PNL-2670
UC-35

Radiological and Toxicological Assessment of an External Heat (Burn) Test of the 105MM Cartridge, APFSDS-T, XM-744

by
R. L. Gilchrist, Project Manager
G. B. Parker
J. Mishima

March 1978

Pacific Northwest Laboratory
Richland, Washington 99352
Operated for the
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Battelle

August 23, 1978

TO RECIPIENTS OF PNL 2670:

Subject: Errata list for PNL 2670, Radiological and Toxicological Assessment of an External Heat (Burn) Test of the 105 mm Cartridge, APFSDS-T, XM-744

The following errors were brought to my attention. Please make these corrections on the cover and on the title page of the document. I apologize for any inconvenience or misunderstanding these errors may have caused.

Cover page: Change the title from ". . . 105 MM Cartridge, APFSDS-T, XM-744" to ". . . 105 mm Cartridge, APFSDS-T, XM-774."

Title page: Change the title from ". . . APFSDS-T, XM-744" to ". . . APFSDS-T, XM-774."

J. S. Burlison

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Editor/Writer
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SUMMARY

Pacific Northwest Laboratory conducted research to assess the potential radiological and toxicological hazard of depleted uranium aerosol release. This type of release might arise from accidents with XM-774 ammunition involving great heat.

Twelve rounds of packaged ammunition were subjected to an external heat (burn) test. Examination of the site on the day following the test revealed that all 12 depleted uranium penetrators were completely intact. Oxidation of the penetrators was not apparent, even on the most severely burned projectile located at ground zero. Eleven of the 12 projectiles were recovered with the sabots intact; some sabots appeared charred.

It was concluded that no airborne release of depleted uranium had occurred and subsequently there had been no radiological or toxicological hazard from DU during this test. However, this conclusion may not apply to the release of depleted uranium in other types of fires involving this ammunition because other factors may affect the fire. These factors include type of fuel, number of ammunition rounds, and type of structure housing the ammunition.

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FOREWORD

This study was conducted on the recommendation of the Joint Technical Coordinating Group/Munitions Effectiveness (JTCG/ME) Working Group on Depleted Uranium and was supported by the Office of Assistant Project Manager for Tank Main Armament Development, XMI Tank System, under Army Project No. IL663608D060. The technical monitors were the Working Group Chairman, Ernest W. Bloore, and Edward F. Wilsey, both of the U.S. Army Armament Research and Development Command's (ARADCOM) Ballistic Research Laboratory (BRL). The study supplemented the Hazard Classification Test[1] conducted by Gary J. Gray of ARADCOM's Large Caliber Weapon Systems Laboratory (LCWSL). The success of the test and this study was attributable to the coordination and support efforts of the U.S. Department of Energy (DOE) Nevada Operation Office, Office of Special Projects; the DOE Nevada Test Site and Contractor personnel, especially Linden Kelly, Site Manager; and the Nellis Air Force Base Explosive Ordinance Disposal (EOD) team, headed by Sgt. Jesse Campbell.

INTRODUCTION

This report describes work done by Pacific Northwest Laboratory (PNL)[a] for the Joint Technical Coordinating Group/Munitions Effectiveness (JTCG/ME) Working Group on DU to supplement the burn test and was conducted simultaneously with the fragment pattern test, to assess the potential for airborne release of depleted uranium (DU) aerosol, and the subsequent radiological and toxicological hazard from XM-774 ammunition exposed to accidents involving extreme heat. Each round of this ammunition contains a penetrator core of 3.3 kg of depleted uranium, which is classified as a radioactive source material and a toxic heavy metal. In this hazard classification test, 12 boxed rounds of ammunition, packaged in conventional shipping/storage containers, were burned in a wood bonfire at Frenchman Flat (within the DOE/Nevada Test Site) on October 17-20, 1977.

OBJECTIVE

The objective of this effort was to assess the radiological and toxicological significance of the potential airborne release of depleted uranium aerosol from XM-774 ammunition during an external heat (burn) test. Each round of this ammunition contains a uranium based alloy penetrator whose composition is uranium-0.75 w/o titanium.

The procedures for establishing and conducting an external heat test are described in TB-700-2.[2] The test is one of a series designed to determine the appropriate hazard classification of ammunition storage and handling. The objective of the standard burn test is to determine the pattern of fragments resulting from the ammunition "cooking-off" during the fire and within a 500-ft radius of the fire. This standard test is not designed to assess the release of DU to the atmosphere.

BACKGROUND

There was no previous experience in the burning or fragmentation of XM-774 ammunition. Preparations were made assuming that the DU penetrators

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(a) PNL is operated by Battelle Memorial Institute.

would fragment and burn, and that an aerosol would be released during the test. Work was done before the test to determine procedures to account for the uranium found on the ground and, by mass differences, to estimate the airborne release of DU. These procedures are explained more fully in the section on Test Preparations.

The conventional method of measuring the release of a substance to the atmosphere normally would require an extensive air sampling network consisting of several towers and several hundred samplers in a predetermined downwind array, from which measurements would be taken during several release periods. However, because the radiological and toxicological assessment was not to interfere with the standard burn test, the time available for preparation was limited, and only one bonfire was to be conducted, an alternative approach was formulated. This approach required careful collection of all readily visible depleted uranium fragments after the test and a determination, by mass balance, of the amount of DU released as an aerosol.

It was anticipated that the majority of the DU fragments could be visually identified and recovered. The difference between the total weight of the twelve penetrators and the total weight of the fragments would give the mass of DU unaccounted for, and this difference would be assumed to be the maximum airborne release of DU from the test. If the mass difference unaccounted for was greater than approximately 30% of the original mass of DU, an additional search for DU would be conducted. This second search would be performed using either a standard Geiger-Mueller (GM)[a] counter or Field Instrument for Detection of Low Energy Radiation (FIDLER)[b] to locate DU fragments. Three two-man teams composed of engineers from PNL and personnel from Reynolds Electrical and Engineering Company, Inc. (REECO) at the Nevada Test Site would conduct this second DU recovery operation.

To prepare for this part of the task, PNL personnel spent time in the field evaluating techniques for using these instruments to detect small

(a) Eberline E-140 Count Meter with Microwindow GM Probe.
(b) Eberline SAM-2 with RO-21 Stabilized Scintilation Detector.

amounts of DU. It was demonstrated that the GM counter was the best instrument for detecting DU quantities as small as 1 g (about 1/4 in. in diameter) from about 2 in. above the sample. The FIDLER was found to be more sensitive for small samples (<10 g) which were slightly buried in the sand. Both instruments could detect an unburied 1 g sample of DU; however, the GM was found to be more convenient to use due to its lighter weight.

The accuracy of this method to estimate aerosol release was determined to be no better than 20% to 30%, unless most of the projectiles could be recovered intact. Only one test was scheduled and this test was to include 12 rounds of ammunition. Data from this test were also to be used to estimate release of airborne DU from much larger quantities of ammunition.

After computing the fraction of DU unaccounted for, which was assumed to be airborne, the airborne concentration downwind and integrated dose to an individual at a selected distance downwind would be calculated. From a radiological standpoint, it is known that a relatively large amount of depleted uranium can become airborne without exceeding the maximum allowable exposure to humans some distance downwind. From a chemical toxicity standpoint, the maximum allowable release of DU that will not exceed the threshold limit value (TLV) is calculated according to correlations available for chemical sources released to the atmosphere.

TEST PREPARATIONS

An area within the Nevada Test Site was chosen for the burn test based upon the following criteria: 1) the site was relatively free of vegetation and debris within a radius of 500 ft from the burn center, 2) the area was flat, 3) the radiation background level in the area was low and uniform, and 4) there was a shelter nearby for weighing the test specimens and observing the test. The site chosen, Frenchman Flat, is a dry lake bed about 10 miles north of Mercury, Nevada (Figure 1).

A grid pattern was plotted with white chalk link to locate fragments thrown out by the exploding mounds in the fire. This pattern had radial lines 30 degrees apart which extended 500 ft from the center of the pattern. Each radial line was marked with chalk at 20-ft intervals from the center to 100 ft and at 100-ft intervals from 100 ft to 500 ft. Circumferential lines were plotted connecting all radial distance marks out to 200 ft. The radial distances and angles were marked with black spray paint. The close-in portion of the pattern is shown in Figure 2.

REECO personnel performed a radiation survey of the burn area to assess background readings in the area. The background readings were measured with both a GM counter and a FIDLER. Background reading on the FIDLER was low and uniform, between 300 to 400 counts/min. It was determined that interference from the background would not be a problem if it became necessary to survey the area to locate DU fragments. A single high volume air sampler was set at the 100-ft mark at 270^{o}, the anticipated downwind direction, to collect a sample for use by the radiological safety personnel at the test site. A trailer located near the burn site was to be used for the field weighing work.

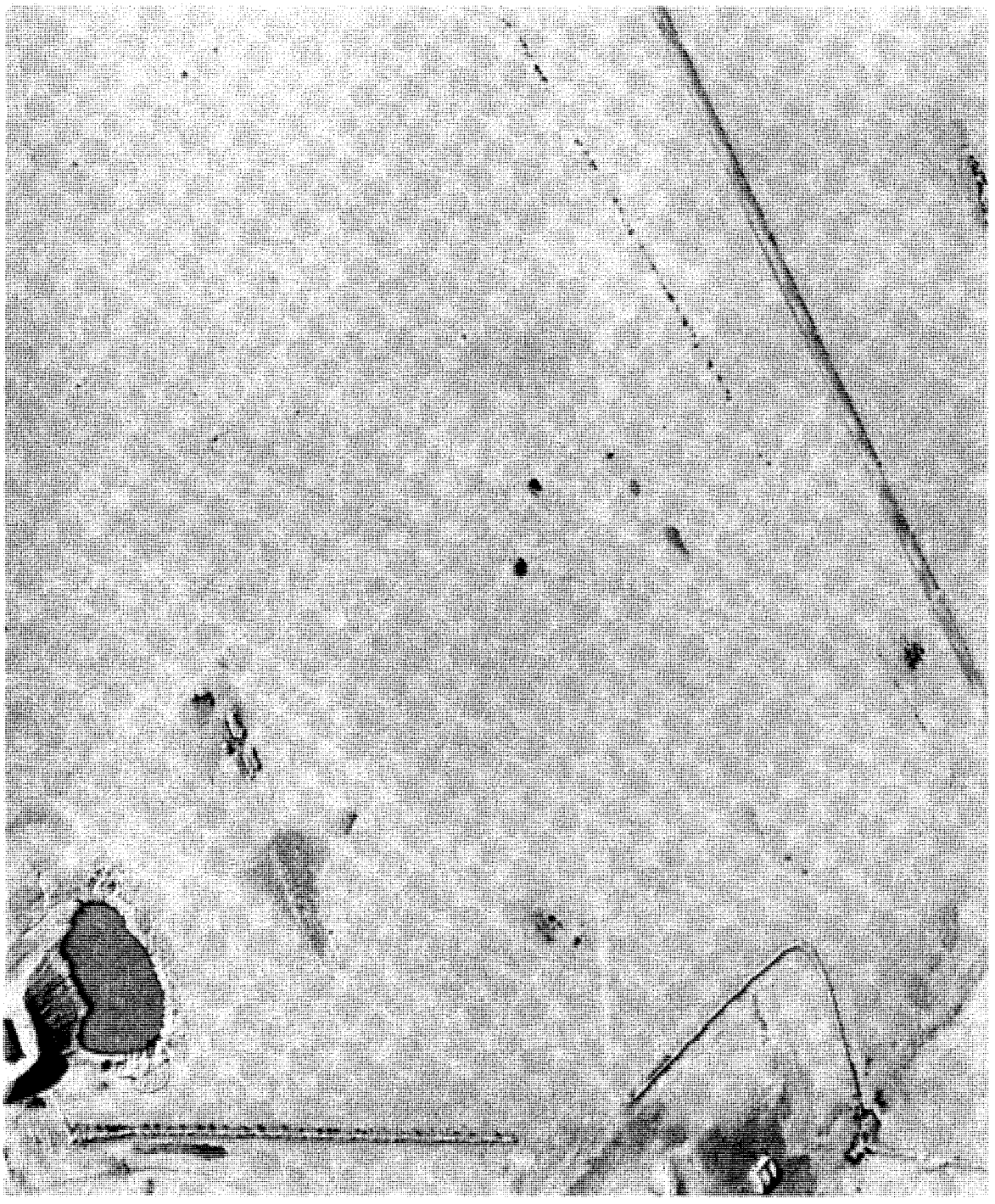


FIGURE 1. Aerial Photograph of Burn Test Site

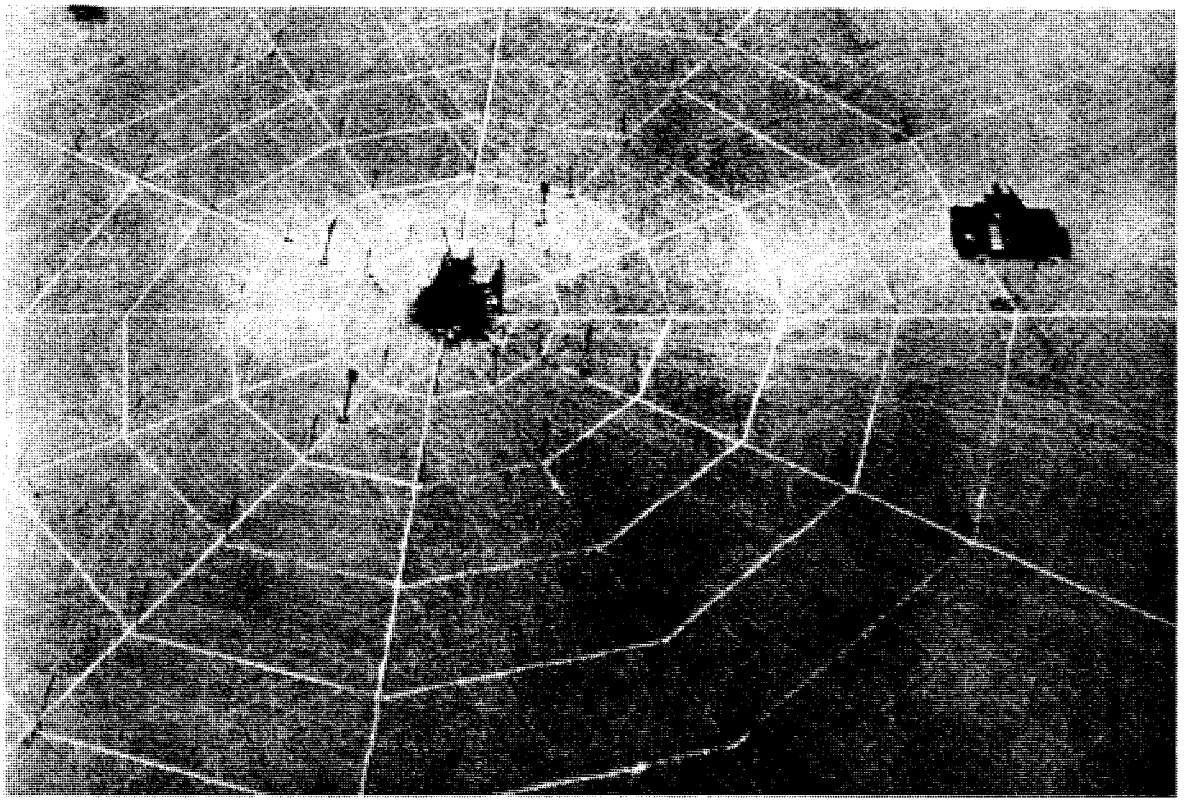


FIGURE 2. Aerial Photograph of First 100 ft of Grid for the Burn Test

TEST DESCRIPTION

Twelve rounds of ammunition were stacked and strapped to an open metal "table" at the center of the grid. Each round was encased in a cylindrical, impregnated, fiber-reinforced cardboard container with plastic packaging inserts and metal cap ends. Two containers with the rounds positioned in opposite directions were placed in a standard shipping container for 105 mm ammunition, a rectangular wooden box with a hinged lid. The six boxes were oriented east-west along the 90^{o}-270^{o} lines of the grid. Wood was stacked under, around, and on top of the boxes and soaked with 50 gallons of diesel fuel. Figure 3 shows the boxes and the wood before the fire was ignited. An Air Force Explosive Ordinance Demolition (EOD) team set a time detonator fuse in the pile to initiate burning. The actual burn started at 1615 hours on October 18, 1977.

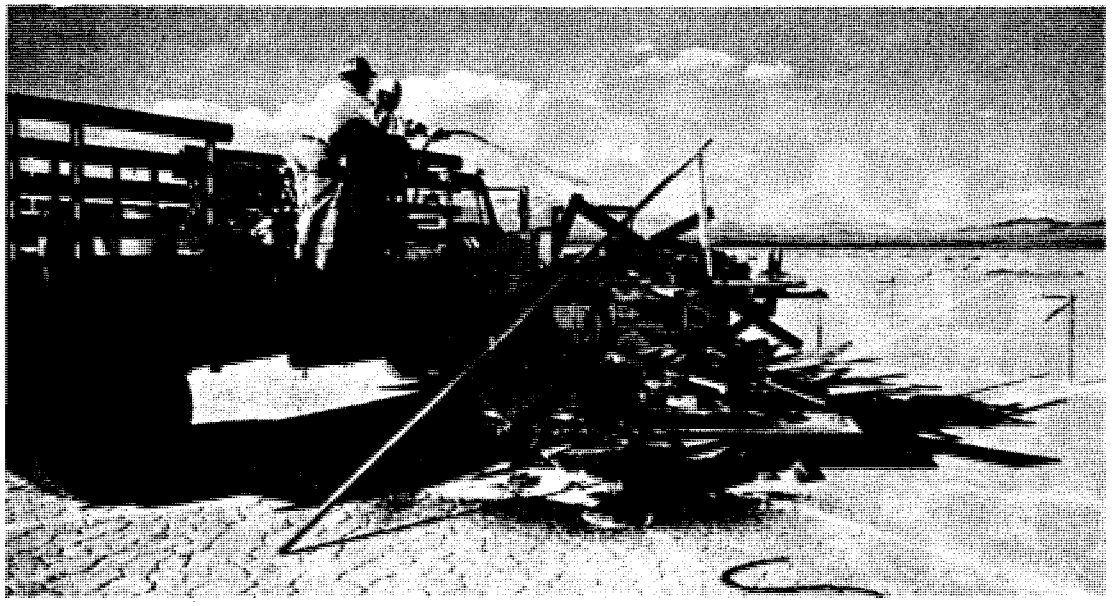


FIGURE 3. Ammunition and Wood Prior to Burning--Fuel Being Added

The fuel and wood burned for approximately 17 minutes before the first round exploded. In 10 minutes, from about 1632 to 1642 hours, nine more explosions occurred. Burning of pink-orange tracers was noted on several occasions. Figure 4 shows the fire and one of the explosions. The fire extinguished itself shortly after the last explosion. No one was allowed to enter the area until the next day. During the fire, complete photographic coverage was provided by two video tape units at 500 ft and 1000 ft, a movie camera at 1000 ft, still pictures at 1000 ft, and still aerial photography from a helicopter.

FIGURE 4. Fire and Explosion During Burn Test

RESULTS

The test site was entered and inspected on the morning of October 19, 1977 by the Air Force EOD team and was declared safe to enter. The area was littered with debris of all kinds, including shell casings, container sections, and a large number of propellent pellets. All 12 projectiles with their DU penetrators were located within the 500-ft grid and were completely intact. No penetrator had fragmented during the test.

Locations of the projectiles were identified first by painting a circle around them with fluorescent orange paint, and then by noting their exact location on the grid. Each projectile was then photographed. Figure 5 is a schematic of the grid with the location of each projectile noted by the radial distance in feet from ground zero and labeled with a letter designation. Figure 6 is an aerial photograph of the burn site showing the 12 projectiles circled with orange paint and labeled with letters corresponding to Figure 5.

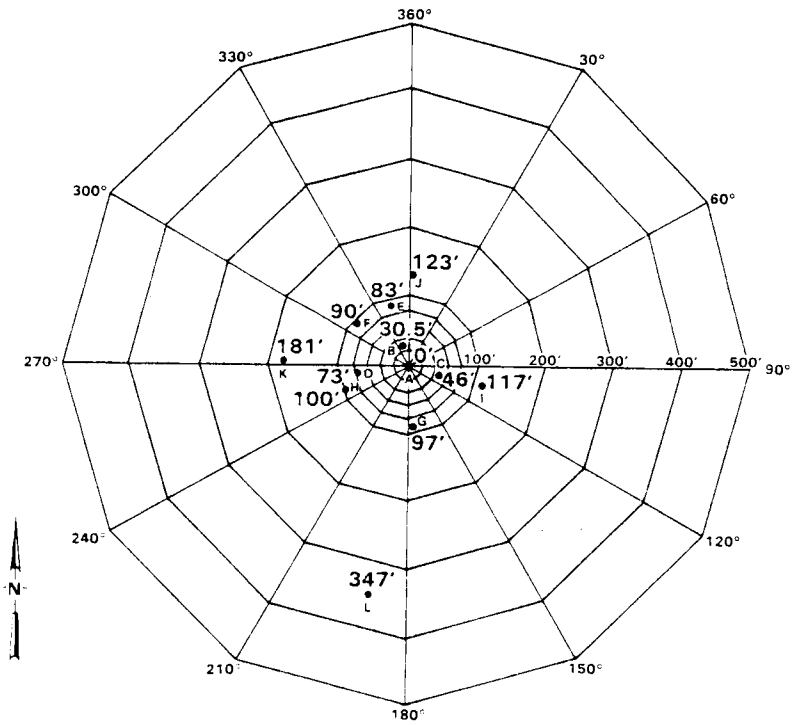


FIGURE 5. Schematic of Test Grid Indicating Position and Distances from Ground Zero of Projectiles After Burn Test

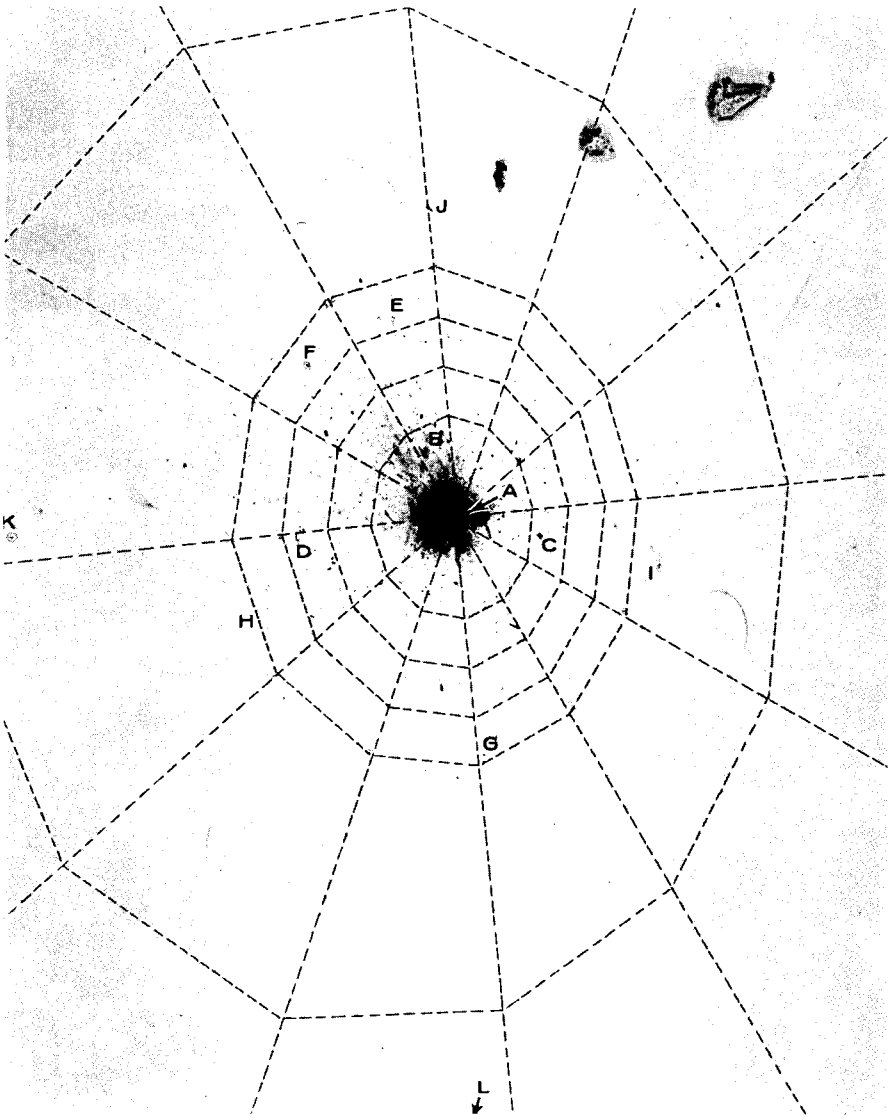


FIGURE 6. Aerial Photograph of Burn Site Noting the Location of Each Projectile

Figure 7 is a composite of the 12 projectiles as they were found at the burn site. They are given letter designations according to the radial distance at which they were found from the center of the test (ground zero); projectile A is the closest (0 ft) and projectile L the farthest away (347 ft). As shown in Figure 6, no two projectiles were found at exactly the same distance from ground zero. A brief physical description of each follows.

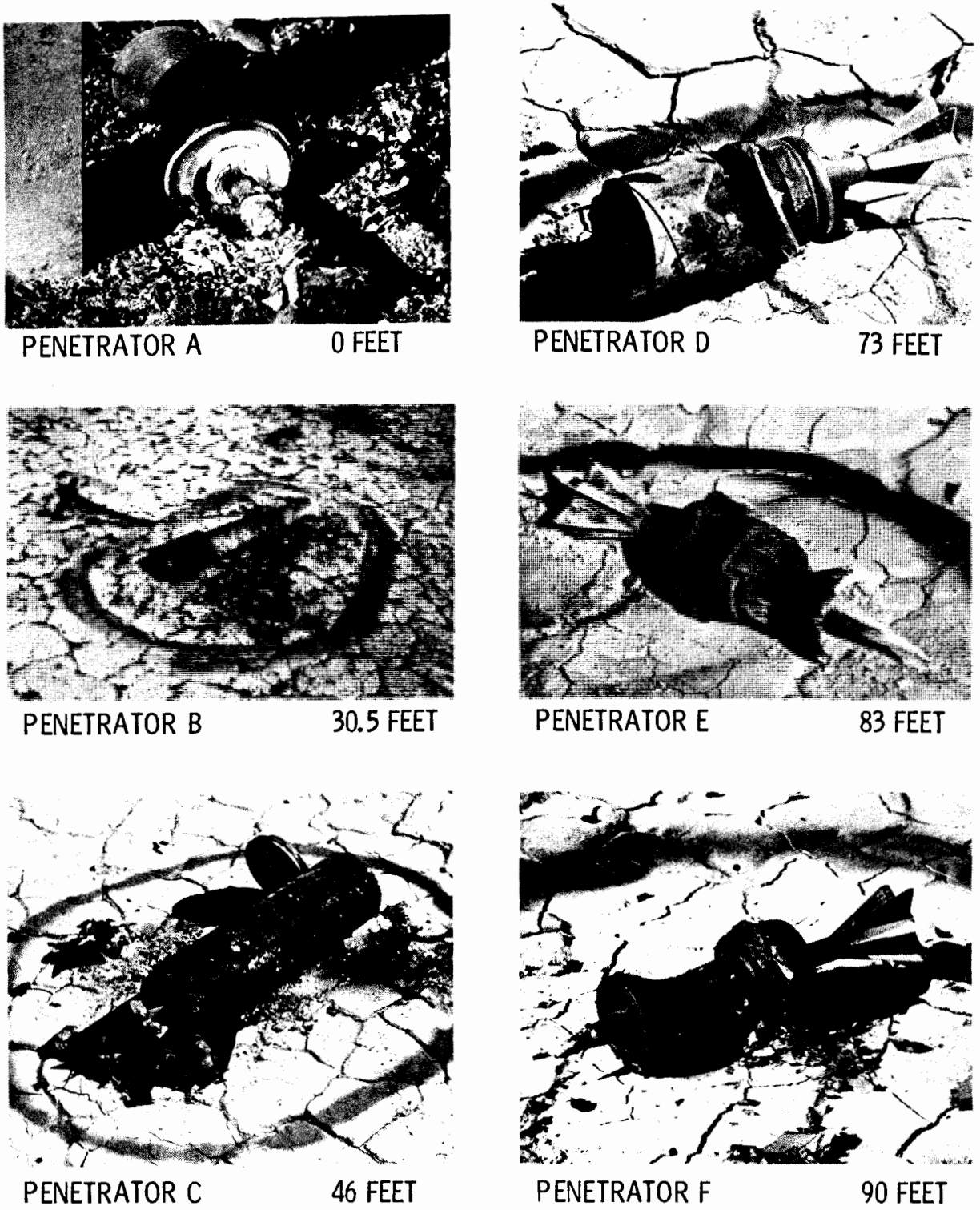
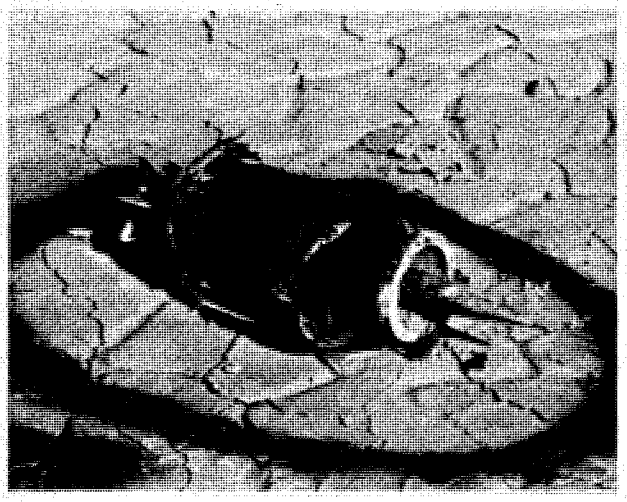
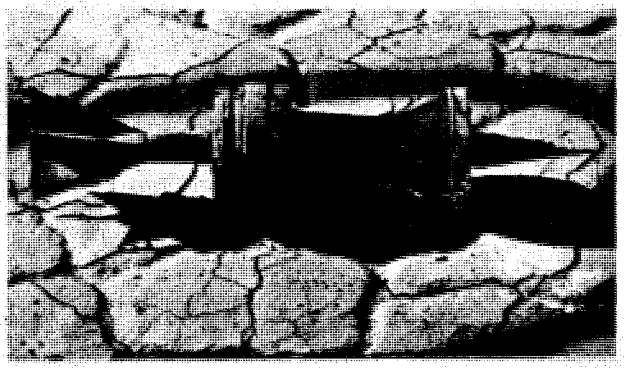


FIGURE 7. Composite Photograph of the Twelve Penetrators as Discovered After Burn Test

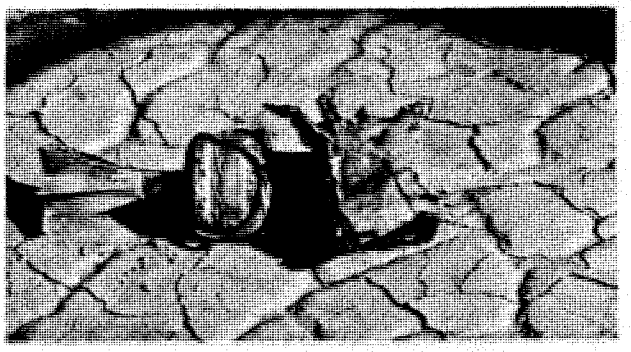


PENETRATOR G 97 FEET

PENETRATOR J 123 FEET

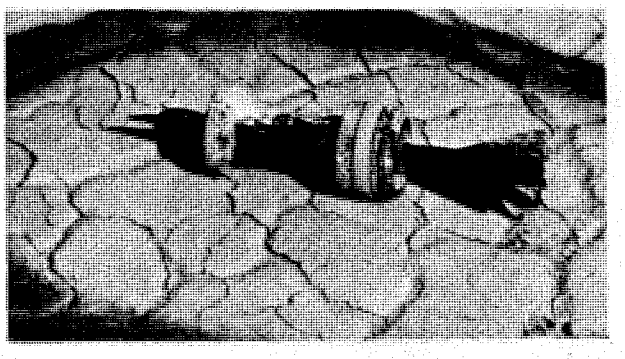


PENETRATOR H 100 FEET



PENETRATOR K 181 FEET

PENETRATOR I 117 FEET

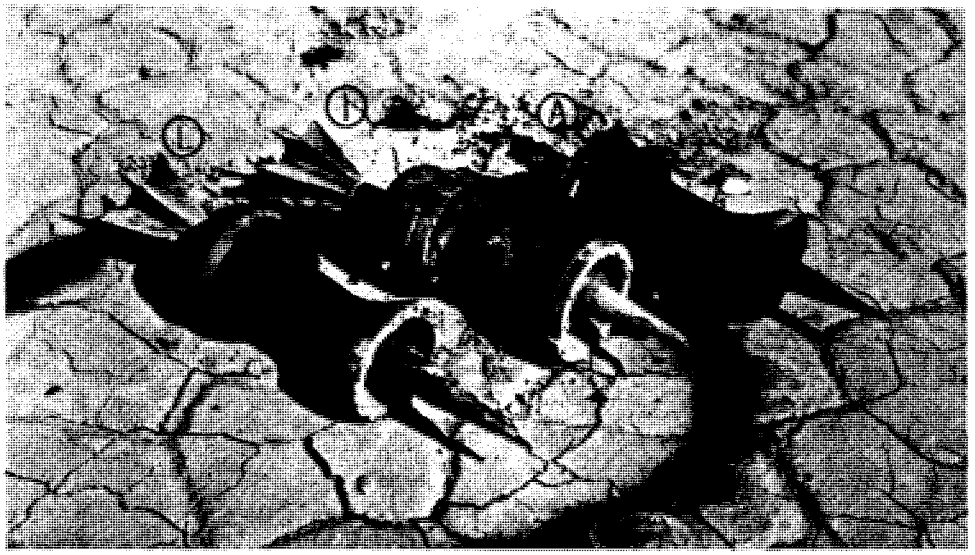


PENETRATOR L 347 FEET

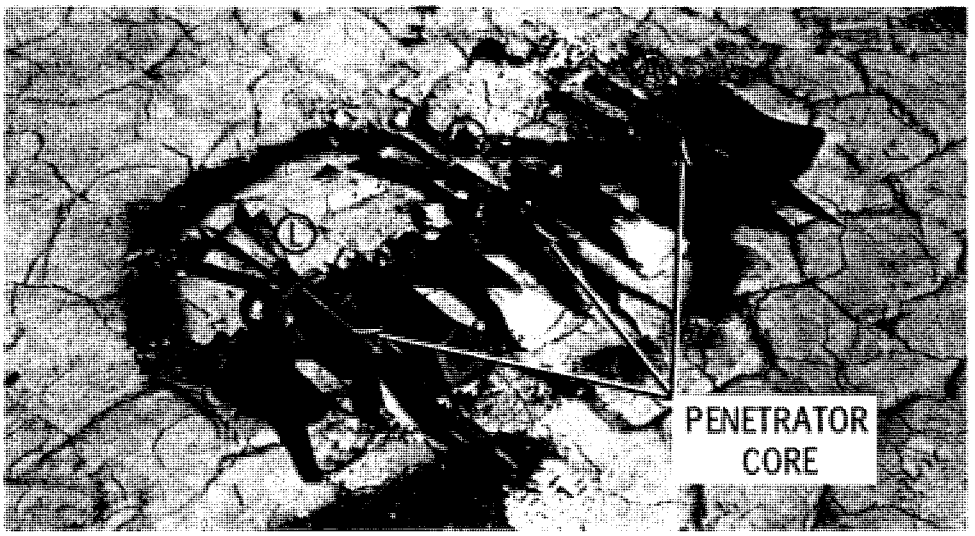
- Penetrator A. Penetrator A was found at ground zero (0 ft) underneath the metal table with the sabot completely intact but with the tail fin completely melted away. Only the base of the fin remained. This penetrator was probably subjected to the greatest heat for the longest period of time. White powder was discovered at the base of the projectile. The powder appeared to be oxidized sealant.
- Penetrator B. Penetrator B was found at 30.5 ft and was still part of a complete round which had not exploded. Part of the fiber container was attached to the round. Because the original orange paint on the sabot was still visible, it was concluded that the projectile had not been subjected to much heat.
- Penetrator C. This penetrator was found at 46 ft and was part of a complete projectile which was partially enclosed in a fiber container. Only the tail fin of the projectile was exposed. It appears that the container had been slightly charred.
- Penetrator D. Penetrator D was found at 73 ft and was still part of the complete projectile. This projectile was partially encased in the fiber canister and did not appear to be charred.
- Penetrator E. This penetrator was found at 83 ft and was still part of the complete projectile. The projectile was not charred and the orange paint on the sabot could still be seen. Part of a fiber container enclosed the projectile. The windshield was slightly bent, probably due to impact with the ground.
- Penetrator F. Penetrator F was found at 90 ft and was definitely subjected to fire as seen from the discoloration of the rear of the sabot and tail fin. Except for a melted or missing plastic compression ring, the projectile was complete.
- Penetrator G. This penetrator was found at 97 ft and was part of a complete projectile. The projectile was only slightly burned as shown by the discoloration of the sabot and section of fiber container surrounding the projectile. No other damage was noted.

- Penetrator H. Penetrator H was found at 100 ft as part of a complete, undamaged projectile. The orange paint on the sabot was only slightly discolored due to heat.
- Penetrator I. Penetrator I was found at 117 ft as a complete, projectile. The sabot was slightly discolored at the rear due to fire and was beginning to separate, possibly due to impact. The windshield was noticeably bent, again, likely due to impact with the ground.
- Penetrator J. This penetrator was found at 123 ft and was definitely subjected to heat, as indicated by partial melting of the tail fin. The penetrator was still a part of the complete projectile and was encased in part of the fiber container. Partial melting of the plastic insert was noted. The white powder present at the rear of the sabot was assumed to be oxidized sealant.
- Penetrator K. Penetrator K was found at 181 ft as a complete projectile. Part of the cartridge container was attached to the projectile. The paint on the sabot was slightly charred but the sabot was completely intact.
- Penetrator L. Penetrator L was thrown the farthest, 347 ft, and was found as a complete projectile. The projectile was not burned nor was the penetrator damaged except for a slightly bent windshield.

Figure 8 shows three projectiles, each subjected to apparently varying degrees of degradation. The extremely black projectile (A) at the far right was found at ground zero; it is believed that this penetrator was subjected to the most severe burn conditions. Projectile L, at the far left of was found at 347 ft and was most likely subjected to the least severe burn conditions but was thrown the farthest distance. The middle projectile (I) shown in Figure 8 was found at 117 ft and suffered a damaged windshield, bent tail fin, and slightly separated sabot upon impact. The sabot of each was opened by cracking the compression ring to expose the complete penetrator. Although the penetrators were subjected to different conditions, the integrity of the depleted uranium appears to have been equally unaffected. Only the physical condition of the fins, windshields, and sabots were affected in this test, either by actual heat from the fire or by impact after being thrown from the fire.



Sabots Intact



Sabots Laid Open

FIGURE 8. Comparison of Three Projectiles Subjected to the Burn Test

CONCLUSIONS

The following conclusions about the atmospheric release of depleted uranium can be drawn from the external heat (burn) on October 17, 1977:

- The video tape, movie, still photos, and visual observation during the period of the burn show no yellow smoke characteristic of burning uranium. Absence of such smoke indicates that no significant release of uranium to the atmosphere occurred during the test.
- All twelve penetrators were found intact, complete, and with no apparent oxidation. Therefore, no depleted uranium was released to the atmosphere during the burn test.

Based on the above, it is concluded that there was no airborne radiological or toxicological hazard caused by burning twelve rounds of XM-774 ammunition in this test.

The above conclusions may not apply to the release of depleted uranium in other types of fires involving this ammunition because other factors may affect the fire. These factors include type of fuel, number of rounds, type of structure, etc.

A discussion of conditions that could cause possible oxidation and release of uranium is presented in the Appendix.

APPENDIX:

OXIDATION AND IGNITION OF DEPLETED URANIUM

APPENDIX

OXIDATION AND IGNITION OF DEPLETED URANIUM

Twelve rounds of 105 mm XM-774 antitank ammunition containing depleted uranium alloy penetrators were subjected to a burn test at Frenchman Flat at the Nevada Test Site on October 18, 1977. Ten of the 12 projectiles were recovered following the test as complete projectiles (sabots, penetrators tail fins and windshields intact and complete). As shown in Figure 7 of this report, two projectiles, designated A and J, exhibited some degree of burn damage, but there was no indication of unusual oxidation or ignition of either penetrator. Melting of a single fin in the aluminum tail assembly was observed in projectile J (Figure 7), which was recovered 123 ft from ground zero. No charring of the plastic compression ring or melting of the aluminum windshield was noted. A second unit (A in Figure 7), recovered at ground zero under the test stand, exhibited charring of the plastic compression ring and complete loss of the aluminum tail assembly. The aluminum windshield remained intact, however.

Some listed melting points of aluminum and aluminum alloys range from 480^{o} to 650^{o} C.[3] It appears that portions of the two penetrators of units A and J were subjected to temperatures in this range during some period of the test. Following the test, the compression rings were removed from the sabot of A and two other units that showed little external fire damage, I and L. Appearances of all three penetrators were similar (Figure 8), indicating the conditions imposed by the burn test did not result in observable additional oxidation.

The oxidation of uranium in air is by diffusion of oxygen ions through the oxide film.[4] The reaction is exothermic.[4] The rate can be controlled by the kinetics of the reaction or the diffusion of oxygen, depending on the characteristics of the oxide film and temperature.[5] Oxidation rates for various temperature regimes have been reported.[6,7,8] Baker and Bingle[8] present three equations for the oxidation of β-quenched uranium:

$300 < T < 450$ $\quad W^{0.8} = 1.0 \times 10^5 \, t \, [\exp - (16{,}800/RT)]$

$T = 450$ $\quad W = 0.840t$

$T = >450$ $\quad W^{1.2} = 1.8 \times 10^4 \, t \, [\exp - (14{,}300/RT)]$

where

T = temperature, ^{o}C

W = quantity of oxygen consumed, mg/cm^2

t = time, minutes

R = universal gas constant

The reaction accelerates slightly between 300^{o} and 450^{o} C and decelerates slightly above 450^{o} C.[9] "Alloying additions have a profound effect on the oxidation and ignition of uranium."[9] The presence of a few atom percent of titanium results in an increased reaction rate around 500^{o} C.[9]

It has been suggested that the ignition of uranium metal results simply from the accumulation of heat generated by oxidation.[9] Ignition is defined as when "the slope of the temperature-time curve of a self-heating specimen becomes nearly vertical and substantial increase in temperature occurs."[4] The ignition temperature often is determined experimentally by the "intersection point between linear extensions of the pre-ignition heating rate and the post-ignition self-heating rate taken from the temperature-time record."[9] The temperature is that of the metal mass and depends upon a balance of heat loss and gain. Figure A-1 plots the calculated heat loss or generation rate of uranium versus temperature. The external temperature at which ignition occurs depends upon a variety of factors.

Ignition temperatures vary with specific area--the smaller the surface-to-mass ratio, the higher the ignition temperature. Figure A-2 shows this relationship for uranium. The DU penetrators are cylinders approximately 2.5 cm in diameter by 35 cm long, with a mass of 3.3 kg. Threads are machined into the surface for attaching the sabot and tail assembly. The surface-to-mass ratio is estimated to be in the 0.1 to 0.2 cm^2/g range, which is lower than any values plotted in Figure A-2. This indicates an ignition temperature in excess of 700^{o} C. The presence of an alloying material such as titanium could reduce the ignition temperature.

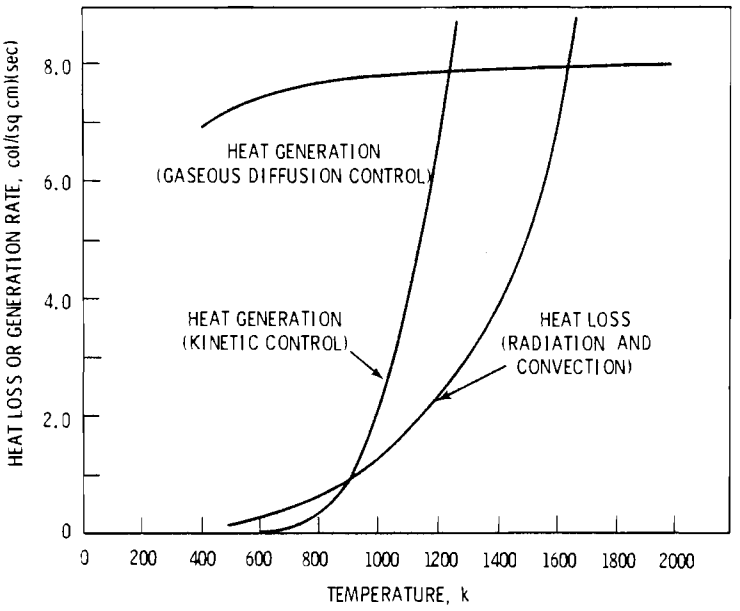


FIGURE A-1. Effect of Temperature on Heat Loss or Heat Generation Rates(5)

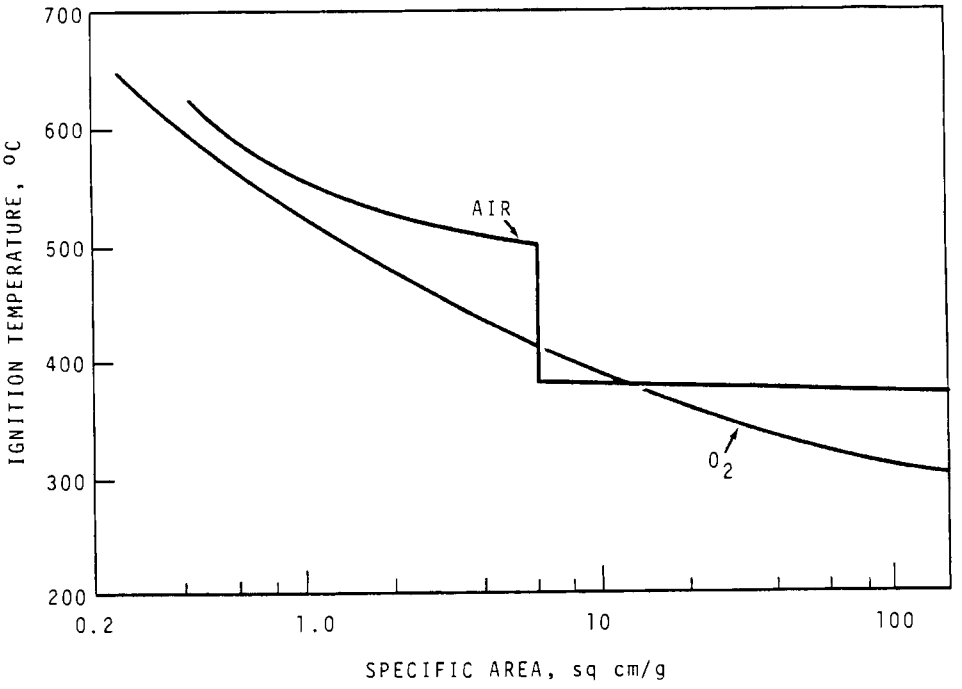


FIGURE A-2. Dependence of Uranium Ignition on Specific Area(8)

The appearance of the projectiles following the burn test indicates that test conditions may not have been sufficiently rigorous to assess the potential for airborne release of uranium from penetrators when subjected to high temperatures. In the burn test, banded boxes of munitions were burned in the open. The vigorous reaction of the most heat-sensitive element, the propellant, hurled 11 of 12 projectiles out of the fire. The fire burned for only about one-half hour, but that was long enough to cause the rounds to explode.

It appears that a fire within an enclosure, such as a warehouse, railway car, ship, etc., could impose more severe conditions than those in the burn test. The enclosure could prevent the projectiles from escaping the fire zone and could be sufficiently rigid to cause fragmentation of the penetrators, thereby increasing the surface-to-mass ratio. The penetrators, then, might be subjected to conditions that could lead to ignition. Once ignited, oxidation of uranium in air could lead to metal temperatures around 1400^{o} C[8] and could be a strong ignition source. Some consideration should be given to methods of extinguishing fires involving burning penetrators. Figure A-3[8] shows that all the oxide would ultimately be U_3O_8 if heated to $>200^{o}$ C in air. The size distribution of U_3O_8 particles produced by heating UO_2 in air is shown in Figure A-4. The size distribution tends to be more coarse at temperatures above 800^{o} C.

It is recommended that experiments with full sized penetrators be conducted to determine if they can be ignited in air (or oxygen-depleted air) at temperatures to $\sim 1200^{o}$ C, the flame temperature of petroleum fires, with natural convection. If the penetrators can be ignited, the following questions need to be answered: what is the probability of such an occurrence, and what are the characteristics of the aerosol fraction and residue, such as size distribution, and solubility of oxides in body fluids?

This information would provide a more reliable estimation of the potential radiological downwind consequences of DU projectile involved in fires.

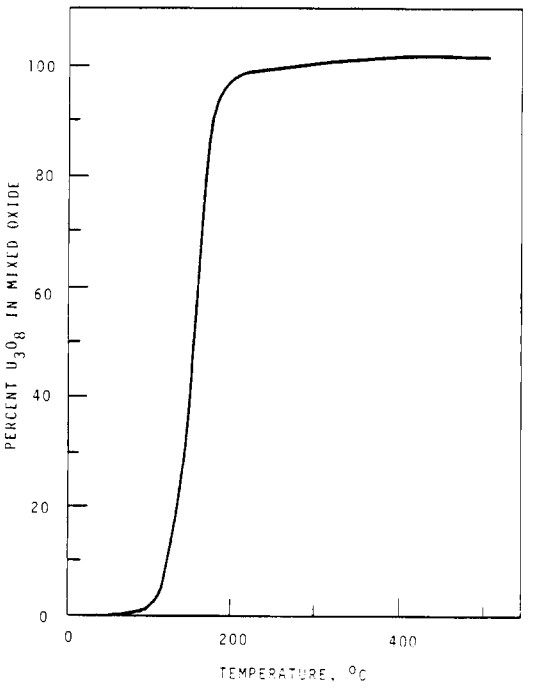


FIGURE A-3. Percentage of U_3O_8 Formed by Oxidizing Uranium in Air(8)

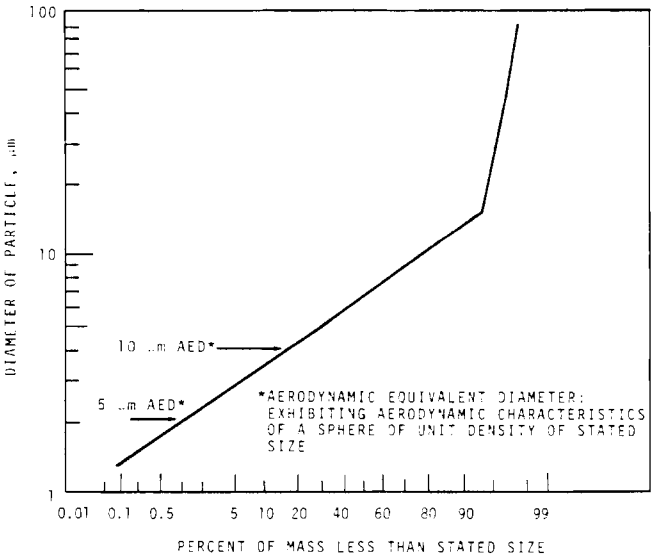


FIGURE A-4. Size Distribution of U_3O_8 Powder by the Air Oxidation of a Sintered UO_2 Pellet at 500° C for One Hour(10)

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