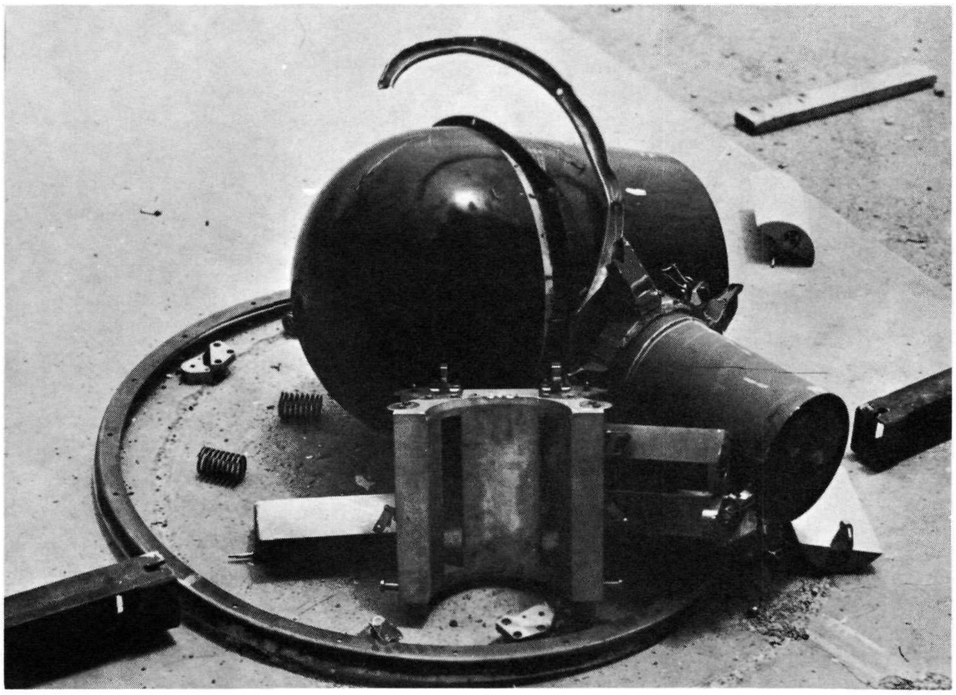

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Figure 11. Reactor After 100-ft, Tail-On Drop Test

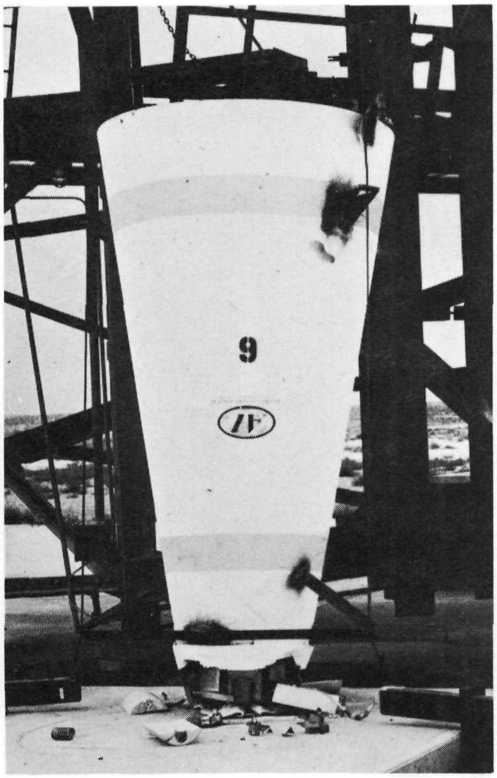

Figure 12. Test Article After 100-ft, Nose-On Drop Test
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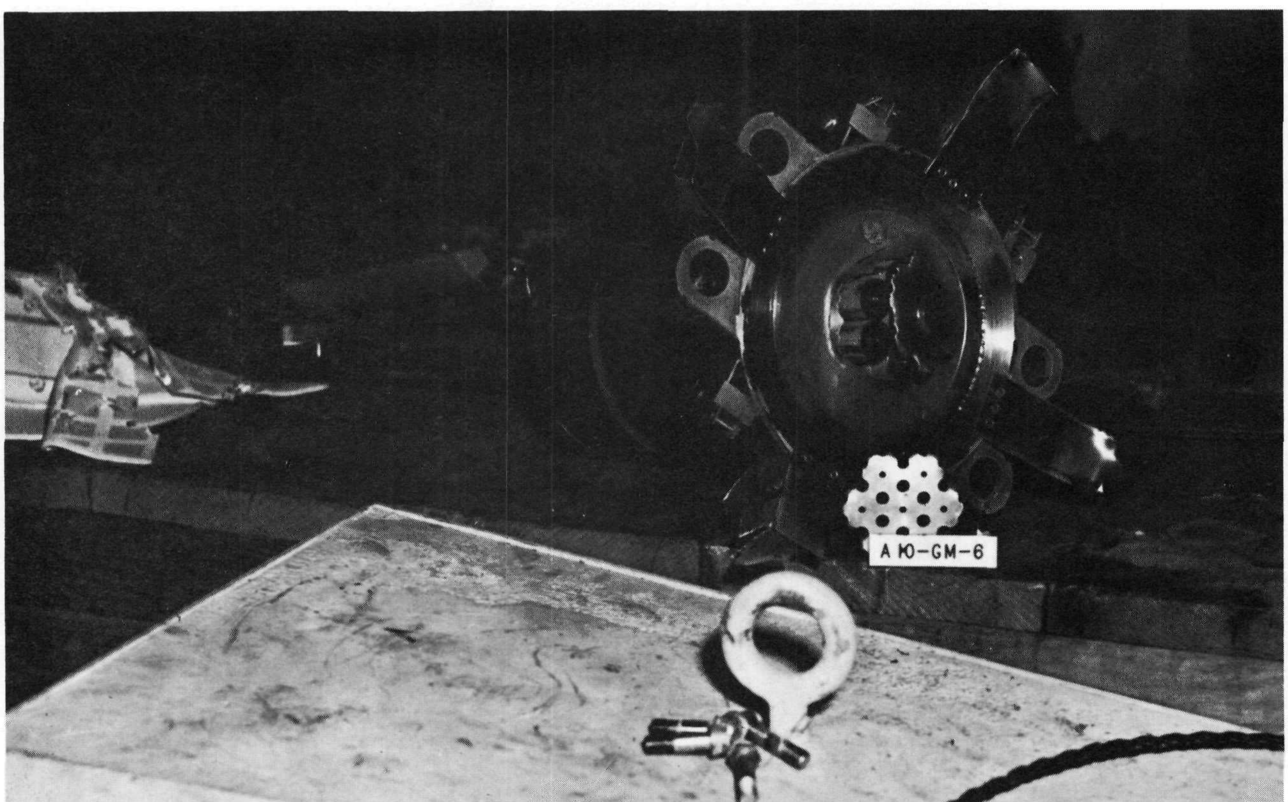

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Figure 13. Reactor Vessel After 100-ft, Nose-On Drop Test

that no nuclear hazard would result as a consequence of the APU falling from the top of the launch vehicle, unless the reactor is subsequently immersed in water.

F. FIRE TEST

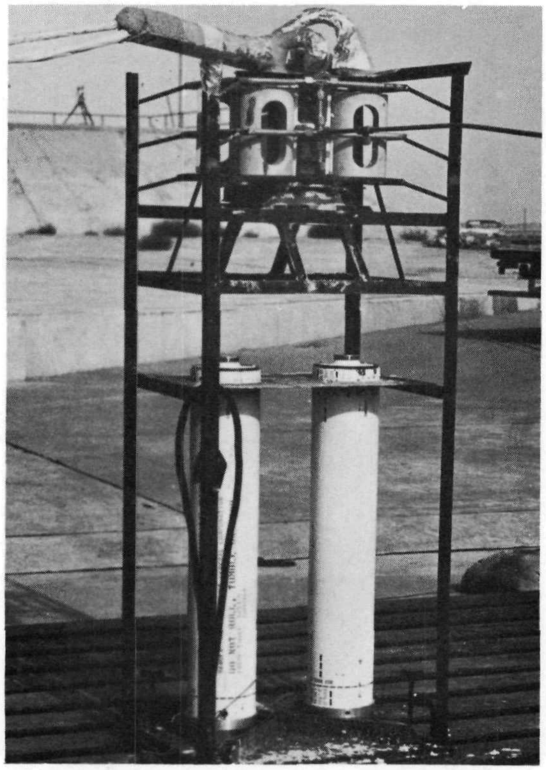
The purpose of this test was to measure differential expansion and to observe evidence of structural failure of the reactor when subjected to a high thermal flux environment. It was intended to simulate a prelaunch or postlaunch abort and subsequent propellant fire.

This test was performed on July 19, 1962. The test article, including the reactor vessel and reflector assembly, was mounted on a horizontal test stand (see Figure 14). A burning cycle of 4000°F flames for 2.2 sec, and 1500°F flames for 15 min completely surrounded the reactor. Two Sparrow rocket motors, with expansion nozzles removed, provided the high temperature for the 2.2 sec. A triple-ring butane burner, using an oxygen-rich mixture, was used for the 15-min soak. This burning cycle was chosen based upon data obtained from the Martin Company report number MND-P-2352. The nose cone was not installed on the test article. In the event of fire with the nose cone attached, a destruct charge (HMX explosive, self-igniting at 720°F) would ignite and separate the reflector assembly from the reactor.

Instrumentation for this test included onboard strain gages and thermocouples, 16-mm color documentary film coverage, and black and white still photographs.

Figure 15 shows the test article after the test. The steel tension band was severed during the initial high-temperature run. This allowed the reflectors to separate from the vessel. The reflectors, as shown in Figure 15, were prevented from falling away from the vessel by the triple-ring butane burner. A local deflection inversion, 6 in. in diameter, was also observed on the lower head. These were the only visible effects of the test. No nuclear hazard would have existed unless the reactor was subsequently immersed in water.

Some question exists as to the conditions during this test and how they would compare to an actual missile abort fire. Indications are that the energy generated during the test was less than that which would be released during a launch pad abort; therefore, the test results are a conservative indication of the consequences.



7611-5516
Figure 14. Test Article Before Fire Test

7611-5515
Figure 15. Test Article After Fire Test

G. WATER IMPACT TESTS

The purpose of these tests was to observe the reactor assembly during and after water impact. These tests were intended to simulate an abort at 58 sec after launch (10,000 ft) or at any subsequent time, including a free fall from the apogee.

Three reactor assemblies and one APU (including the converter and shield) were impacted, at different attitudes, into an 8 x 8 x 16-ft water tank. Since the nose cone is a low-energy absorbent structure and approximately 7000 ft-lb, out of the total reactor impact energy of 1,500,000 ft-lb at 560 ft/sec, will deform it against the reactor head, it was not included on these test articles. Instrumentation for the tests included pressure transducers, strain gages, and accelerometers. High-speed color motion picture coverage of the pretest, test, and posttest activities was provided. Black and white still photographs were also taken.

The side-on water impact test was performed on August 1, 1962. Impact velocity in this test was 550 ft/sec; the reactor passed through the water tank and came to rest on a mound of loose dirt behind the tank. The fixed reflector blocks and the reflector drums were completely separated from the reactor vessel in the water. The vessel was found intact (see Figure 16). No useful data were obtained from the onboard instrumentation because the recording equipment failed to operate.

The nose-on water impact test was performed September 12, 1962. Impact velocity in this test was 573 ft/sec; the reactor passed through the water tank and came to rest on a mound of dirt 20 ft behind the tank. The reflector assembly separated completely from the reactor vessel in the water. Also, the NaK pump, the upper head, and the upper grid plate were severed from the test article. Fuel elements were displaced longitudinally in such a manner as to form a spherical pattern at the ends. Sufficient disassembly of the core did not occur to prevent its criticality in the water.

The tail-on water impact test was performed on October 4, 1962. Impact velocity in this test was 596 ft/sec. The reflector assembly was separated, and the core vessel split open axially. Fuel elements were displaced longitudinally through the bottom of the vessel. Two elements were completely ejected from the array (see Figure 17). The core would have gone critical in the water.

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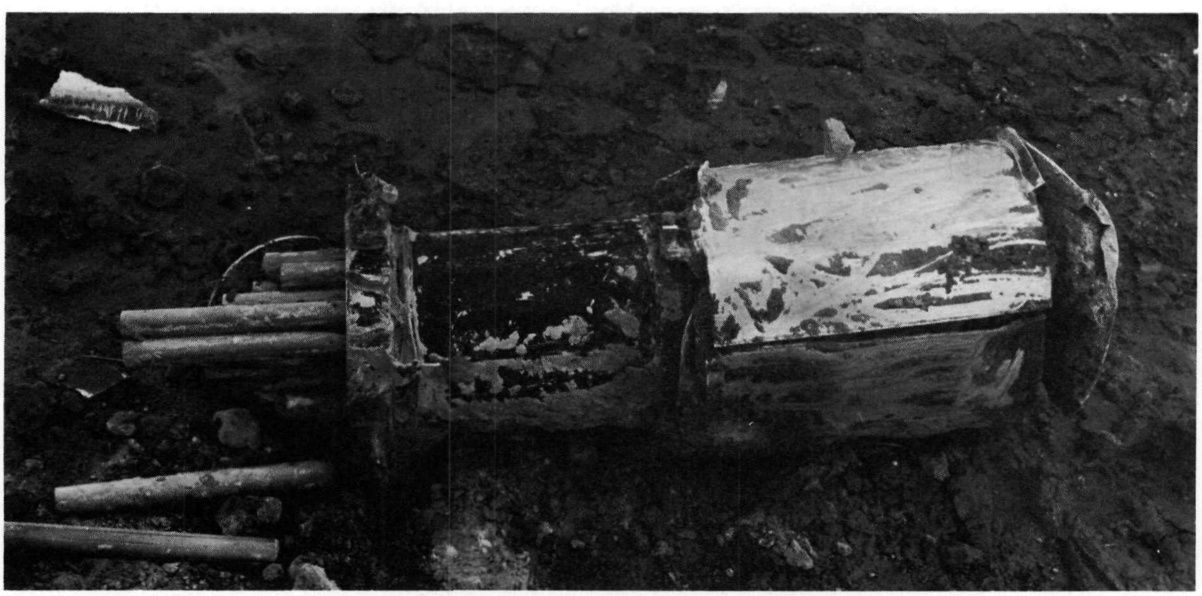
Figure 16. Reactor Vessel After Side-On Water Impact Test



7568-0282
Figure 17. Reactor Vessel After Tail-On Water Impact Test

In Test No. 14, it was planned to impact the APU at 750 ft/sec. A malfunction of one of the sled rocket stages limited the impact velocity to 428 ft/sec. The reflector assembly, NaK pump, shield, converter structure, bottom grid plate, and bottom head separated from the core vessel. Fuel elements were displaced through the open end of the vessel (see Figure 18). Core disassembly was not sufficient to prevent criticality in the water.

H. CONCRETE IMPACT TEST

The purpose of this test was to observe the reactor assembly during and after a high-speed concrete impact. This test was intended to simulate an abort at 58 sec after launch (10,000 ft) or a free fall from the apogee.

The test article included the NaK pump, core vessel, internals, and reflector assembly. Five strain gages and an accelerometer were on board. High-speed film coverage and still photography were provided.

The test was performed on August 15, 1962. A concrete-faced monorail sled was impacted at 560 ft/sec onto the pump end of the test article (see Figures 19 and 20). The impact completely destroyed the reactor. The vessel was in three parts: the upper head, lower head, and the shell. The lower head was not found, but some shrapnel-shaped pieces of the upper head were collected. The shell was completely flattened and had many local failures. Figure 21 shows the pieces of the test article which were gathered after the test.

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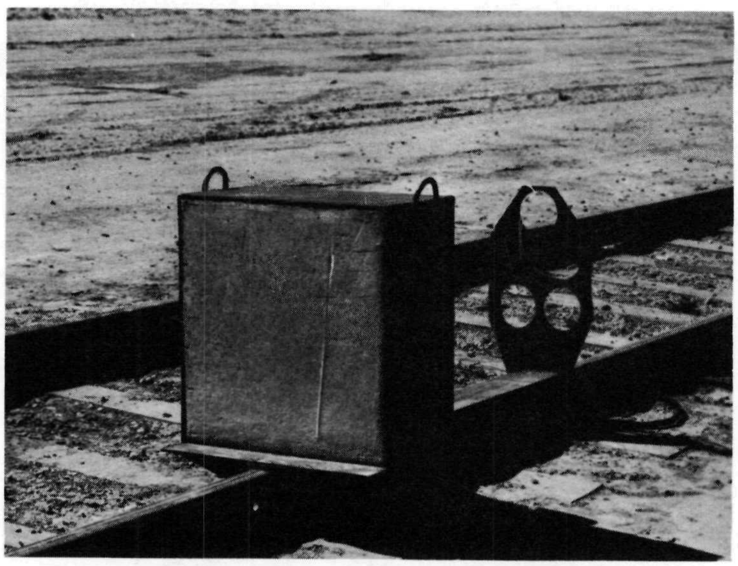
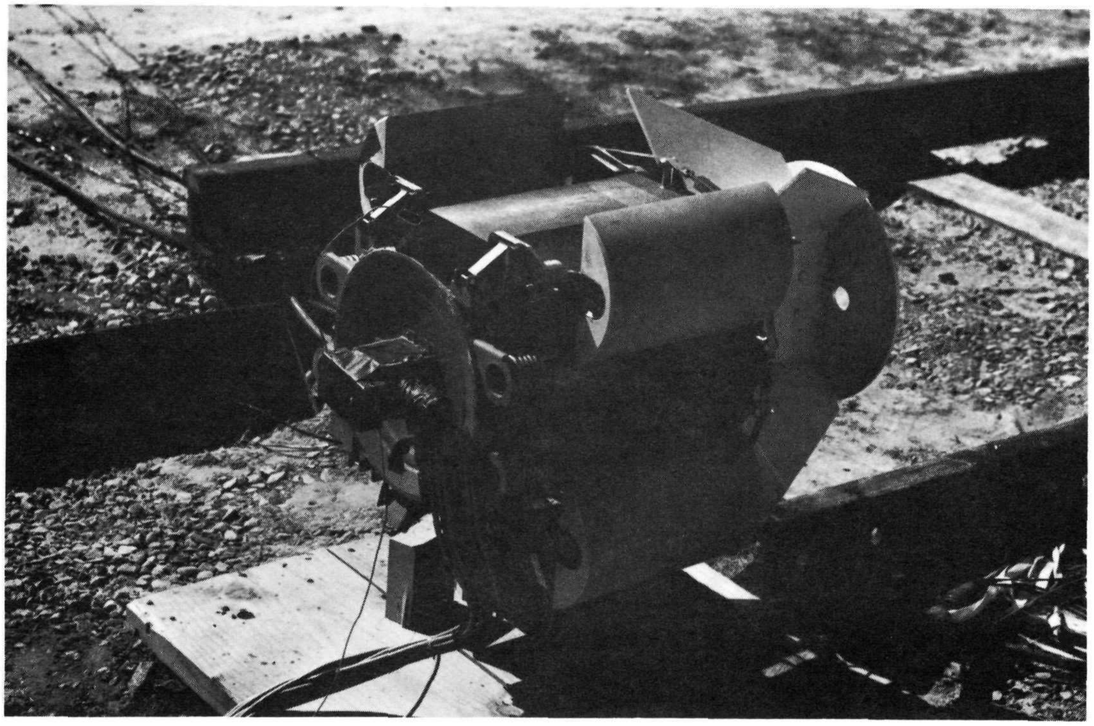
Figure 18. Reactor Vessel After Nose-On Water Impact Test



7611-5504

Figure 19. Concrete-Faced Monorail Sled Used in Concrete Impact Test



7611-5513
Figure 20. Test Article Before Concrete Impact Test

7568-0284
Figure 21. Pieces of Test Article Recovered After Concrete Impact Test