Development and Technical Bases of US Department of Defense Intermagazine Distances to Earth Covered Magazines

Abstract

Defense Explosives Safety Regulation (DESR) 6055.09 establishes explosives safety standards for the US Department of Defense (DoD). These standards are designed to manage explosives-related risk associated with DoD operations and installations by providing protection criteria to minimize serious injury, loss of life, and damage to property.

Typically, DoD explosives safety requirements are satisfied by maintaining the minimum separation distances between a Potential Explosion Site (PES) and an Exposed Site (ES), as defined in DESR 6055.09. These separation distances vary with the explosives hazard (e.g., blast overpressure, fragmentation, thermal flux, etc.) and the level of protection required.

Within DoD, an Earth Covered Magazine (ECM) is typically used for the storage of Ammunition and Explosives (AE). The required separation distance between two ECMs, or Intermagazine Distance (IMD), is based directly on full-scale detonation tests of ECM designs. IMDs vary both with the relative orientation of the donor and acceptor ECMs and with the blast resistance of the acceptor ECM.

The IMDs applied to DoD's 7-bar ECMs were introduced in 1974 and have not changed. As time has passed, considerable confusion has arisen over the technical bases of these IMDs and the corresponding protection afforded AE in an acceptor ECM.

This paper will examine the development of DoD's IMDs to HD 1.1 storage magazines, starting with their introduction by Congress in 1928. It will review the full-scale detonation tests which have been used to increase HD 1.1 storage limits in ECMs and to reduce the required IMDs between them, highlighting changes in the protection criteria applied. Finally, it will assess the application of these IMDs to more recent ECM designs which have been specifically designed to withstand the expected blast loads defined in DESR 6055.09.

Introduction

During the World War II era, the Army and Navy constructed large numbers of arch-type Earth Covered Magazines (ECMs) for the storage of Hazard Division (HD) 1.1 (mass detonating) Ammunition and Explosives (AE). Many of these ECMs remain in use, providing the primary storage facilities for the Services' AE.

The minimum permissible scaled separation distances required between ECMs is termed the Inter-Magazine Distance (IMD). This scaled distance is calculated using the equation, $z = R/W^{1/3}$ where z is the IMD, R is the separation distance between two ECMs, in feet, and W is the HD 1.1 storage limit in an ECM, in pounds. The IMDs applied to legacy, arch-type ECMs designs constructed between the 1940's and 1960's are based on the damages sustained by these ECMs when acting as exposed sites in full-scale detonation tests. While the arch, rear wall and floor slab of arch-type ECM designs have performed well in these tests, the damage sustained by an acceptor ECM's headwall and door – and by extension, the protection it affords AE stored therein – depends on the specific headwall and door design.

By the 1960's, overpressure gages had been developed which were capable of measuring the blast overpressure versus time history at close-in separation distances from a donor ECM. Starting in the early 1970's, these measurements were used to define the expected blast load on an acceptor ECM's headwall and door. Similarly, blast load measurements to the front of donor ECMs were used by the Navy in the late 1970's to develop the first box-type ECM design concept for the storage of HD 1.1 AE. The adequacy of the headwall, door and flat roof designs developed using these loads was validated through detonation tests.

In 1997, "DoD Ammunition and Explosives Safety Standards," (DoD 6055.09-STD) introduced new criteria for the design and siting of ECMs. The expected blast loads on an acceptor ECM's headwall and door were defined for two exposures – K2 rear-to-front (7-bar load) and K1.25 side-to-side (3-bar). In 2000, the 7-bar and 3-bar load definitions were revised to specifically define the total positive blast impulse for each load, and a new flat roof load definition

was introduced for box-type ECM designs. These definitions were implemented in the 2004 "DoD Ammunition and Explosives Safety Standards," DoD 6055.09-STD, and remain in effect.

In recent years, there has been considerable confusion within the explosives safety community on siting requirements for legacy arch-type ECMs. In response, this paper reviews the evolution of ECM designs and their siting. Particular attention is given to full-scale detonation tests of more robust designs, and the application of these tests to increase their HD 1.1 storage limit in ECM designs and/or to reduce the IMD requirements between ECMs. The paper concludes by reviewing the specific protection requirements applied by DESR 6055.09, highlight the technical bases of these requirements.

Nomenclature

The US Department of Defense issued its first explosives safety requirements for mass detonating, Hazard Division (HD) 1.1 AE in 1956. Revisions to these requirements were issued through a variety of documents with varying scopes, reference numbers, and titles. A list of these documents follows, along with the initial issuance date and the date of the last change or revision, if any.

1) "Quantity-Distance Standards for Manufacturing, Handling and Storage of Mass-Detonating Explosives and Ammunition"
    a) DoD Directive 4145.17 – 7 December 1956
    b) DoD Instruction 4145.23 – 11 March 1966

2) "DoD Ammunition and Explosives Safety Standards"
    a) DoD Manual 4145.27 – March 1969
    b) DoD 5154.4S – Jul 1974 through 20 August 1982
    c) DoD 6055.09-STD – July 1984 through 29 February 2008
    d) DoD Manual 6055.09 – 4 August 2010 through 29 December 2017

3) Defense Explosives Safety Regulation (DESR) 6055.09 – 13 January 2019 through 25 November 2025

Similarly, the recently renamed Department of War Explosives Safety Board was previously known as:

- Joint Army-Navy Ammunition Storage Board (1928-1945)
- Army-Navy Explosives Safety Board (1945-1948)
- Armed Services Explosives Safety Board (1948-1971)
- Department of Defense Explosives Safety Board (1971-2025)

1926 Accident at Lake Denmark Naval Storage Depot, New Jersey

On Saturday, 10 Jul 1926 at approximately 5:10 p.m., a lightning strike initiated a fire inside a temporary ammunition storage building at the Lake Denmark Naval Storage Depot. The fire led to two closely spaced mass detonations of the large quantities of AE stored therein about five minutes later. Over the next 25 minutes, fires caused mass detonation of large quantities of AE in two other buildings. Fires and propagations to smaller quantities of AE in other buildings continued for the next three days.

The accident was worsened by surplus WWI AE, leading to the storage of unusually large quantities of AE in some buildings. Approximately 200 buildings were destroyed in the accident including 53 AE storage buildings – 10 for HD 1.1 AE, 19 for smokeless powder, 13 for projectiles, and 11 for black powder. Figure 1 depicts a portion of the damage sustained. The initial detonation occurred after work hours on a Saturday afternoon, reducing the number of injuries and fatalities. Nonetheless, 21 people were killed and a far greater number were injured.

Figure 1 *– View of the damages sustained in the 10 Jul 1926 accident at Lake Denmark Naval Storage Depot.*

Introduction of Army and Navy Explosives Safety Requirements

In response to the Lake Denmark accident, a Special House Subcommittee on Ammunition Storage was established in 1927. This subcommittee directed the Army and Navy to conduct a joint survey of their points of storage of ammunition and components. Based on the survey's recommendations, an act of Congress was approved on May 29, 1928, adopting the 1925 laws of the state of New Jersey as the standard of safety for Army and Navy explosives facilities. In addition to stating requirements specific to AE storage, the NJ law incorporated the "American Table of Distances" (ATD), previously developed for commercial explosives operations.

The 1928 law also created a permanent, joint, Army-Navy board which shall keep advised of storage supplies of ammunition and components. In performing this mission, the board was directed to give special reference to keeping such supplies properly dispersed and stored and to preventing hazardous conditions from arising to endanger life and property within and without storage reservations.

Application of the New Jersey Laws to the Siting of Earth Covered Magazines – 1928 through World War II

Per the following definitions, the 1925 New Jersey laws only considered the storage of AE storage in an Above-Ground Magazine (AGM):

> *9. Magazines*. – Magazines in which explosives may be lawfully kept or stored shall be of two classes:

(a) Magazines of the first class shall consist of those containing explosives exceeding fifty pounds, and shall be constructed of brick, concrete, iron, or wood with outside covering of iron, and shall have openings only for ventilation and entrances…

….(b) Magazines of the second class shall be constructed of brick, concrete, iron, or wood with outside covering of iron, and no more than fifty (50) pounds of explosives shall at any tune be kept or stored therein….

The 1925 New Jersey laws applied an HD 1.1 storage limit of 250,000-lbs to first class magazines/AGMs and required an 800-ft IMD from AGMs sited at this storage limit. This IMD, as well as the other separation distances defined in the New Jersey laws, could be reduced by one-half *"…[W]henever a factory building or magazine is effectively screened from another explosives plant building or magazine, building, railroad or highway, either by natural features of the ground, or by an efficient artificial barricade…"* The term, efficient artificial barricade, was defined as *"…an artificial mound or properly revetted wall of earth of a minimum thickness of not less than three feet at the top."* Accordingly, if an adequate barricade were constructed between two AGMs sited for 250,000-lbs HD 1.1, the IMD between them could be reduced from 800-ft to 400-ft.

The first ECM design concepts were developed by the Services in the 1930's. At its 30 Jul 1940 meeting, the Joint Army-Navy Ammunition Storage Board designated the earth-covered, arch type magazine as the preferable type for future construction for the storage of all types of explosives and ammunition, except small arms ammunition. In accordance with the NJ Laws, the HD 1.1 storage limit in ECMs was 250,000-lbs. The earth cover on the arch and rear wall of an ECM were deemed equivalent to an "efficient artificial barricade," as defined in the 1925 New Jersey laws, allowing IMDs to ECMs of 400-ft (if barricaded) and 800-ft (if unbarricaded).

As World War II progressed, the Army and the Navy became increasingly aware of the inherent limitations of the 1925 New Jersey laws. In response, the Joint Army-Navy Ammunition Storage Board's mission was expanded, leading to the hiring of the first technical support staff in 1944. Initial work focused on assessments of the damages sustained by different types of structures in explosives detonations during World War II.

At the conclusion of World War II, the now renamed Army-Navy Explosives Safety Board (ANESB) funded two series of detonation tests at Naval Providing Ground, Arco, Idaho to assess storage options for the vast quantities of Army and Navy AE which would soon be returning to the United States. The tests had two primary purposes: (1) to evaluate temporary storage facilities to be used until the stocks needed for peacetime use and the war were determined and (2) to determine whether existing AE storage facilities and installations could be safety expanded without large expenditures for additional land, roads, and properties.

1945-46 Full-Scale Detonation Tests at Naval Proving Grounds, Arco, Idaho

A series of eight full-scale detonation tests were performed at Arco Naval Proving Ground in fall 1945. Test 1 evaluated the response of acceptor ECMs at lower IMDs than permitted by the 1925 New Jersey Laws and thus, is of particular interest. One of the acceptor ECMs, designated as Igloo B in figure 2, was located at a side-to-side separation distance of 185-ft from the donor ECM, designated as Igloo A. Igloo B was constructed in accordance with the standard series 652=686 through 652-692 design drawings, the more robust of the two arch-type ECM designs constructed by the Army during WWII. In the test, 250,000-lbs of HD 1.1 munitions were detonated in Igloo A. Igloo B sustained minor damage with no propagation to the acceptor munitions stored therein.

Based on the results on the 1945 tests, a series of five additional full-scale detonation tests were performed at Arco Naval Providing Ground in October 1946. Two of these tests evaluated the damages A second series of full-scale detonation tests were performed at Arco NPG in 1946. Two of the six tests evaluated the protection afforded by the Army series 652-686 through 652-693 arch-type ECM design from a 500,000-lb detonation at reduced IMDs. The test layout is provided in Figure 3.

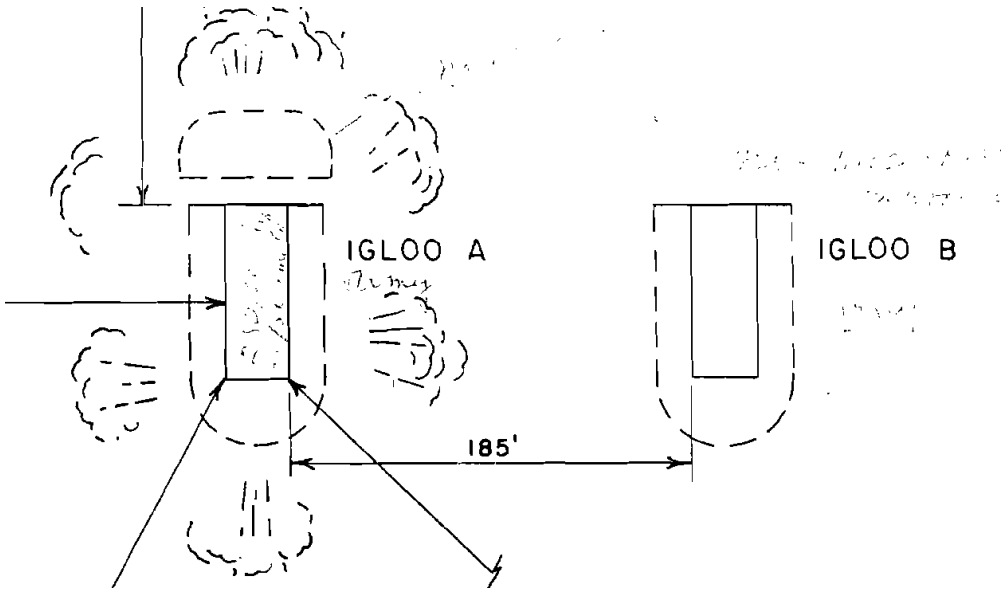

Figure 2 *– Plan view of Igloos A and B in first full-scale detonation test at Naval Providing Ground, Arco, Idaho, 1945.*

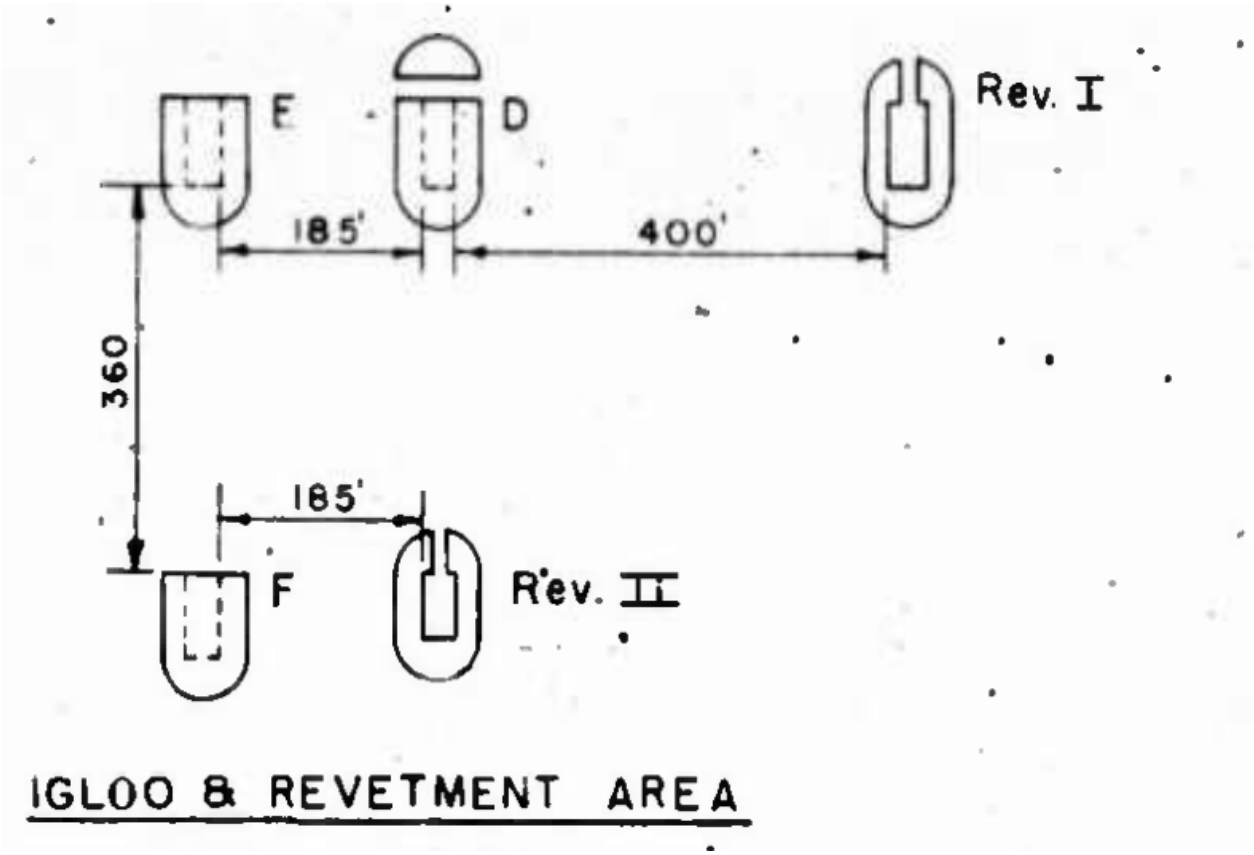

Figure 3 *– Plan view of the AE storage structures in the October 1946 detonation tests at Arco Naval Proving Ground.*

In the first of these tests, the donor ECM was Igloo D. The damages sustained by Igloos E and F and their contents were as follows:

Damage to Igloo E (at side-to-side IMD of 185-ft):

- Fine cracks in arch barrel and rear wall; no arch debris reported.
- Circumferential joint between arch barrel and headwall ruptured with much spalling.
- Main cracks in headwall went through from inside to out and were open to about ½-inch
- Single-leaf door deflected outward at center about 7/16-inch but remained operable.
- No damage or displacement of acceptor munitions.

Damage to Igloo F (at rear-to-front I MD of 400-ft):

- Through cracks in headwall generally following the line of the arch; maximum crack opening of approximately 0.5-inch.
- Slight cracking of floor slab within 10-feet of the headwall along abutments with arch.
- No concrete spalling to the interior.
- Door undamaged.
- No damage or displacement of acceptor munitions.

The second ECM test evaluated the (cumulative) damage to Igloo F from a 500,000-lbs detonation in Igloo E. The following (cumulative) damage was reported to Igloo F and its contents (at rear-to-front IMD of 360-ft):

- Additional headwall cracking; cracks from first test extended and opened wider.
- Outward headwall displacement of approximately 2-inches, creating gap with floor slab.
- Severe spalling of vertical pilasters.
- Door and door frame bent inward slightly but remained operational.
- No appreciable damage to arch and rear wall.
- No damage or displacement of acceptor munitions.

Implementation of 1945-46 Arco NPG Test Results

On 11 Apr 1947, the Army-Navy Explosives Safety Board (ANESB) issued a memorandum to the Department of War and the Department of the Navy recommending an increase in the HD 1.1 storage limit in the Army Standard Series 652-686 through 652-692 ECM from 250,000-lbs to 500,000-lbs and reductions in the IMDs applied to this design to 185-ft (side to side) and 360-ft (rear to front). It was unclear, though, if ANESB had the legal authority to implement explosives safety requirements which deviated from the 1925 New Jersey laws, adopted by Congress in 1928. On 27 October 1949, the US Attorney General issued an opinion advising that the Board in the execution of its statutory duties "…had the authority to establish safety standards and has the authority now to make changes therein…"; these standards "…must be considered binding, but only as minimum safety standards."

On 1 Apr 1950, the now renamed Armed Services Explosives Safety Board (ASESB) issued draft explosives siting requirements for mass detonating AE. These requirements were based both on detailed analyses of the damages sustained by structures in detonations during War II and data from the 1945-46 Arco Naval Proving Ground tests, as summarized in ANESB Technical Papers 3 and 5. After much coordination with the Services, the now renamed Armed Services Explosives Safety Aboard (ASESB) approved the first DoD explosives safety standards in 1955. These standards were officially issued under DoD Directive 4145.17, "Quantity-Distance Standards for Manufacturing, Handling and Storage of Mass Detonating Explosives and Ammunition," 7 Dec 1956.

DoDD 4145.27 introduced four categories of HD 1.1 AE storage structures, defining HD 1.1 storage limits and IMD requirements for each. The Services' most robust, arch-type ECM designs were designated as "Standard Igloo Magazines." The Army standard series 652-686 through 652-692 ECM design, evaluated in the 1945-46 Arco NPG test, was designated a Standard Igloo Magazine. The HD 1.1 storage limit in a series 652-686 through 652-692 ECM

was increased from 250,000-lbs to 500,000-lbs, and the IMDs to this ECM were reduced to 185-ft (if barricaded) and 360-ft (if unbarricaded).

1962-63 Corrugated Steel Arch ECM Tests and initial Siting Requirements

Between January 1962 and December 1963, a series of seven detonation tests were performed at Naval Ordnance Test Station (NOTS), China Lake, CA on prototype corrugated steel-arch ECM designs. Six of these tests were performed at reduced scale. The one full-scale test was used to validate the protection afforded acceptor AE by an O.C.E. Specification 33-15-64-62 corrugated steel arch ECM design at side-to-side IMDs of K1.25 and K1.5 from a donor ECM storing 100,000-lbs Comp B. Reported damages to the acceptor ECMs in this test were as follows.

- Damage primarily to each ECM's double doors; no initiation of acceptor AE in either ECM.
- Acceptor ECM at K1.25 side to side: Both doors bowed leaves blown inward; one leaf remained attached to a door hinge/frame, the other leaf detached, falling immediately inside doorway; igloo floor randomly raised and lowered.
- Acceptor ECM at K1.5 side to side: Both door leaves detached; one leaf fell immediately inside the doorway, the other leaf propelled 50-feet to the front of the ECM.

DoD Instruction 4145.23 (11 March 1966) introduced the following IMDs to the corrugated steel arch ECM design: K1.25 side-to-side; K1.5 rear-to-rear; K4.5 front-to-rear and K4.5 front-to-side. Since the 1962-63 NOTS tests did not consider a rear-to-front exposure, no rear-to-front IMD was defined. In addition, the following caveat was applied: *"…[T]hese criteria are only for prevention of propagation of explosions between adjacent steel arch magazines and will not necessarily prevent damage to acceptor magazines and their contents."*

ESKIMO I Test and the Introduction of IMDs to Standard (now 7-bar) ECMs

Between 1971 and 1986, the Explosives Safety Knowledge IMprovement Operation (ESKIMO) funded seven detonation tests of HD 1.1 ECM designs at Naval Weapons Center, China Lake, CA. The first five tests were performed at full-scale and evaluated arch-type ECM designs and design concepts. The last two tests were used the validate the first box-type ECM design configuration for HD 1.1 AE storage, developed by the Navy in the late 1970's.

In the ESKIMO I test, the donor ECM was a corrugated steel arch-type ECM previously used as an acceptor ECM in the 1963 full-scale test. The four acceptor ECMs faced the donor ECM. They were constructed in accordance with the standard series 33-15-64 corrugated steel arch ECM design drawing with arch barrel lengths reduced to 20-ft. Per Figure 4, the IMDs to the acceptor ECM varied.

Photos of the damage sustained by Acceptor Igloo B, located at K2 rear-to-front, are provided in Figures 5 and 6. Damages to this ECM and its contents were described as follows:

- Both leaves of the double door were forced inward
- Earth cover from the donor ECM, Igloos A, was thrown into the ECM.
- Cracking of concrete headwall, particularly around door frame.
- Acceptor munitions were somewhat damaged but did not initiate.

Based on data from the ESKIMO I and previous ECM test, now renamed Department of Defense Explosives Safety Board (DDESB) reduced the required IMDs to corrugated steel arch ECM designs to K2 (rear-to-front) and K 2.75 (side-to-front). DDESB also revised IMD requirements for front-to-front exposures to K11 for unbarricaded exposures and K6 for properly barricaded exposures.

In May 1974, "DoD Ammunition and Explosives Safety Standards," DoD 5154.4S, reorganized ECM designs into two broad categories, standard magazines and non-standard magazines. ECM design deemed equivalent in strength to the ECMs tested in the 1945-46 Arco NPG, 1963 NOTS, and 1971 ESKIMO I tests were approved for storage of up to 500,000-lbs HD 1.1 AE at the IMDs validated in the 1963 and 1971 tests. These IMDs were subsequently applied to 7-bar ECM designs and have not changed since their introduction in 1974.

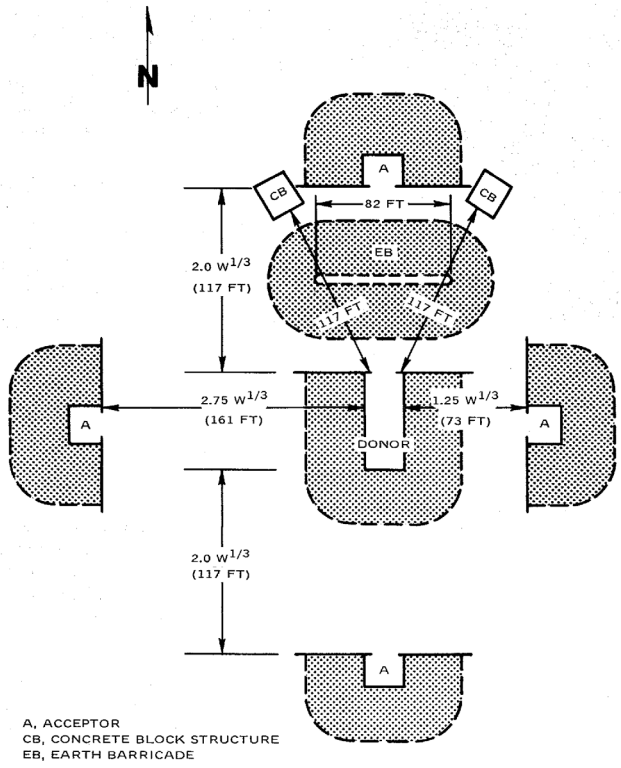

Figure 4 *– Plan view of donor and acceptor ECMs in the ESKIMO I test.*

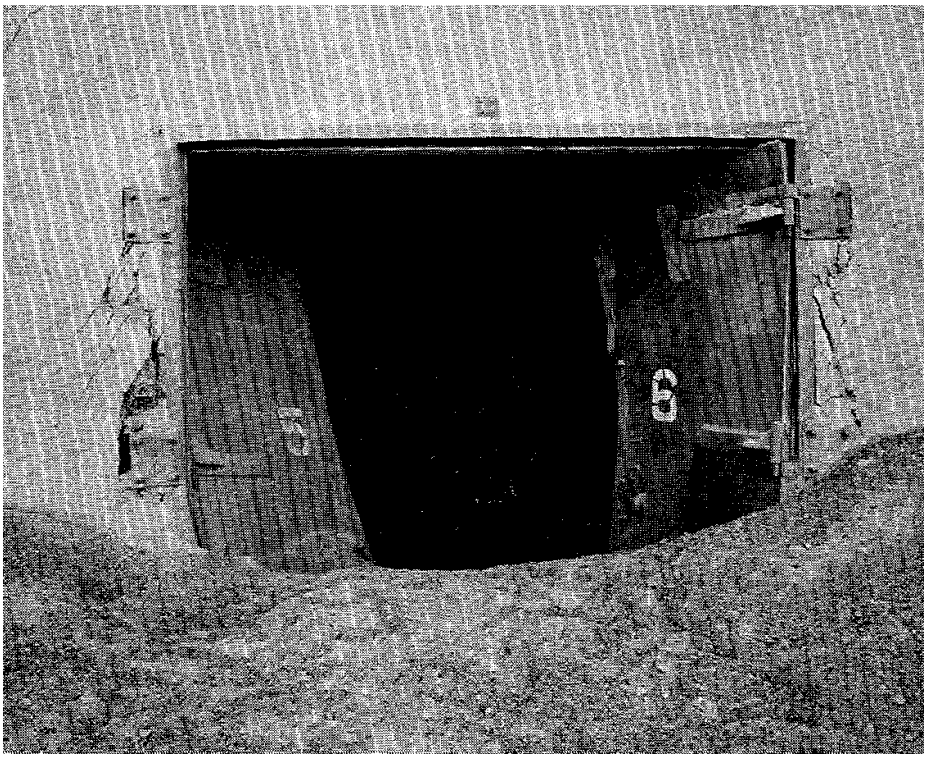

Figure 5 *– Exterior view of Igloo B, located at K2 rear to front, in the ESKIMO I test.*

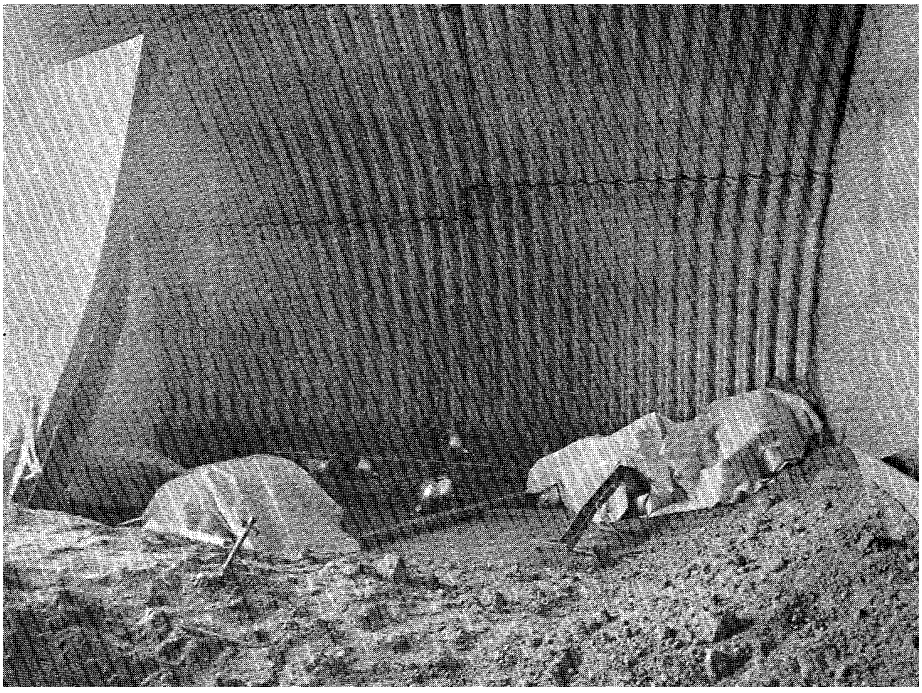

Figure 6 *– Interior view of Igloo B, located at K2 rear-to-front, in the ESKIMO I test.*

The HD 1.1 storage limit in nonstandard ECMs remained at 250,000-lbs, unchanged from the 1925 New Jersey laws. While some of the IMDs applied to nonstandard ECMs were less than those applied by the New Jersey laws, they were typically greater than the IMDs applied to a standard ECM.

Transition to 7-bar, 3-bar and Undefined ECMs

After ESKIMO I, sufficient blast load measurements had been made at close-in distances from donor ECMs to define the expected blast loads on an acceptor ECM's headwall and door at K1.25 side-to-side and K2 rear-to-front. Since an acceptor ECM at K2 rear to front is exposed to reflected overpressures rather than incident overpressures, the expected peak overpressure and total impulse at K2 rear to front was more severe than the corresponding values at K1.25 side-to-side. Accordingly, new headwall and door concepts were designed to withstand the expected blast load at K2 rear-to-front.

Headwall and door concepts designed to withstand the expected blast load at K2 rear-to-front were evaluated in the ESKIMO II through V tests. In these tests, the concepts afforded acceptor AE adequate protection from a prompt propagation, thereby validating their designs. In the late 1970s, blast load measurements to the front of donor ECMs were used to define the blast design blast load on the flat roof of the box-type ECM sited at K2 front-to-rear. A one-half scale prototype of the resulting roof designs was evaluated in the ESKIMO VI test. The roof performed well, affording the required protection to acceptor AE from a prompt validation and validating the design.

As new ECM configurations were proposed in subsequent years, DDESB and Service explosives safety experts recognized the benefit of defining the expected blast load on an ECM's headwall and door at the two minimum IMDs typically considered in ECM tests, K1.25 side-to-side and K2 rear to front. The expected peak reflected overpressure at K2 rear-to-front was defined as 7 times the standard atmospheric pressure and designated as the 7-bar load. Similarly, the expected peak incident overpressure at K1.25 side-to-side was defined as 3 times the standard atmospheric pressure and designated as the 3-bar load.

DDESB technical staff subsequently developed a change proposal which, in addition to adopting the foregoing 7-bar and 3-bar load definitions, redesignated standard and nonstandard ECMs as 7-bar and undefined ECMs, respectively. While no changes were made to the IMDs applied to standard/7-bar and nonstandard/undefined ECMs, the newly defined 3-bar IMDs could be applied to a nonstandard ECM whose headwall and door were capable of withstanding the new 3-bar load. Before voting on this change, DDESB Board members verified that all ECMs previously approved for siting as a standard ECM would be sited as a 7-bar ECM if the proposed change were adopted.

The foregoing change was implemented in the 1997 revision to "DoD Ammunition and Explosives Safety Standards," DoD 6055.09-STD. In 2000, the Services approved a flat roof load definition for box-type ECM designs and revised 7-bar and 3-bar definitions explicitly defining the total positive impulse for each load. The 2004 revision to "DoD Ammunition and Explosives Safety Standards," DoD 6055.09-STD, implemented these revisions. The 7-bar, 3-bar and flat roof load definitions in the 2004 standards remain in effect.

ECM Performance Requirements

While DESR 6055.09 bases ECM siting requirements on the prevention of a prompt propagation to AE in an acceptor ECMs, performance requirements are defined in two sections. Section V2.E5.5. is directly applied to newer ECMs specifically designed to withstand the applicable 7-bar, 3-bar and flat roof loads defined in the standards, as follows: *"**ECM.** An ECM's primary purpose is to protect AE. To qualify for the default IMD in Table V3.E3.T6, an ECM, acting as an ES, must not collapse. Although substantial permanent deformation of the ECM may occur, sufficient space should be provided to prevent the deformed structure or its door from striking the contents."*

Full-scale detonation tests were used to validate the siting of legacy standard/7-bar arch-type ECM designs. In each of these tests, a specific ECM design was evaluated with all acceptor ECMs constructed in accordance with this ECM's design drawings. These acceptor ECMs were located at various exposures and IMDs from the donor ECM. If none

of the AE in an acceptor ECM reacted in a test, the damages sustained by the ECM were assessed. In all test, the arch, floor slab, and rear wall of the acceptor ECMs sustained minimal damage, so assessments focused on the headwall and door. If the risk of propagation due to acceptor AE impacts by the observed headwall and door debris were judged sufficiently low, the ECM design was approved for siting at the tested IMD.

Typically, Service detonation tests are used to evaluate more robust ECM designs. One of the acceptor ECMs in the ESKIMO II tests was an exception. The headwall and door of this ECM were constructed in accordance with a less robust, arch-type ECM design from the 1950's. In this test, the donor explosives was a hemispherical charge in the open meant to simulate the blast load at K2 rear-to-front from a 500,000-lb detonation in a donor ECM. In the test, the applied impulse of this ECM's headwall was 60% greater than anticipated. While the headwall and door failed, the headwall's smooth welded wire reinforcing remained in place. Given the minimal bonding of concrete to these wires, the concrete disengaged from the wires and was blown into the ECM in small pieces, lessening the detonation hazard from these debris.

DESR 6055.09, section V1.E8.2.1.4.3, Earth-Covered Magazines (ECMs) reflects the foregoing basis, stating that *"…[W]hen separated from each other by the minimum distances required by Table V3.E3.T6, ECMs (as addresses in section V2.E5.5) provide virtually complete protection of AE against the propagation effects of an explosion. However, AE in adjacent ECMs may be damaged and structural damage ranging from cracks in concrete to damage to ventilators and doors to complete structural failure [of these elements] may occur."*

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