Hazard Classification Test of the Cartridge, 120 mm, APFSDS-T, XM829

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**Prepared for
Tank Ammunition Section
Munitions System Division
Large Caliber Weapons System Laboratory
Army Research and Development Center**

**Pacific Northwest Laboratory
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SUMMARY

Pacific Northwest Laboratory, with support services from Nevada Test Site (NTS) DOE contractors, conducted research to determine the behavior of the ammunition XM829 when subjected to (1) detonation of an adjacent XM829 cartridge, and (2) a sustained hot fire. Department of the Army Technical Bulletin TB 700-2, 1967 identifies these tests as "Test B" (detonation) and "Test C" (external heat).

Five iterations of "Test B" and one "Test C" were conducted at the NTS in March 1982. "Test C" was repeated in April of 1983, again at the NTS, under an improved set of control conditions.

It was concluded, based upon observations of "Test B", that the functioning of an XM829 cartridge, in one shipping container, will not cause immediate functioning of XM829 cartridges in adjacent containers. However, if a fire results and is sustained, adjacent cartridges may ignite, resulting in some scattering of debris within a maximum radius of 40 feet.

Further, the XM829 cartridge can be expected to remain in a kinetic controlled regime with vigorous oxidation occurring early in such a fire but dropping off as the temperature cools toward ambient.

Mass balance analyses data indicated a recovery of at least 80% in the 1982 "Test C"; in the 1983 test, the recovery percentage was improved to approximately 100% of the original depleted uranium weight volume. Therefore, it may be concluded that a significant airborne release of the depleted uranium material did not occur.

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1.0 INTRODUCTION

Standard hazard classification tests were performed from March 22-25, 1982 and from April 18-22, 1983 at Frenchman Flat/Department of Energy (DOE), Nevada Test Site (NTS), Mercury, Nevada. These tests were to determine the reaction of the 120 mm, APFSDS-T, XM829 Cartridge to specified initiating influences. Based on the reactions obtained, the appropriate hazard classifications (i.e., Quantity-Distance Class, Storage Compatibility Group, ICC Class, and ICC Markings) are to be assigned.

Pacific Northwest Laboratory (PNL is operated for DOE by Battelle, Pacific Northwest Laboratories) was contracted by the Tank Ammunition Section, Munition System Division, Large Caliber Weapons System Laboratory, Army Research and Development Center (ARDC) to provide technical assistance and coordination for the tests. The pre-operational, operational and data evaluation phases of the tests involved four professional PNL staff members consisting of three health physicists and one aerosol physicist. Operational support consisted of DOE contractors, affiliated with NTS, who provided the following services: radiation protection, photography, surveying and painting of grid patterns, meteorology, security, communications and general labor. A two man explosive ordnance demolition (EOD) team was supplied by the Tactical Fighter Weapons Center at the U.S. Nellis Air Force Base, Nevada. This team was to provide the initiating influences (detonator fuses and plastic explosives) for the tests and to ensure the safety of personnel with respect to explosive material. In addition to the above personnel, two professional staff members from ARDC were part of the testing group. Their function was to observe the tests and provide technical expertise as required.

The tests were conducted in accordance with the Department of the Army Technical Bulletin, TB 700-2, 1967. Two separate types of tests, involving a total of 34 ammunition rounds, were conducted.

The first series of tests was identified by the TB 700-2 document as detonation "Test B." The tests were performed to determine if functioning of items in one shipping container would cause functioning of items in adjacent

containers (sympathetic detonation). Five iterations of two ammunition rounds each were performed to complete "Test B." This series of tests was conducted during the period March 22-25, 1982.

The second type of test was identified as external heat "Test C." It was conducted to simulate a condition where the containers of explosive items were completely enveloped in a hot fire. This test was performed in order to determine the appropriate hazard classifications for the XM829 cartridge. Radiological and toxicological hazards were not specifically addressed by these tests but have been evaluated in the past at Aberdeen Proving Ground, Aberdeen, Maryland (Hooker et al. 1983, PNL-4392). "Test C" was performed using 12 ammunition rounds simultaneously. This test was performed twice, once during the period March 22-25, 1982 and again during April 18-22, 1983.

The ammunition cartridge that was used is a kinetic energy antitank round and is intended for use in 120 mm guns against armored targets. An external view of the XM829 cartridge is shown in Figure 1 on the following page. The projectile consists of a subprojectile and sabot. The subprojectile is composed of three major sections: a monolithic depleted uranium penetrator, an aluminum windshield with steel tip, and an aluminum fin assembly. The aluminum sabot consists of four 90° sections and is assembled around the subprojectile behind the windshield prior to the fin assembly. The projectile is illustrated in Figures 2 and 3.

The ammunition functions when an electrically ignited primer ignites the propellant. The gases produced from the burning, propel the projectile down the gun muzzle. Air resistance strips away the sabot sections upon leaving the gun. The fin stabilized subprojectile then travels downrange and penetrates the target solely by kinetic energy.

FIGURE 1. XM829 Cartridge

FIGURE 2. Projectile Schematic

FIGURE 3. XM829 Projectile

2.0 DETONATION "TEST B"

Detonation "Test B" was conducted to determine if functioning of items in one shipping container would cause functioning of items in adjacent containers (sympathetic detonation).

2.1 TEST SET-UP

An Operations and Safety Plan was developed for the tests to be conducted at the NTS during March of 1982. This plan was developed for "Test C" and included the five iterations of "Test B." The period from March 18-21, 1982 was reserved for cleanup of the proposed "Test C" area, performance of radiological surveys, and establishment of a grid pattern. This was to be followed by the initiation of "Test C" on the morning of March 22, 1982. However, when the PNL staff members arrived at Frenchman Flat on March 18, it was discovered that the planned location for "Test C" was flooded. A decision was made to delay the test set-up until the morning of March 22, 1982 at which time the test conditions would be re-evaluated. On the morning of March 22 it was observed that the area was still flooded and that this condition would not be expected to change within the next several days. Therefore, it was decided that a new "Test C" area would be chosen and that the set-up and initiation of "Test B" would be commenced. The proposed "Test C" location (flooded area) and the final "Test B" and "Test C" locations are depicted in Figure 4.

FIGURE 4. Frenchman Flat Test Locations

The "Test B" set-up was designed as follows:

- Two wooden shipping containers were placed side by side.
- One ammunition round was placed in each container.
- The rounds were oriented to point in the same direction.
- Six additional shipping containers (filled with sand) were placed next to and on top of the two rounds.

"Test B" required five iterations of this test set-up (Figure 5).

At approximately 0900 hours on March 23, 1982, NTS Security set up a roadblock at the intersection of Road 5-01 and the Frenchman Flat access road (Figure 4). The roadblock was established to help ensure the health and safety of nontest personnel during the performance of "Test B". Traffic beyond this point was restricted to predesignated members of the test team. Restrictions to the Frenchman Flat area were removed at approximately 1630 hours on March 23, 1982. This time coincided with the completion of the "Test B" series and

FIGURE 5. Sympathetic Detonation Test Configuration

the evaluation by the PNL Project Manager and the EOD team that the conditions for re-entry were acceptable.

In order to initiate each iteration of "Test B", it was necessary for the EOD team to ignite the propellant of one round. The preferred method to accomplish this was to electrically ignite the M83 primer. The primer is centrally located on the end of the cartridge as shown in Figure 6. In order to expose the primer for each iteration of "Test B," it was necessary to remove the cartridges from the shipping containers. The protective cardboard sleeves were taken off and the cartridge was placed back in the shipping container with the primer exposed.

2.2 TEST

The first iteration of "Test B" was attempted at 1015 hours on March 23, 1982. One of the centrally located rounds was electrically primed by the EOD team but failed to ignite the propellant upon initiation. At 1030 hours, a C-4 plastic explosive charge was placed over the primer and was electrically initiated. This action caused the ignition of the propellant (Figure 7) with a debris scatter radius of approximately 40 feet. The base of the initiated round, on which the C-4 had been placed, was found approximately 550 feet to the east of ground zero. The round in the adjacent shipping container (second round) did not sympathetically initiate at this time. However, as a result of the test, a fire occurred. The fire was fueled by the wooden shipping containers and burned for 1 hour and 10 minutes. At its peak, the flames of the fire reached a height of 6 to 8 feet (Figure 8). The sustained fire produced a high temperature environment in which the propellant from the second round ignited at 1140. A small amount of debris, resulting from the second round initiation, was scattered within a radius of a few feet.

The second iteration of "Test B" was attempted at 1120 hours using an electrical initiation of the primer. The primed round did not initiate and the EOD team again used a C-4 plastic explosive to cause an initiation at 1132. This attempt was successful; the second round did not sympathetically initiate. A small fire resulted and burnt itself out within a few minutes. Most of the debris was scattered within a radius of about 30 to 40 feet from

FIGURE 6. Exposed XM829 Cartridge with M83 Primer

FIGURE 7. Detonation of Primer by C-4 Plastic Explosive

FIGURE 8. Sustained Fire Fueled by Shipping Containers

ground zero; however, two pieces were found at 250 and 325 feet. It was observed that the cause for debris being thrown to large distances was the use of plastic explosives and not the initiation of ammunition propellant. It was decided to initiate the remaining three iterations of "Test B" with C-4 plastic explosives due to the problems experienced with electrical ignition of the primer.

The third iteration was initiated at 1405 hours. The adjacent round did not initiate sympathetically. A small fire resulted and quickly burnt itself out. A 10- to 15-foot radius debris pattern resulted from the initiation of the round.

The fourth iteration was initiated at 1407 hours. The adjacent round did not initiate sympathetically at this time but a small sustained fire was produced. At 1431 hours, the adjacent round propellant was initiated as a result of the small sustained fire. The resulting debris pattern, from the combination of both rounds, had a radius of approximately 20 feet.

The fifth iteration of "Test B" was initiated at 1430 hours. The adjacent round propellant initiated at 1453 as a result of a sustained fire. The resulting debris pattern was similar to that of the fourth iteration with a radius of about 20 feet.

Two types of debris patterns were observed as a result of the five iterations of "Test B." The first pattern had a scatter radius of 30 to 40 feet and is depicted in Figure 9. A 10- to 25-foot scatter radius, as shown in Figure 10, was typical of the second pattern. Iterations one and two can be characterized by the first debris pattern, whereas iterations three, four, and five can be characterized by the second. As mentioned previously, the debris scatter was observed to be primarily a function of the C-4 explosive used. The EOD team established the amount of C-4 required by trial and error during the first two iterations. As a result, they determined that a smaller C-4

FIGURE 9. 30- to 40-foot Scatter Radius

FIGURE 10. 10- to 20-foot Scatter Radius

charge would be sufficient to cause the primer to initiate. Therefore, a smaller debris scatter radius was obtained on the last three iterations.

The expected debris scatter radius resulting from an accidental initiation of a cartridge primer cannot be determined from the results of the above tests. However, it is possible to predict a maximum debris scatter radius of 40 feet based on the first two iterations. It would not be expected that this maximum would be exceeded unless other ordnance than XM829 cartridges were involved.

Figures 11, 12 and 13 indicate the condition of the shipping containers and cartridges after the fires had burnt themselves out and ignition of propellant pellets had ceased.

2.3 CONCLUSIONS

It may be concluded that the functioning of an XM829 cartridge, in one shipping container, will not cause immediate functioning of XM829 cartridges in adjacent containers. However, if a fire results and is sustained, adjacent cartridges may ignite. In this series of tests, the time frame for the second cartridge to ignite varied from 20 to 70 min. Finally, it may be concluded that some scattering of debris may occur with a maximum radius of 40 feet.

FIGURE 11. Partially Burned Shipping Container Box Containing Cartridge

FIGURE 12. Partially Burned Shipping Container Tube With Cartridge

FIGURE 13. Partially Burned Shipping Container Tube Containing Cartridge

3.0 EXTERNAL HEAT "TEST C"

The external heat "Test C" was conducted to simulate a condition where XM829 cartridges (within the appropriate wooden shipping containers) are completely enveloped in a hot fire. This condition is meant to be representative of a worst-case overland shipping accident or a depot storage fire of depleted uranium ammunition.

3.1 INTRODUCTION

Test criteria used for the external heat "Test C" are outlined in the Department of the Army Technical Bulletin, TB-200-2, 1968. The objective of the test is to determine if an airborne release of a depleted uranium aerosol would result from envelopment of ammunition in hot fire conditions. In addition, if a release did occur, a quantification of the percentage released could be determined using a mass balance approach.

The mass balance methodology assumes that the amount of depleted uranium, present in the XM829 ammunition (U_{amm}), is known before the ammunition is enveloped in a hot fire. In addition, the depleted uranium content of the surrounding soil and debris, upon completion of "Test C", needs to be measured (U_{mea}). Determination of the depleted uranium content of the soil assumes that the soil has been characterized prior to the test for its radioactive material content and that the post-test measurements have been corrected accordingly. To determine the total amount (U_{air}) and the percentage ($U\%$) of depleted uranium that becomes airborne, the following relationships can be used: $U_{air} = U_{amm} - U_{mea}$ and $U\% = U_{air}/U_{amm}$. However, it must be noted that the calculated value, U_{air} , may be conservative. This is due to the error introduced in U_{mea} by not being able to measure or account for all of the non-airborne post-test depleted uranium (especially in the soil). This point is discussed further in Section 3.4.

The mechanism that allows for a potential release of a uranium aerosol is the oxidation of uranium in air at high temperatures. This reaction is exothermic and therefore may continue on its own once the reaction has started. The resulting oxide material is weakly bound to the remaining uranium metal and may become airborne as a result of the physical and chemical conditions

involved. Oxidation and ignition characteristics of depleted uranium are discussed in more detail in Section 3.3.2 of this document.

The exothermic oxidation reaction for uranium requires a high temperature for a sustained period of time in order to initiate oxidation. Previous experience in the burning and fragmentation of XM774 depleted uranium ammunition indicated that envelopement in a hot fire would not result in an airborne release of a depleted uranium aerosol. In particular, the external heat test performed on the XM774 ammunition in October 1977 at Frenchman Flat, resulted in the cartridges being blown clear of the fire by propellant ignition, before oxidation could occur (Gilchrist, Parker, Mishima 1978). A factor that appeared to be critical for the XM774 ammunition to be blown clear of the fire was the design of the cartridge case. This particular case is made of a metal alloy which allowed for the confinement of the propellant gases. Upon initiation of the propellant, the gases produced would be directed out one end of the cylindrical case. The resulting displacement of the ammunition from ground zero would therefore be maximized. The XM829 cartridge case is made of combustible material as opposed to metal and its confinement characteristics are potentially different than those of the XM774 cartridge case. However, based on XM774 experience, preparations for "Test C" on the XM829 ammunition were made based on the potential that the depleted uranium penetrators would fragment and burn, and that an aerosol would potentially be released during the test.

The conventional method to measure the release of a substance to the atmosphere would require an extensive air sampling network. This would consist of several towers and several hundred air samplers in a predetermined downwind array, from which measurements would be taken during several release periods. However, because a release was not expected (based on the XM774 tests) and only one test was to be conducted, an alternative method was chosen to measure a release. This method required careful collection of all readily visible depleted uranium fragments after the test and a determination by mass balance of the amount released as an aerosol. It was anticipated that the majority of the fragments could be visually identified and recovered. The remaining depleted uranium or oxidized uranium was to be located with the use of portable radiation survey instruments. After computing the fraction of depleted

uranium unaccounted for (which was assumed to be airborne), the airborne concentration downwind and the integrated dose to an individual at a selected distance downwind may 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 that will not exceed the threshold limit value (TLV) may be calculated according to correlations available for chemical sources released to the atmosphere.

3.2 MARCH 1982 TEST

An external heat test was conducted during the week of March 22, 1982.

3.2.1 Test Set-Up

The site chosen for the external heat test was a dry lake bed named Frenchman Flat at the NTS (Figure 4). As mentioned previously, a new "Test C" location on Frenchman Flat had to be chosen due to flooding on the original site. The new location was identified on March 22, 1982 using the following criteria: 1) the test location was relatively free of vegetation and debris within a radius of 500 feet from the burn center or ground zero, 2) the area was flat, 3) the radiation background level in the area was low and uniform, and 4) there was a shelter nearby from which to observe the test.

The radiation background was characterized by performing radiation surveys of the test area from ground zero out to a radius of 500 feet. These surveys were performed on the morning of March 22, 1982 between 0800 and 1100 hours by the four PNL members of the testing team. The background readings were measured with both a Geiger-Mueller (GM) thin-window pancake probe survey meter and a micro-R survey meter. GM survey meter background readings ranged from 200 to 400 counts per minute. It was observed that this background radiation field was low and would not significantly interfere with the detection of depleted uranium material by radiation survey techniques.

Upon completion of the radiation surveys, a polar coordinate grid pattern, centered at ground zero, was established. The purpose of the grid was to identify the location of ammunition components blown from the hot fire. This was to be done both by distance from ground zero and by radial angle with respect

to compass directions. Ammunition components expected to be identified by this system were: depleted uranium fragments, projectile metal parts and primers, in addition to shipping container components. The grid pattern was layed out by a Reynolds Electrical and Engineering Company, Inc. (REECO is a DOE contractor at the NTS) land surveying team, from 1300 to 1600 hours on March 22, 1982. The surveyor's markers were then connected using white painted lines layed out by a REECO painting crew on the desert floor. The grid pattern consisted in part of radial lines 30 degrees apart which extended 500 feet from the center of the pattern. Each radial line was marked at 20-foot intervals from the center to 100 feet, and at 100-foot intervals from 100 feet to 500 feet. Circumferential lines were then plotted and painted connecting all radial distance marks out to 100 feet. In addition, distance and radial angle values were painted on the grid pattern to help in the identification of fragment locations. Painting of the grid pattern encompassed the time frame from 0900 to 1600 hours on March 23, 1982. The inner 100-foot radius portion of this pattern is shown in Figure 14. Orientation of the pattern was chosen so

FIGURE 14. Inner 100 feet of Grid Pattern

that the 0° to 180° line was from the north to south compass directions, respectively.

Blast meters (supplied by ARDC) were placed at 90° intervals (north, east, south and west), 4 feet above ground level and 30 feet from ground zero in order to record the blast pressures in psi, that would be expected from the initiation of the XM829 ammunition. The blast meters can be seen at the four compass directions in Figures 14 and also close up in Figure 15.

Electronic instrumentation, measuring temperature and pressure parameters, was supplied and set-up by REECO with data collection sensors located at ground zero (for temperature only) and on the four blast meter posts. The sensors were connected by cable to an instrumentation truck located to the south of

FIGURE 15. Blast Meter

ground zero. Figure 14 shows the path of this cable in the lower left hand corner. The cable was covered with dirt from ground zero to a distance of 80 feet to protect it from the test environment. Placement of blast meters and other instrumentation to measure environmental parameters was accomplished during the afternoon of March 23, 1982 and prior to the test on the morning of March 24, 1982.

Two video-tape recorders were positioned 90° apart at approximately 500 feet and 1000 feet from ground zero. Still photographs were to be supplied during the test by both NTS and PNL photographers, one located at a shelter to the north and the other in an air force helicopter circling the test area.

Twelve shipping container boxes, with one XM829 ammunition round each, were stacked and secured with steel straps to an open metal stand at the center of the grid. This stand was made of welded angle iron and secured to iron posts that had been driven into the ground. The top surface of the stand was approximately 30 inches above ground level as shown in Figure 16. Figures 17 and 18 show the 12 ammunition shipping containers strapped together and on top of the test stand. Lumber (mostly 4-inch by 4-inch posts) was then piled under, around and on top of the shipping containers and metal stand as shown in Figure 19.

The test set-up consisted of the stand, shipping containers, and lumber soaked with 50 gallons of diesel fuel immediately prior to the test initiation. The lumber and diesel fuel were used to create the conditions of a sustained fire of a worst case shipping accident. Worst case, as used in this context, means that the fire would not be extinguished by firefighting techniques and that sustained high temperatures (fueled by diesel oil) would be obtained. The test set-up, showing the EOD team and their escape truck, as seen from the helicopter prior to test initiation is depicted in Figure 20.

3.2.2 Test and Recovery Description

On the morning of March 24, 1982 from 0800 to 1000 hours, NTS personnel moved twelve XM829 ammunition rounds, each in their wooden shipping container, to the "Test C" location. The shipping containers were secured into their test configuration; lumber was added as fuel for the test fire. At 1000 hours, the EOD personnel sprayed the entire test configuration with 50 gallons of diesel fuel using a hand-powered pump. The vehicle to be used as an escape

FIGURE 16. Iron Stand With Securing Posts

FIGURE 17. Shipping Container Set-Up

FIGURE 18. Test Stand Set-Up

FIGURE 19. "Test C" Set-Up Prior to Initiation

FIGURE 20. Test Set-Up Immediately Prior to Initiation

truck was backed up to within a distance of 40 feet from ground zero along the 0° radial at 1010 hours. An NTS radiation protection staff member was assigned to drive the truck with a PNL staff member assisting the two EOD personnel in the back of the truck. At 1015 hours, an air force helicopter landed 1500 feet to the north of ground zero, picked up the NTS photographer and took off again at 1025 hours. The helicopter circled the test location throughout the performance of "Test C" to collect aerial photographs and observe the test.

At 1034 hours, the EOD team initiated the ignition of the diesel fuel and then were evacuated using the escape truck to a knoll (elevation ranging from 15 to 20 feet) 1500 feet north of ground zero. The knoll was used as protective cover for these personnel during the course of "Test C." In addition, its elevation above the level surface of Frenchman Flat allowed the PNL photographer to obtain photographs with a better perspective. The resulting fire, immediately after the EOD team had evacuated the area, can be seen in Figure 21. As more of the diesel-soaked lumber ignited, the fire increased in intensity as can be seen in Figures 22 and 23 for the time periods of 1039 and 1044 hours,

FIGURE 21. Initiation of "Test C"

FIGURE 22. "Test C" at 1039 Hours

FIGURE 23. "Test C" at 1044 Hours

respectively. The burning of the lumber, shipping containers and diesel fuel produced a dark-colored plume that rose straight up for about 100 feet and then slowly drifted to the north. Wind velocities were observed to be relatively constant and low at ground level with a slight increase at upper elevations directed towards the north. At 1049 hours, an incandescent spray was observed to be released from the fire and directed towards the west as can be seen in Figure 24. This was determined to be the ignition of the propellant from the first XM829 ammunition round to be affected by the heat of the test. A primer, which was most likely associated with the above ignited propellant, was observed to initiate at 1050 hours. The other eleven XM829 rounds initiated (both propellant and primers) during the time periods from 1051 to 1117 hours. Specific times of initiation are given in Table 1. It has been assumed that the order of initiation of the primers followed exactly the order of initiation of the propellant.

All initiation times listed in Table 1 were based solely on visual observations. Two separate PNL observers, one located at the shelter to the north

FIGURE 24. Ignition of Propellant From First XM829 Ammunition Round

TABLE 1. Time Schedule of Propellant and Primer Initiation

XM829 Ammunition Round	Time of Initiation (hours)	
	<u>Propellant</u>	<u>Primer</u>
1	1049	1050
2	1051	1051
3	1052	1053
4	1052	1054
5	1053	1054
6	1053	1055
7	1056	1058
8	1059	1059
9	1104	1105
10	1113	1114
11	1114	1114
12	1116	1117

and one located 1500 feet to the south of ground zero, documented the initiation times. The two records were compared at test completion and it was observed that the data sets agreed. All twelve ammunition rounds were accounted for. The U.S. Air Force helicopter, carrying the NTS photographer, continued to circle ground zero on a decreasing spiral until 1130 hours, at which time it landed at the northern shelter location. The intensity level of the fire was sustained from the time of the last primer initiation until 1129 hours. At that time, the intensity level started to slowly decrease with no visible flames by 1303 hours.

The personnel encircling the test area, both on the ground and in the air, did not observe any fragments being blown from the fire during the period from 1034 to 1129 hours. At 1303 hours, the EOD team entered the test area to within 20 feet of ground zero in order to determine the criteria for re-entry by other test team personnel. At 1320 hours, the EOD team informed the PNL project manager that the conditions for re-entry were acceptable excluding the area from ground zero out to a radius of approximately 20 feet. The basis for exclusion from this area was the potential for personnel injury from the high residual thermal temperatures of the remaining materials. Entry to this area was made on the morning of March 25, 1982 after temperatures had approached acceptable levels.

The post-test conditions for the afternoon of March 24, 1982 are shown in Figure 25. In addition, Figure 26 shows a close up of ground zero on the morning of March 25, 1982. This particular figure shows the cooled down test conditions after the blast meters have been removed from their securing posts. It was observed that a maximum debris scatter radius of approximately 10 feet existed as a result of the external heat "Test C" as is evidenced by Figures 25 and 26. In addition, the integrity of the four blast meter detectors was not compromised and additional instrumentation indicated that no measurable over-pressure occurred at a distance of 30 feet from ground zero.

After initial examination of the test area on the morning of March 25, 1982, it was determined that access to the area would not endanger the health and safety of personnel as far as explosive hazards. There was some concern due to the presence of radiological contamination; however, the team members felt that the contamination could be adequately controlled. In response, NTS

FIGURE 25. Initial Post-Test Conditions

FIGURE 26. Post-Test Conditions After Cooldown

security roadblocks were removed at 0800 hours on the morning of March 25, 1982. A security check point was maintained at the intersection of Road 5-01 and the Frenchman Flat access road until 1400 hours (Figure 4). The check-point was established to ensure that only authorized personnel entered the test area as opposed to ensuring the health and safety of personnel.

At 0900 hours on the morning of March 25, 1982, the PNL and ARDC team members inspected the debris within the 10-foot radius of ground zero. It was observed that all but three of the DU penetrators had been melted down or oxidized completely. In the case of melting, the DU was observed to be alloyed with melted aluminum and steel from the fin, sabot, windshield, and windshield tip. During the course of the test and the subsequent cooldown period, the melted metal alloy collected in a depression at ground zero as a solidified mass. Figures 27a and 27b show selected examples of alloyed masses against the typical surface soil pattern of Frenchman Flat. In addition, these two figures also show several partially melted sabot components. The team members noted, in handling the melted alloy fragment, that it was composed primarily of aluminum, based on its weight to volume ratio.

The DU that had oxidized was observed to be in two forms. The first, which was most prevalent, was a fine powder that had high local concentrations restricted to the area immediately around the test stand. Evidence of this fine powder was also found to be present at greater distances, although at a significantly reduced concentration level. This was thought to be due to the high local winds experienced in the afternoon of March 25, and which continued for the remainder of the day. The remaining oxidized DU was in the form of aggregated material affixed to the surface of the test fragments in the debris. This form of the DU can be seen in Figure 28; it is the coarse textured material surrounding a partially oxidized DU penetrator.

As mentioned previously, three DU penetrators were not completely melted or oxidized. Two were somewhat intact and the third was partially oxidized. This penetrator is depicted in Figure 28 where the steel-tipped windshield end of the penetrator can be seen protruding from the mass of oxidized material.

Cleanup of the test area consisted of collecting readily visible fragments and the surrounding contaminated soil. The fragments were separated

FIGURE 27a. Aluminum/DU Alloy Sabot Components

FIGURE 27b. Aluminum/DU Alloy Sabot Components

FIGURE 28. Partially Oxidized DU Penetrator

into two groups based on whether they contained DU (penetrators and radiologically contaminated material) or not. The DU material was doubly bagged (to help ensure control of the radioactive material) and stored for later analysis. Other debris material which was not composed of or contaminated by DU (including the debris from "Test B") was disposed of by NTS personnel as nonradioactive waste.

The contaminated soil was removed with shovels, trowels and small brushes, placed in double bags and stored for future analysis. Identification of contaminated soil and fragments was accomplished with the use of portable GM survey instruments. The criterion used for DU identification was a measurement of 100 counts per minute above the background level (at the test location).

The cleanup operation was performed by the PNL and the EOD team personnel. Respiratory protection and protective clothing were worn throughout the operation by the personnel involved. The health physics monitoring coverage for

personnel contamination was provided by PNL. NTS collected and analyzed air samples both during the test and for the duration of the cleanup. All air sample results and personnel contamination surveys indicated that the health and safety of the workers was not compromised by the cleanup operation.

Debris and contaminated soil were removed from the test area. Final radiological surveys by PNL indicated that all residual materials read less than 100 counts per minute above background on PNL's portable GM survey instruments. Test locations for the March 1982 tests ("Test B" and "Test C") were released to NTS personnel at 1500 hours on March 25, 1982 by the PNL project manager.

3.2.3 Mass Balance Data and Analysis

The DU-bearing residue resulting from the burn test was segregated into two groups: contaminated debris and contaminated soil/partially intact penetrators. The contaminated debris was shipped to PNL at the Hanford Site in Washington State for analysis of radionuclide content, and the contaminated soil/penetrators were analyzed by the REECO Environmental Sciences Laboratory at NTS.

The PNL Radiological Sciences Department received approximately 13 kg of contaminated debris from the burn test. It consisted of metal fragments composed of melted uranium, aluminum and steel mixtures. Four packages of the metal mixtures were assayed using a fission neutron coincidence well counter. The purpose of the assay was to determine the fraction of uranium to total metal in the four samples. Each package was counted overnight in the fission neutron coincidence well counter for a total of 20,000 seconds to measure the spontaneous fission neutrons from ^{235}U . The percent fraction of uranium in each of the four packages was then determined by multiplying the resulting value by the ratio of one over the decimal percent of ^{235}U in the depleted uranium of the XM829 cartridge. Results of the analyses are given in Table 2. The total uranium content of the material analyzed by PNL was determined to be 5.18 ± 0.30 kg.

The REECO Environmental Sciences Laboratory at NTS received approximately 516 kg of contaminated soil and metal parts from the burn test as follows:

- Soil -- 494 kg
- Metal Parts
 - penetrators -- 8.10 kg
 - bases -- 7.07 kg
 - metal scrap -- 4.00 kg
 - sabots -- 2.94 kg

TABLE 2. Uranium Fraction Analysis Data

Weight of Metal (kg)	Fraction of Uranium	Uncertainty at ± 1 Std. Dev.	% Uncertainty at ± 1 Std. Dev.(a)
1.20	0.29	0.04	13.8%
3.16	0.37	0.02	5.4%
3.28	0.35	0.02	6.4%
5.13	0.49	0.02	4.5%

(a) The uncertainty listed does not include a possible error in the weight % of ^{235}U of an estimated 10%.

For the soil analyses, the 494 kg of material were dried and sieved. The fine fraction contained 308 kg and the coarse fraction contained 173 kg of soil. The remaining 13 kg of material consisted of rocks and bits of metal. The fine fraction was divided into 20 batches, the coarse into 10, and the miscellaneous material into 6 batches. Each was homogeneously mixed. Two aliquots of about 200 g were taken from the fine fraction batches and one aliquot from each of the others. These were to be analyzed for ^{238}U by the detection of the emitted gamma rays with a Ge(Li) system set up for quantitative isotopic-gamma analysis. The fine fraction of the soil contained 19.870 kg of ^{238}U , the coarse fraction 2.088 kg of ^{238}U , and the miscellaneous material contained 2.718 kg of ^{238}U .

There were four bags of metal parts. The contents of each were placed in a bath of 3 normal nitric acid overnight. The acid was then diluted to 10 liters and an aliquot of each was taken to be analyzed for ^{238}U with the Ge(Li) system. The weights of the metal parts, both before and after the acid baths

were measured, and the net weight losses into the acid were determined. The breakdown of the uranium content of the metal parts was:

- a. penetrators -- 51 grams of ^{238}U leached into solution; 7927 grams of ^{238}U remained after leaching
- b. bases -- 2 grams of ^{238}U
- c. metal scrap -- 5 grams of ^{238}U
- d. sabots -- 11 grams of ^{238}U .

The total error of the ^{238}U measurement was difficult to estimate accurately. The errors associated with the uranium content of the metal parts were negligible, since the ^{238}U leached from these constituted less than 1% of the total uranium. The major uncertainty comes from the analysis of the soil. The errors associated specifically with the Ge(Li) analyses of the soil were well defined and averaged less than 10% at the 2σ level; however, there were significant uncertainties inherent in analyzing such large quantities of soil. The analyses of the duplicate aliquots of the fine fraction indicated that an error of about $\pm 20\%$ could be expected. This error dominated the final ^{238}U weight total.

In summary, the PNL and REECO analyses accounted for 38.0 ± 6.9 kg of total uranium recovered from the March 1982 external heat "Test "C at the NTS. Prior to the initiation of the external heat test, the total DU content of the 12 ammunition rounds amounted to 47.7 kg.

3.2.4 Conclusions

It may be concluded, based upon the data presented in the previous section, that at least 80% of the DU can be accounted for in the PNL and REECO analyses. However, because of difficulties involved in collecting the residual DU, it cannot be determined exactly by mass balance techniques whether DU became airborne as a result of the test. As a result, it was necessary to perform a followup external heat "Test C" during April 1983 under more controlled recovery conditions.

3.3 APRIL 1983 TEST

The second iteration of the external heat "Test C" was conducted during the week of April 18, 1983.

3.3.1 Test Set-up

Defense Supply Agency Regulation (DSAR) 8220.1, March 1981, requires that "external heat tests" be conducted to ensure that, under identical conditions, all DOD Agencies and Departments and all other Government agencies will use identical hazards classifications for ammunition, explosives, and solid propellant items.

Section 3.2 of this document describes the external heat "Test C" of the ammunition XM829, which was conducted in March, 1982. The test criteria were based upon the Department of the Army Technical Bulletin, TB-200-2, 1968, which stipulated that the test ammunition be completely enveloped in a hot fire to determine if an airborne release of depleted uranium aerosol would result. The fire was to simulate a hypothetical shipping accident.

In the March 1982 test, the XM829 rounds did not react to the hot fire environment as had the preceding tests with XM774 rounds. The XM774 rounds were tested in October of 1977 (see Section 3.2). Because of the results obtained from the XM774 rounds, it had not been anticipated that the XM829 rounds would remain at the ground zero location throughout the burn, but rather that they would be blown clear of the fire as had the XM774. For this reason, the test preparation did not include an adequate facility to collect the DU residue after the burn. To ensure the reliability of the recovery data, it was decided to repeat "External Heat Test C" on the ammunition XM829.

The second iteration of "Test C" was conducted on April 19, 1983. Test criteria were again based upon the Department of the Army Technical Bulletin TB-700-2, 1967. Major changes were made in the test facility as compared to the March 1982 test; however, test procedures for the two tests were very similar. The ground zero location for the 1983 test was at the approximate site of the 1977, XM774 test. This site is approximately 1000 yards northeast of the 1982 site at Frenchman Flat, Nevada Test Site (NTS).

In order to better contain the DU residue resulting from the fire, a containment structure was designed by PNL scientists and fabricated by REECO. The structure consisted of a steel tray, 30 feet by 30 feet square, which was fabricated in place at the Frenchman Flat ground zero point.

This 1/4-inch thick steel tray had 3-inch side plates attached to the entire outer edge and was equipped with steel pipe receptacles to allow for insertion of 1 1/4-inch steel upright pipes (Figure 29) to support the enclosure walls (plastic sheeting), after the fire had sufficiently cooled. A 10-foot by 10-foot area in the center of the tray was sunk 5 inches lower than the tray's floor and filled with sand to allow for a thicker insulating barrier between the fire and the steel plate. The purpose of the added insulation (sand) was to discourage the molten metals from becoming attached to the steel, thus complicating the DU retrieval operation. The entire tray floor was then filled with 2 to 3 inches of sand.

The center point of the tray was the ground zero point. Nine 10-foot square grids were established within the tray. A radiological background survey preceded the central placement of a support stand for the ammunition. This stand (Figure 30a) was constructed of 3-inch angle iron and measured 2.5 ft h x 2 ft w x 3.5 ft L. Each support leg had an 8-inch steel plate welded to the bottom to lend stability to the unit during potential explosion events.

FIGURE 29. Containment Facility Tray Prior to Igniting

FIGURE 30a. Ammunition Test Stand and Temperature Sensing Elements

Figure 30a also shows positioning of the heat sensing elements which were installed under the support stand to monitor temperatures during and following the fire. As the photo indicates, two sensors were positioned near the center point and one was positioned near (approximately 8 inches) each corner of the stand. The positions of the individual temperature sensors, with respect to the test stand, are shown in Figure 30b. Temperature monitoring readouts and

FIGURE 30b. Positions of Individual Heat Sensors

recorders were remotely located in a van which was equipped for this purpose. Temperature equipment and measurements are supplied by EG&G.

The mass balance methodology (Section 3.2.1) that was used in the March 1982 test was again anticipated for use in the April 1983 analysis to define the amount of recovered DU material after the fire. Therefore, preparation for this test was keyed toward the optimum containment of the DU material. Dispersion of DU oxide, resulting from increased wind velocities, had proven to be a major factor impacting the 1982 test's recovery operation. The plastic sheeting (Figure 31), which would make up the walls of the containment enclosure after the burn, were intended to minimize this problem. Seven high volume air samplers were also positioned around the outside perimeter of the enclosure to monitor for airborne radioactive releases. The collection media were placed immediately above the walls of the enclosure at a height of about 8 feet above the ground. One air sampler was positioned at about 4 feet above the ground and just outside of the access opening to the structure. Air sampling equipment is shown in Figure 31.

FIGURE 31. Containment Enclosure and Post Test Air Sampling Systems

The program plan called for downwind monitoring and air sampling by the REECO radiation monitoring team during the burn. This was to be accomplished by a mobile sampling unit which was capable of plume tracking by use of a very sensitive condensation nuclei monitoring system.

On April 15, 1983, a radiological characterization of the test area was conducted by a ground survey using portable GM pancake probes attached to appropriate count-rate meters. Measurements were also taken at several locations, about 3 feet above the ground, using micro-R meters. These micro-R meters were equipped with a 1-inch sodium-iodide, thallium-drifted [NaI(Tl)] crystal and were designed to measure low levels of photon radiation as may be expected to be found in the natural environment. Average ground levels of beta-gamma radiation ranged from 100 to 150 counts per minute, with 200 counts per minute as the maximum, when measured by the GM instruments. Three-foot levels averaged 14 micro-R per hour with maximum measurements to 18 micro-R per hour. These levels indicated that background radiation levels were sufficiently low so that the depleted uranium, which may be deposited in the area as a result of the burn, would be easily detected. All radiation detection instruments used in this and forthcoming surveys during the test operation carried calibrations which were traceable to the National Bureau of Standards (NBS).

A polar coordinate grid pattern was not established for the 1983 test because the 1982 test information showed that a low probability existed for the XM829 rounds to be blown free of the fire. Rather, it was anticipated that the rounds would fragment and burn in a small concentrated area around the ground zero point.

Photographers from Pan-Am (NTS) and PNL were on site to take still photographs intermittently during the test setup, and during and after the burn.

The program plan called for the initiation of "Test C" at 0830 hours on Monday, April 18, 1983. On Friday, April 15, 1983, all phases of the program plan were on schedule including the following major tasks:

- the steel tray for the containment structure was in place
- grids had been established within the tray's perimeter
- the test area and surrounding area had been cleared of debris

- a radiological survey of the area had been completed
- heat sensors were in place at ground zero
- a mobile van for temperature monitoring was in place at a sheltered, remote location beyond 1000 feet from ground zero
- a trailer to be used for mass balance and storage purposes was also in place at the 1000-foot location
- a power generator was onsite to supply power to the van and trailer
- a steel, ammunition support stand had been set in place at ground zero
- communications equipment (portable radios) were available for use onsite
- protective equipment and anti-C clothing were available onsite, as well as a decontamination facility
- high volume air sampling equipment was in place on site
- NTS security measures from the site were in force.

Two problems were apparent by Friday afternoon, April 15, 1983. These were: (1) the conduit which was installed under the steel tray to route the heat sensor cables had developed condensation which shorted the cables, and (2) much of the wood, which was to be used for the fire, contained a large amount of nails. The nails would have complicated the recovery operation by requiring the removal of additional metal pieces from the residue. The cable problem was solved by routing the cables under the sand but not through the conduit. Nail-free lumber was brought in to replace the original fire wood. By late Friday evening all conditions were in a state of readiness for the test.

The full compliment of DOE, PNL, NTS, EOD, and ARDC test team members arrived onsite at 0630 hours on Monday, April 18, 1983. Although weather conditions at the test site appeared to be suitable to conduct the test; the forecast from the Las Vegas National Weather Service predicted high winds later in the day. The test munitions were removed from the secured storage bunker and stacked in readiness on the support stand at ground zero. The 12 rounds were in wooden shipping/storage containers. All were banded to the support stand by means of steel strapping (Figure 32). Fire wood was stacked in place. As

FIGURE 32. Test Munitions Secured to Test Stand

this task progressed, the wind velocity began to increase. At 0825 hours, it was mutually agreed upon by the ARDC, DOE and PNL project managers that the test should be postponed because of high winds, until 0630 hours on Tuesday, April 19, 1983. The test area was placed under tight security during this period of time.

3.3.2 Test and Recovery Description

PNL and ARDC personnel were assembled at the test site on Frenchman Flat at approximately 0630 hours on April 19, 1983. The munitions, lumber and fuel were present but not in the final test configuration due to the prevailing winds and threat of rain. At approximately 0700 hours, after consultation with the onsite meteorologist and professional staff present, the ARDC program

manager authorized initiation of the test based upon the forecast that the weather during this timeframe was the most favorable anticipated over the next few days, and possible conflicts in the work schedule towards the end of the week. The stacked munitions and lumber (all cartridges were oriented in a test north direction) were wetted thoroughly with 55 gallons of fuel (Figure 33). All personnel except the EOD team retreated beyond 1000 feet from the test configuration while the initiating charge, shown in Figure 34 (1 gallon of gasoline in a plastic container wrapped with detonation cord), was located and activated.

The test configuration was ignited by radio controlled detonation of the gasoline at 0741 hours and all components were engulfed in flames (Figure 35). Burning was vigorous (Figure 36). The temperature sensors under the test stand (Figure 37) rose rapidly to 900°C-1050°C by approximately 0800 hours, when the initial round ignited. All 12 rounds had ignited by 0830. The temperature at the edges of the test stand remained at the 0800 hour level, while those in

FIGURE 33. Saturation of Fire Wood With Diesel Fuel

FIGURE 34. Test Configuration Prior to Ignition

FIGURE 35. External Heat Test Ignition

FIGURE 36. External Heat Test Initial Phase Fire

the center had decreased to 500-800°C. Figure 38 shows a typical explosion of a round within the fire.

The fire burned vigorously for approximately 3 hours (Figure 39) during which the readily available fuel (pyrolyzates from wood) was consumed. The temperature (measured 6-9 inches above the surface) remained in the 800°C to 1100°C range around the edge of the stand with an excursion to 1200°C at approximately 0915 hours at the southwest corner. The south edge appeared to burn more vigorously and cooled more rapidly at later stages of the fire. After the vigorously burning phase was completed, the EOD team re-entered the area (Figure 40) and preliminary findings indicated no significant relocation of DU from the immediate area of the test stand and no unusual hazards.

FIGURE 37. External Heat Test Time Vs. Temperature

After a second evaluation by the EOD, the PNL and ARDC personnel re-entered the test area to make a preliminary survey of the test pad and visual observations. The fire was confined to flames and glowing embers under the stand. The recorded temperatures ranged from 500°C to 800°C. Eight primer and the remnants of 2 DU penetrators were discernible along the south edge of the test stand (Figure 41). Remains of a third DU penetrator were visible along the eastern edge of the stand (Figure 42) and of a fourth projecting northward near the NW corner (Figures 43 and 44).

On the basis of the favorable assessment (no spread of contamination to the edge of the test pad and no discernible temperature effect), construction

FIGURE 38. Round Exploding in Fire

FIGURE 39. External Heat Test Vigorous Burning Phase

FIGURE 40. EOD Re-Entry into Test Area

FIGURE 41. Debris Along South Edge of Test Stand

FIGURE 42. Remnant DU Core Lying Along Eastern Edge of Test Stand

FIGURE 43. Remnant DU Core at NW Corner

FIGURE 44. Remnant DU Penetrator at NW Corner

of the four-sided plastic enclosure was initiated at 1248 hours (Figure 45). Construction of the enclosure and location of air samplers along each wall were completed by 1500 hours. The bottom edge of the plastic wall was sand bagged to hold it in place. The maximum radiation level measured at the perimeter of the enclosure was 25 μ R/hr and was found to be emanating from the centrally located DU residue resulting from the burn. A more detailed radiation survey indicated that all significant levels of contamination were limited to an area extending from ground zero out to approximately a 3-foot radius.

Recovery operations were resumed at approximately 0800 hours on April 20. A thorough contamination survey that worked inward from the periphery of the test pad again indicated no significant relocation of debris. The uncontaminated debris away from the test stand (large pieces of charred lumber and charcoal) were cleared away. The temperature in the ash and material under the test stand was still in excess of 350°C. Initial inspection of the material under and immediately around the test stand indicated the DU penetrators which were visible had undergone substantial additional oxidation (compare Figures 43 and 44 to Figures 46 and 48). Visible bulky metal pieces (i.e., bases and primer tubes, sheet metal cartridge tube ends and straps, cartridge box hinges

FIGURE 45. Plastic Enclosure Around Test Pad

FIGURE 46. Oxidized DU Penetrator

FIGURE 47. Recovery Operation

and screws, etc.) were carefully picked from the pile after checking the temperature and brushing the material clinging to the items back into the pile. Recovery proceeded from the edges of the debris pile inward (Figure 47) concentrating initially on obvious concentrations of oxidized DU penetrators.

Wind velocities increased substantially during the day and recovery operations were terminated by the early afternoon due to the concern for potential airborne relocation of contamination from disturbance of the pile during recovery operations. A plastic cover was placed over the pile using poles to prevent contact with the ash. The edges were weighted down using locally available material (e.g., scrap lumber, tools, etc.), as the wind velocity increased. The enclosure itself was subjected to increasing strain and measures to reinforce the structure were taken. During these and subsequent episodes of high wind, the value of the enclosure to the operation was repeatedly demonstrated.

Recovery operations resumed on April 21, 1983 and proceeded as planned for the remainder of the operation. The ash and debris under and around the test stand had cooled to some tractable level and collection of the material

FIGURE 48. Oxidized DU Penetrator

for the mass balance measurements could proceed. Remnants of oxidized DU penetrators, which were cool enough to handle, were carefully segregated. Oxidation had continued; some penetrators oxidized completely. Obvious piles of oxide from the DU penetrators were meticulously segregated and bagged. A special oxide sample was taken for size distribution. Contaminated ash, charcoal and soil (combined) were handled in a similar fashion. Ash and other material clinging to metal pieces was brushed or vacuumed off and the pieces checked for contamination, as were all items. As the exterior layer of material was cleared, additional remnants of DU penetrators and pockets of oxide, as well as other items, were uncovered. At the bottom layer and adjacent to the surface, various sized lumps of cooled metal (assumed to be the aluminum from projectile components) were found. The metal was found to

contain pockets of contamination and, at one location, what appeared to be an unoxidized cross section of a DU penetrator. The large pieces were segmented to fit into sampling cans by a variety of techniques.

After a delay for other NTS activities, all items and material registering significant levels of activity on a GM meter were bagged and cataloged by the afternoon of April 22, 1983 (Figure 49). Figure 50 shows the only remaining remnants of the projectiles. As a final act, potentially contaminated soil under and around the test stand for a radius of 5 or 6 feet was shoveled into 55-gallon drums for retention at the test site and a final radiation survey was made; no levels above background were detectable.

Based upon visual observations during the burn and recovery along with the temperature history obtained, it appears that most of the projectiles on the bottom row fell essentially in place along the northern edge of the test stand as the wooden and cardboard containers burned and the propellant ignited. Burning of the subsequent layers of cartridge cases allowed the projectiles to slide backwards landing on or beyond the southern edge of the test stand. The

FIGURE 49. Test Pad After Recovery of Mass Balance Material

FIGURE 50. Remnants of Projectiles Recovered After Fire

projectiles were subjected to temperatures exceeding the melting point of aluminum (660°C) for an extended period of time, allowing the aluminum to become fluid and puddle. The iron strap and angle iron in the test stand were warped but there was no indication of melting of iron (1180°C to 1550°C). There were also no indications of melting of the DU penetrators (melting temperature of uranium 1132°C) or ignition. Ignition of uranium is a function of surface to volume ratio, and the specific area of the DU penetrators lies to the left of the plot shown in Figure 51. The DU penetrators would not be expected to ignite until the temperature greatly exceeded 700°C , if they can ignite at all. Elder and Tinkle (1980) subjected similar DU penetrators to temperatures ranging from 500°C to 1000°C in air and air CO_2 mixtures for 2 or 4 hours without ignition. Maximum observed oxidations were found at 700°C in air and 800°C in 50% air-50% CO_2 mixture. Some inhibition of oxidation at higher temperatures was postulated. Both the temperature range and atmosphere were within the range of conditions inside the pile during the burn and recovery operation.

Apparently, the uranium penetrators remained in what is known as the "kinetic controlled" regime (see Figure 52). Oxidation, which is a function

FIGURE 51. Dependence of Uranium Ignition on Specific Area (L. Baker, Jr., J. G. Schnizlein and J. D. Bingle 1966)

FIGURE 52. Effect of Temperature on Heat Generation Rates (Leibowitz et al. 1962)

of surface area and temperature (Figure 53), was fairly vigorous initially due to high temperatures and surface area. The DU penetrators continued to oxidize for at least 2 days at a discernible level but dropped off once the metal had cooled to ambient. Some remnants of cores were recovered while others

FIGURE 53. Oxidation Rates of Uranium in Air and Oxygen (L. Baker, Jr. and J. D. Bingle 1966)

oxidized completely; thus, conditions were not uniform. Uniform conditions would not be anticipated in any mass of burning combustible materials, such as was used in the external heat test.

It can be concluded that bare DU penetrators, subjected to fairly intense fire conditions (temperature up to 1200°C), do not appear to ignite. The oxidation pattern is qualitatively consistent with published information on uranium and DU penetrators (Tinkle and Elder 1980). The oxidation continues at some discernible rate as long as the temperature remains elevated and air is available. Therefore, cooling the mass (without spreading the contamination) would reduce the contamination potential by reducing the formation of oxide powder. Time is an important factor. These conclusions apply to the DU penetrators used in these tests and to similar bare penetrators. Other configurations may behave in radically different fashions. An additional concern is the presence of molten aluminum during the fire. If such materials are dropped into pools of water under certain conditions, a physical explosion is possible.

3.3.3 Mass Balance and Analysis

The mass balance procedure described in Section 3.1 of this document was again used in the 1983 recovery operation. A very intensified effort was made to retrieve the maximum amount of the original DU weight volume. To achieve this goal, all residue that registered 100 counts per minute or more above background, with a GM detector, was collected and packaged within four DOT-17H shipping drums. These drums were shipped to the Hanford Site in Washington State for analysis of radionuclide content by PNL's Radiological Sciences Department. Total shipping weight was approximately 570 kilograms (kg), including the drums and sample containers (tin cans).

From the total weight volume, only the residue with sufficiently high concentrations of DU, to be assayed by fission neutron coincidence counting techniques, was assayed. This amount totaled 122 kg of residue, excluding sample container weights. The samples were segregated into two basic categories: (1) DU oxides and small fragment residues contained within a sand matrix, and (2) highly concentrated DU oxides and larger metallic pieces, including penetrator remnants. The total amount of residue assayed (122 kg) included 64.9 kg of the sand mixture and 57.1 kg of the metallic pieces and

concentrated oxides. Penetrator remnants, which were identifiable as such, accounted for 7.6 kg of the metallic sample category.

The total uranium accounted for from the sand matrix and the metallic samples were 13.9 kg and 34.1 kg, respectively. The additional residue which was not counted contained DU levels that were below the sensitivity levels of the fission neutron counting system; however, it was observed that measurable amounts of DU were present in these samples, when measured with a GM detector.

In summary, approximately 100% of the original DU weight volume was recovered in 1983 (48.0 kg $\pm$ 5.0 kg recovered from the original 47.6 kg at the 95% confidence level), as opposed to 80% in 1982.

3.3.4 Conclusions

Based upon collected data and observations of the 1983 external heat test, it may be concluded that:

- The behavior of the XM829 cartridge during the 1982 external heat test was reproduced in the 1983 test.
- Approximately 100% of the original DU weight volume was recovered after the burn.
- No detectable levels of DU were found in soil samples taken from the ground zero point after the recovery operation was completed.
- No positive indication of airborne radioactivity resulted from the analysis of sampling media. Seven high-volume air sampling systems were in operation at the site during both the DU oxidation period and the recovery operation.
- Respiratory protection filtration canisters worn by personnel during the recovery operation showed no measurable levels of radioactive material.

4.0 CONCLUSIONS

It may be concluded that the functioning of an XM829 cartridge, in one shipping container, will not cause immediate functioning of XM829 cartridges in adjacent containers. However, if a fire results and is sustained, adjacent cartridges may ignite. In the "Test B" series, the time frame for the second cartridge to ignite varied from 20 to 70 minutes. It is concluded that some scattering of debris may occur. Based upon the test conducted, the scattering may have a maximum radius of 40 feet.

The behavior of the XM829 cartridge during the 1982 external heat test was reproduced in the 1983 test. The recovery facilities and techniques used in 1983 were improved from 1982 and were shown to provide an effective test method. Approximately 100% of the original DU weight volume was recovered in 1983 (48.0 kg $\pm$ 5.0 kg recovered from original 47.6 kg at 95% confidence level), as opposed to approximately 80% in 1982.

Samples of sand taken from the ground zero point, after the recovery operation was completed, indicated that no detectable levels of DU remained at the test site.

Based upon the analysis of collection media from seven high-volume air sampling systems, airborne concentrations of DU aerosol and particulates remained at or below natural background levels during the oxidation and recovery periods. It should be noted, however, that great care was taken during this time to prevent the residue from being scattered by winds and that under different conditions these values could vary.

Respiratory protection filtration canisters worn by personnel during the recovery operation yielded no measurable levels of DU, thus indicating that cleanup operations after such a fire can be conducted safely when proper care is maintained.

It may be concluded that DU does not ignite but behaves as described by Elder and Tinkle (1980) when subjected to the 1982 and 1983 test conditions. Therefore, it would be beneficial to fight such a fire before and possibly after the munitions ignite. Caution must be taken for possible steam explosion hazards that may result from the interaction of water and metals.

5.0 RECOMMENDATIONS

The following recommendations should be considered when dealing with a fire involving the XM829 ammunition. These recommendations apply only to the XM829 or similar rounds in which the component parts, primarily the cartridge material, are very like those used to construct the XM829.

- Such a fire should be extinguished as soon as possible after ignition and may be done without the use of respiratory protection for firefighters; however, distance should be considered due to possible minor explosions.
- After the first two hours of vigorous burning, oxidation of the DU may occur; at this point, supplied air respirators should be worn and care should be taken to avoid dispersal of the burning material.
- The potential for a steam explosion should be considered due to the interaction of water with molten metals, such as aluminum; the study of this hazard was beyond the scope of this test.
- Firefighting and recovery procedures should be developed and implemented for dealing with XM829 ammunition fires and subsequent cleanup operations.

Based on the results of the hazards classification test conducted in accordance with the Department of the Army Technical Bulletin, TB-700-2, 1968, the radiological evaluation by Pacific Northwest Laboratory, and the outer shipping container determination by the Department of Transportation (DOT), the following explosive hazard classifications were recommended by the Armament Research and Development Center (ARDC) Safety Office of the U.S. Army Armament, Munitions and Chemical Command, Dover, N.J.:

DARCOM Hazard Class	1.3
DARCOM Storage Compatibility Group	C
DOT Hazards Class	Class B Explosive
DOT Container Marking (Box)	Ammunition for Cannon with Solid Projectiles
DOT Bill of Lading	Class B Explosive - Radioactive exempt from specification packing, marking and labeling found in 49CFR 173.424.

However, as a result of the oxidation of depleted uranium during the explosive hazard classification test, it is necessary to evaluate the implications of ashing on occupational and public safety. As a minimum, the characterization is to include the determination of particle size distribution, and the oxide solubility in interstitial lung fluids. In addition, the determination of oxide composition and percentage, fractional airborne release, and downwind transport potential are important. These studies will require the use of laboratory and possible field tests. The conclusions drawn from these studies could result in changes being made to the hazard classifications.

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