Safe Separation Study for MK 437 MOF*N* (Multi-Option Fuze *for Navy*)

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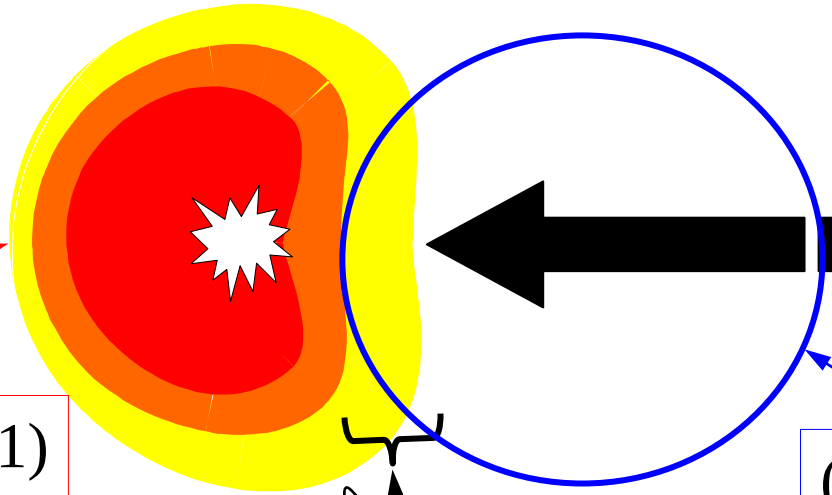
Introduction

- During the assessment of safe separation for MOFN there was much debate concerning methodology.
- This presentation is offered that other programs may benefit from the precedent set by MOFN which follows a safe separation assessment methodology of MIL-HDBK-504 *Guidance On Safety Criteria For Initiation Systems*.

Background on Safe Separation

- The need to perform a separation analysis is codified in MIL-STD-1316.
- Para 4.2.2, Requirement
  - *"A safety feature of the fuze shall provide an arming delay which assures that a safe separation distance can be achieved for all defined operational conditions."*
- Para 3.29, Definition
  - *"The minimum distance between the delivery system (or launcher) and the launched munition beyond which the hazards to the delivery system and its personnel resulting from the functioning of the munition are acceptable."*

General Methodology for Safe Separation Assessment



(4) Fly Out Conditions
Modify Lethality Effects
- *Speed*
- *Direction*

(1) Warhead Lethality Effects
- *Fragmentation*
- *Over pressure*
- *Sound level*
- *Underwater Shock*

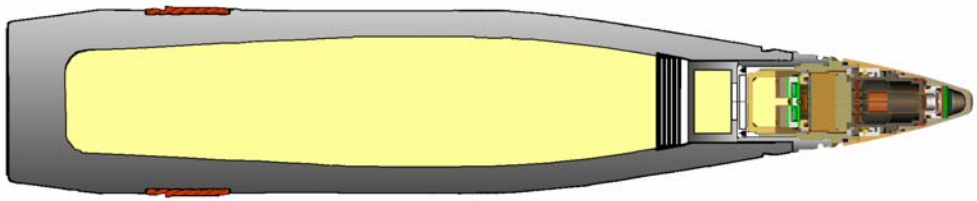
(3) Acceptable Hazard Level for Safe Separation
- *Safety Board Guidance*
- *MIL-HDBK-504*
- *MIL-STD-882*

(2) Platform Vulnerability
- *Material*
- *Personnel Protected*
- *Personnel*

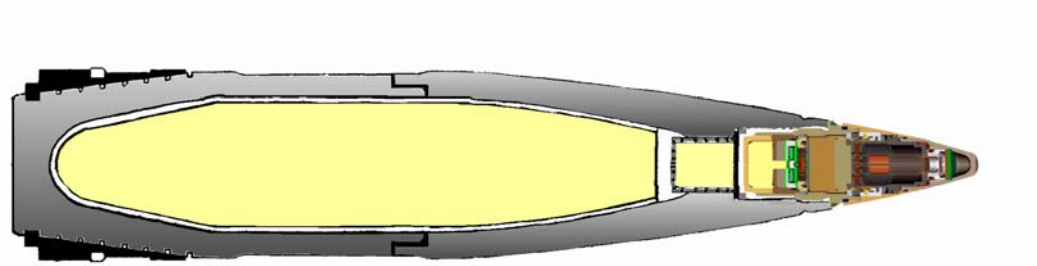
Analyzed at Worst Case Operational Condition

Warhead Lethality

MOFN has two potential warheads



EX 183 HE-MOFN
- MK 64 PROJECTILE BODY
- PBXN-106 EXPLOSIVE FILL



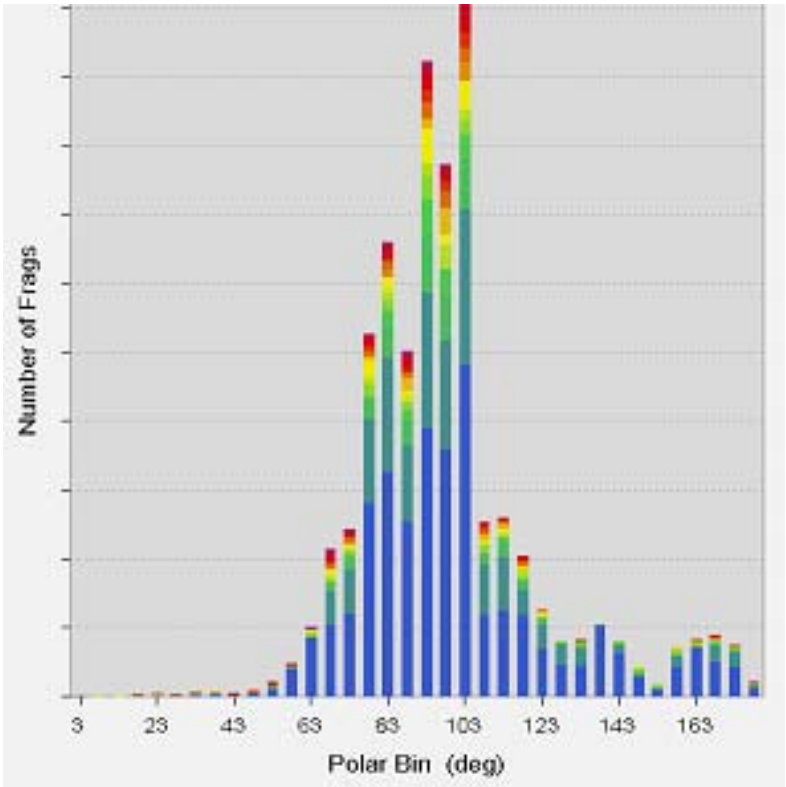
EX 184 HE-MOFN
- HIFRAG PROJECTILE BODY
- PBXN-106 EXPLOSIVE FILL

Warhead lethality effect is fragmentation

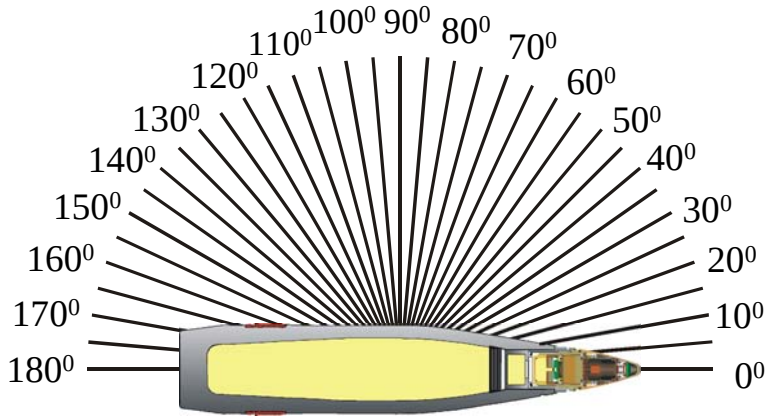
Warhead Lethality

- Warhead fragmentation characteristics determined with Arena Tests, min 3 tests of all-up munition (ref MIL-HDBK-504).
- Fragment size, location, and velocity captured.

Warhead Lethality



- Data is put into JMEMs[1] format:
- For each 5º spherical arc
  - Fragment size quantized into bins & averaged
  - Fragment velocity averaged



[1]JMEMs – Joint Munition Effectiveness Manuals

Platform Vulnerability

- Two ships carry the 5” gun: Destroyers and Cruisers.
- Cruiser was selected for study because it is a longer ship with a larger deck area.
- Cruisers have two 5” guns. The forward gun was selected for study because it has a greater range of motion.

DDG-51 Arleigh Burke class (Aegis) Destroyer

CG-47 Ticonderoga class Cruiser

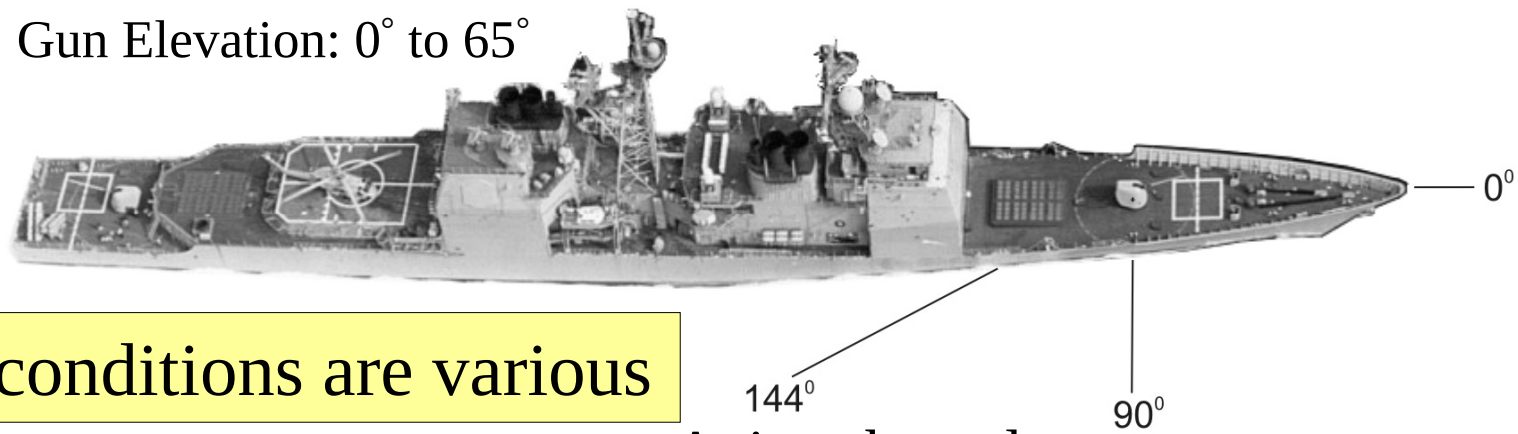
Platform Vulnerability

- Ship superstructure not as susceptible to damage as personnel who may be on deck.

Vulnerability based on personnel on deck using JMEM vulnerability models.

Fly Out Conditions

- Fly out defined by velocity and direction:
  - Velocity
    - MK 67 Mod 3 Standard Prop Charge: IV = 2650 fps
    - MK 68 Mod 2 Reduced Prop Charge: IV = 1500 fps
  - Direction
    - Gun Azimuth: 0˚ to 144˚
    - Gun Elevation: 0˚ to 65˚



Azimuth angles

Fly out conditions are various

Acceptable Hazard Level for Safe Separation

- MIL-HDBK-504, *Appendix A**, guidance:
  - Safe Separation Distance is the shortest distance where probability of a hazardous fragment hit from functioning of the munition is no greater than one in ten thousand (.0001)
  - A hazardous fragment is one with velocity greater than V_{50} for skin penetration.

Acceptable hazard level based on MIL-HDBK-504

**Note: Appendix B is for Air Launched Munitions*

Defined Operational Conditions

SAFE SEPARATION SCENARIOS										
Scenario #	1	2	3	4	5	6	7	8	9	10
Mission	AAW				NSFS		ASuW			
Elevation	+65°		+65°		+46°		0°		0°	
Azimuth	-144°		-144°		-90°		-144°		-144°	
Projectile	MK 64		HIFRAG		MK 64		MK 64		HIFRAG	
IV (ft/s) **	2,400	1,400	2,400	1,400	2,400	1,400	2,400	1,400	2,400	1,400

Ten scenarios correspond to 3 types of engagements:

- air targets (AAW),
- long range shore targets (NSFS), and
- close in surface targets (ASuW).

Worst case operational scenarios identified

***Note: IV includes 8% to 10% penalty as worst case*

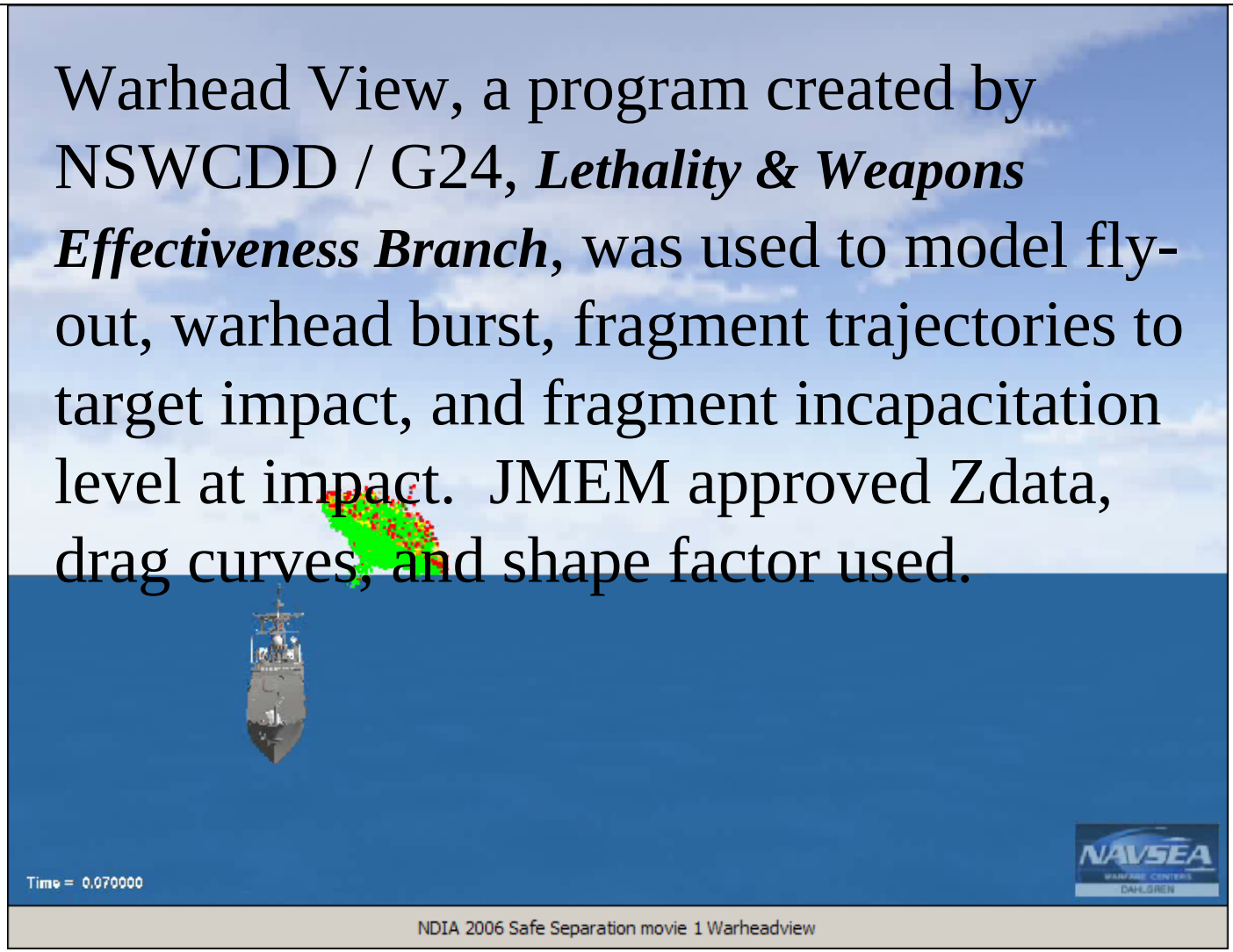
Safe Separation Distance

MK 64 proj.
150 ft range
Std Charge
90° Azimuth
60° Elev.

Frag Colors:

- 0 to 5 grams
- 5 to 10 grams
- 10 to 20 grams
- Above 20 grams

Warhead View, a program created by NSWCDD / G24, ***Lethality & Weapons Effectiveness Branch***, was used to model fly-out, warhead burst, fragment trajectories to target impact, and fragment incapacitation level at impact. JMEM approved Zdata, drag curves, and shape factor used.



NDIA 2006 Safe Separation movie 1 Warheadview

Safe Separation Distance

- Probability of incapacitation of each fragment computed following JMEM methodology

$$P_{I/H} = 1 - e^{-a\left(mV^{2/3} - b\right)^{n}}$$

- Each summed to obtain total probability and normalized to the area of a person.

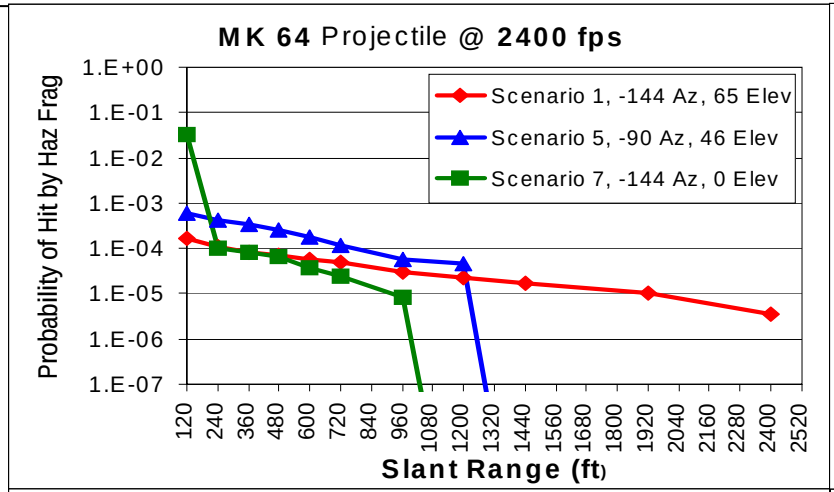
$$P_{Inc} = \left(\frac{A_{pers}}{A_{Ship}}\right) \sum_{N_{Hits-ship}} P_{I/H}$$

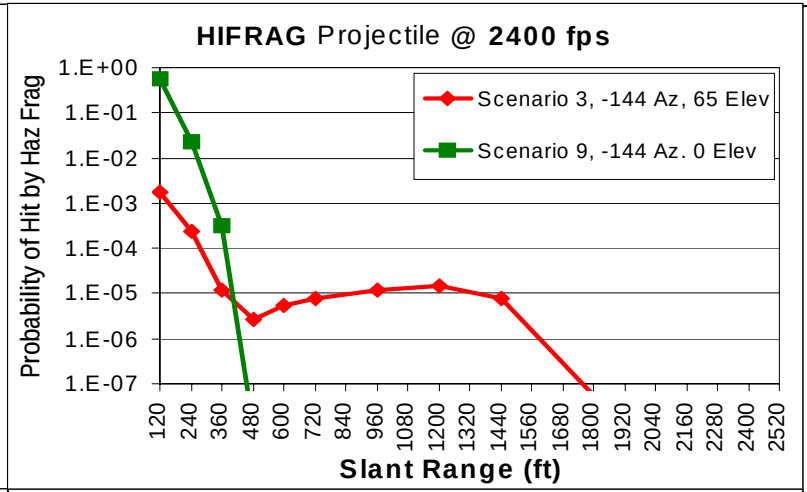
Safe Separation Distance

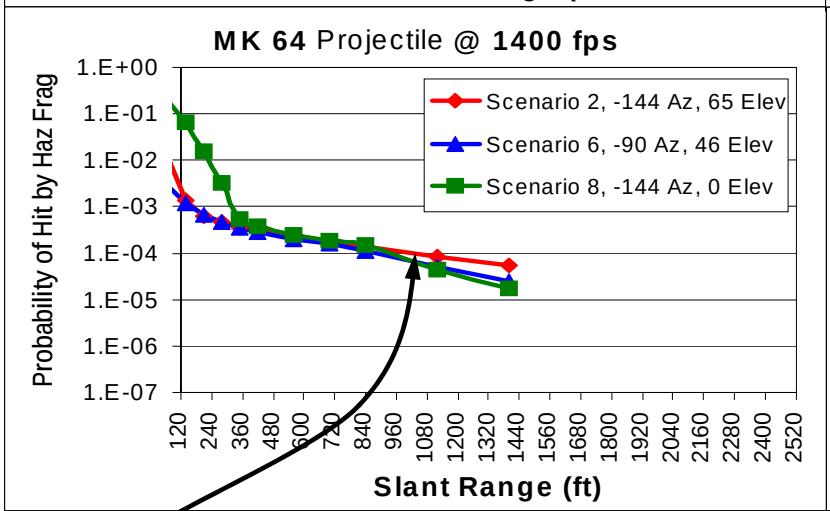
Sample data from Warhead View, 3 incapacitation levels computed

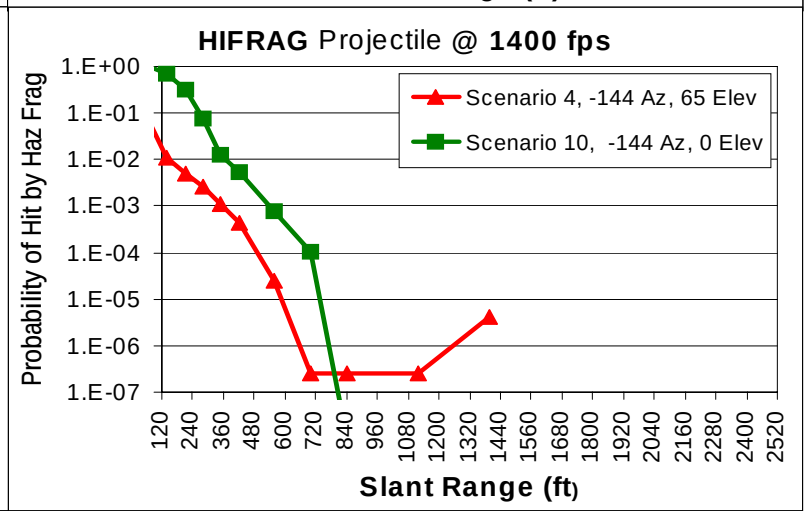
Scenario 1, -144° Azimuth, 65° Elevation				Probability of Incapacitation, 1 person		
Burst Time (s)	Slant Range (ft)	Average Number of Fragments Impacting ship	Average Fragment Mass (grains)	Lethal Wounding, Summer Clothing	Serious Wounding, Summer Clothing	Skin Penetration, Nude
0.05	120	398.1	10.78	0.0000710	0.0001648	0.0001705
0.10	240	446.9	8.73	0.0000413	0.0001060	0.0001105
0.15	360	494.7	8.04	0.0000280	0.0000800	0.0000843
0.20	480	459.5	8.95	0.0000205	0.0000648	0.0000693
0.25	600	330.4	12	0.0000153	0.0000520	0.0000568
0.30	720	216	17.8	0.0000120	0.0000443	0.0000490
0.40	960	79.9	43.06	0.0000063	0.0000255	0.0000290
0.50	1,200	35.2	83.67	0.0000045	0.0000195	0.0000225
0.60	1,440	17.1	134.37	0.0000033	0.0000148	0.0000170
0.80	1,920	4	387.64	0.0000020	0.0000085	0.0000100
1.00	2,400	1.7	634.26	0.0000008	0.0000030	0.0000035

Safe Separation Distance









Safe separation distance is 1010 ft

Operational Requirement for Close Engagement

- MOFN has a requirement for close-in engagement for ship self defense against small surface attack craft.
- MIL-HDBK-504 guidance is that a System Safety Risk Assessment (SSRA) be developed, per MIL-STD-882, and signed off by the Developer (PM) and User acknowledge and accepts the risk.
- 2 additional hazard assessments were performed.
  - Hazard of engaging target at min range.
  - Hazard of early burst at min arming.

Min Engagement Hazard

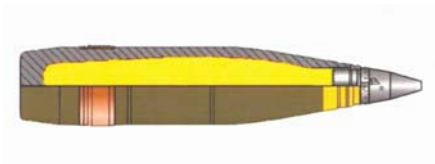
To determine hazard of Engaging Targets at Min Range:

1. Identify operational configuration.
2. Determine Incapacitation Probability due to warhead function.

$$P_{inc/Det}$$

Min Engagement Hazard

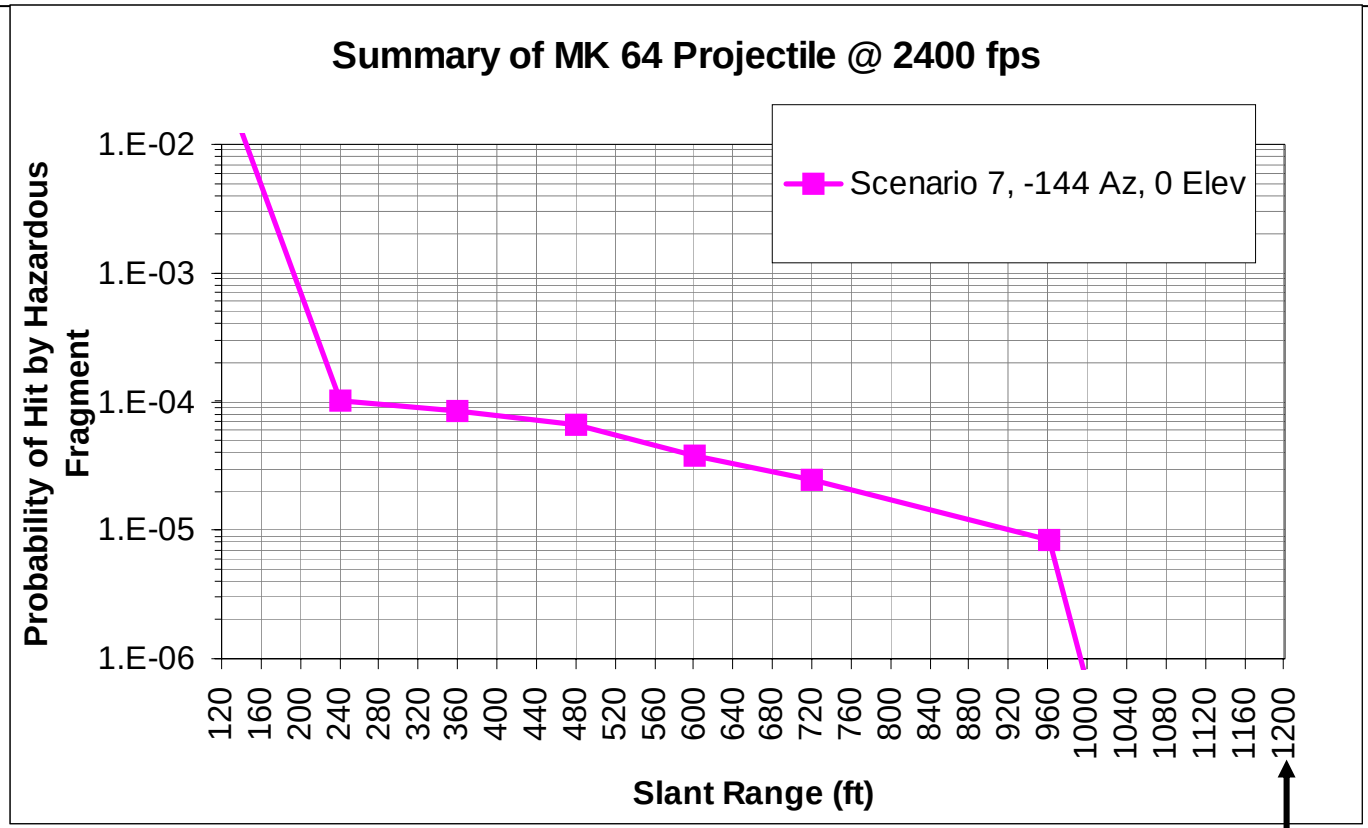
- Worst Case Operational Configuration:
  - Projectile = EX 184 HE-MOFN
    - MK 64 Projectile w PBXN-106 fill



  - Propelling Charge = MK 67 Mod 3 Std Prop Charge
    - IV = 2650 fps
  - Platform = US Navy CG-47 Class Cruiser
    - Gun direction – 144 ˚ azimuth, 0˚ elev

  - Min Engagement Distance is 0.5s.
    - Firing Circuit disabled until 0.5s

Min Engagement Hazard



The hazard of engaging targets at minimum range is zero.

0.5s Minimum Engagement distance

Early Burst Hazard

- Early burst hazard at min arming presents a hazard that must be identified per MIL-STD-882 and accepted by the program.
- To determine hazard:
  1. Identify operational configuration.
  2. Determine probability of incapacitation from warhead function.
  3. Determine probability of warhead function.

$$P_{inc} = P_{Det} \times P_{inc/Det}$$

Incapacitation Probability

Warhead Function Probability

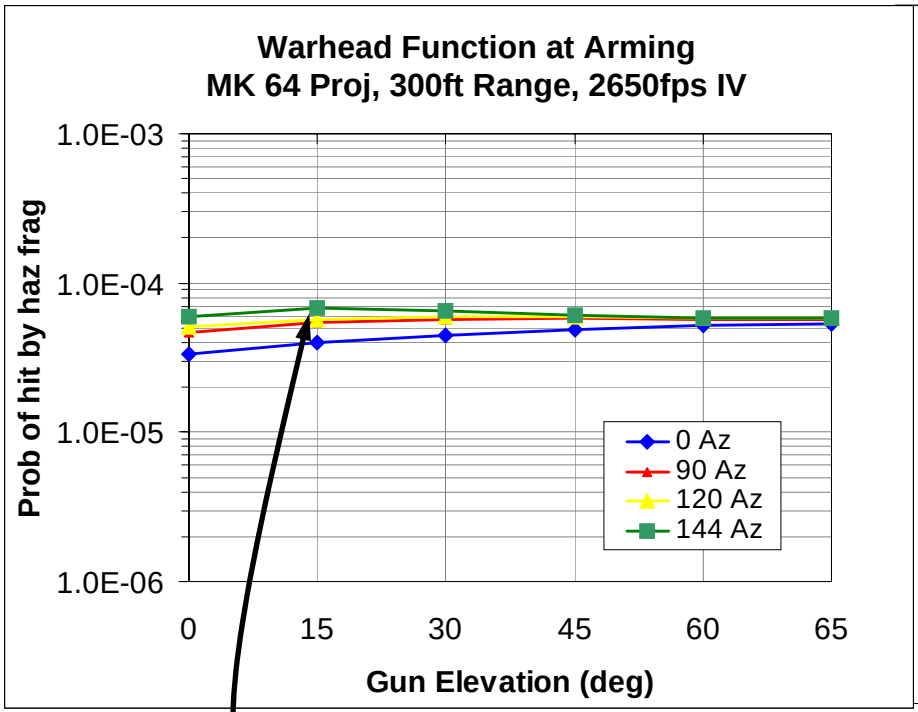
Early Burst Hazard

- Worst Case Operational Configuration:
  - Projectile = EX 184 HE-MOFN
    - MK 64 Projectile w PBXN-106 fill

  - Propelling Charge = MK 68 Mod 2 Reduced Prop Charge
    - IV = 1500 fps
  - Platform = US Navy CG-47 Class Cruiser
    - Gun direction – survey of all
  - Average arming at 290 ft
    - Std Dev 7.1 ft

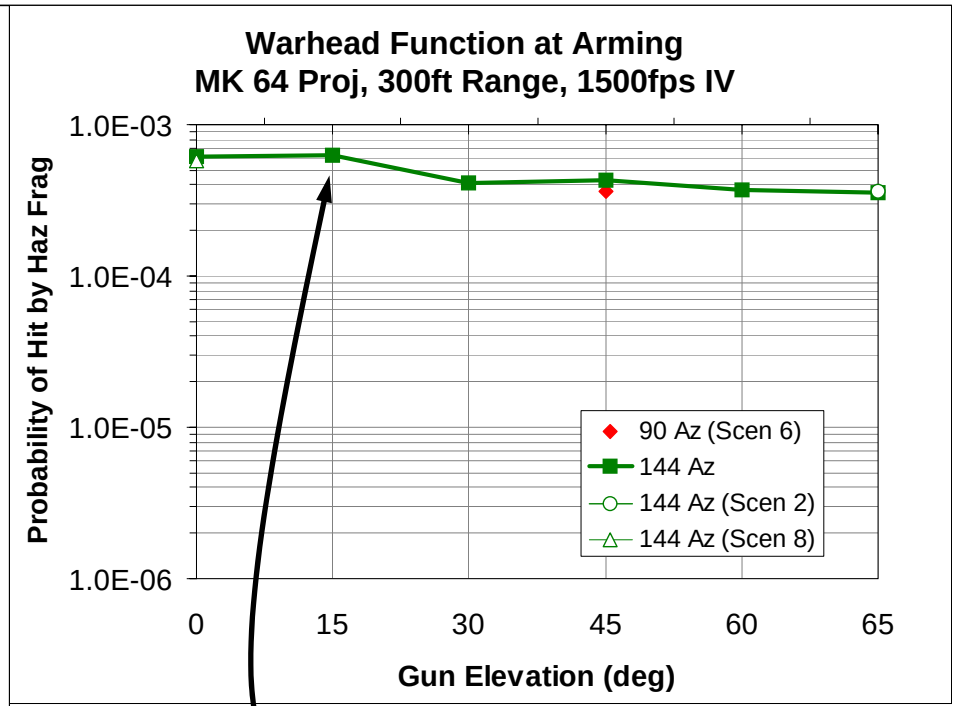
Incapacitation Probability

Probability of hit by hazardous fragment at arming distance



$$P_{inc/Det} = 5.0 \times 10^{-5}$$

At 2650 fps flyaway



$$P_{inc/Det} = 6.2 \times 10^{-4}$$

At 1500 fps flyaway

Warhead Function Probability

- Fuze is primary source of inadvertent warhead function.
- Quantity of test data is available from M782 MOFA production.
- Two failures (early bursts) out of 1,975 Lot Acceptance Test gun shots. Demonstrated failure rate of 1.0×10^{-3} *(note that that these failures caused rejection of the lot and are not representative of the stockpile).*
- MOFA will be less than this because …….

Warhead Function Probability

- Improvements to MOFN that will reduce safety failure rate.
  - Software rewritten following procedures for safety critical applications (IEEE/IEA 12207.1, 12207.2, and EIA/IEEE J-STD-016).
    - Over half a million software tests were performed with zero failures.
  - Cause of early bursts in MOFA tests has been identified and will be corrected in MOFN production. Army estimate of safety failure rate, between arming and safe separation distance, is $1x10^{-8}$.

Early Burst Hazard

- Early burst hazard at min arming distance is:

$$P_{inc} = P_{Det} \times P_{inc/Det}$$

$$P_{inc} = \left(2.6 \times 10^{-8}\right) \times \left(2.6 \times 10^{-4}\right)$$

$$P_{inc} = 2.6 \times 10^{-12}$$

- Probability of hit by a hazardous fragment is less than 1 in a million for the worst case condition.
- Severity of hit is skin penetration (50% probability) which corresponds to level III of MIL-STD-882 (injury resulting in one or more lost work days).

Early Burst Hazard

Hazard Risk Index of MIL-STD-882

Frequency of Occurrence (over the life of an item)	Severity of Occurrence: CATASTROPHIC (I)	CRITICAL (II)	MARGINAL (III)	NEGLIGIBLE (IV)
FREQUENT (A) $P > 10^{-1}$	I-A	II-A	III-A	IV-A
PROBABLE (B) $10^{-1} > P > 10^{-2}$	I-B	II-B	III-B	IV-B
OCCASIONAL (C) $10^{-2} > P > 10^{-3}$	I-C	II-C	III-C	IV-C
REMOTE (D) $10^{-3} > P > 10^{-6}$	I-D	II-D	III-D	IV-D
IMPROBABLE (E) $10^{-6} > P$	I-E	II-E	III-E	IV-E

Level of Risk Acceptance, Navy
High ASN-RDA
Serious PEO
Medium PM
Low PM

Hazard Risk Index per MIL-STD-882 is III-E.
This hazard must be formally accepted by the Program Manager.

USS Lassen Malfunction Investigation

Real Life Example of why we do safe separation studies

- 2 Feb 2005, USS Lassen DDG-82, had a close aboard detonation at a reported distance of 150 feet.
- Weapon was a D350 5” High Explosive projectile:
  - M732 Fuze, MK 64 body, Comp A-3 fill
  - Standard Propelling charge
- The gun barrel was pointing 82° azimuth to port side, and 7.1° elevation.

USS Lassen Malfunction Investigation

- Model of USS Lassen incident

Color Code

Fragment size

1000 grains

100 grains

30 grains (22 bullet)

10 grains (BB)

1 grain

USS Lassen Malfunction Investigation

- No injuries resulted from incident.
- Very little data was available for the incident; no IV, video, or audio to confirm estimated distance of detonation. Crew reported 2 “small” fragments on deck. Fragments were discarded.

The “small” fragments found on deck are not inconsistent with predictions.

USS Lassen Malfunction Investigation

- *Malfunction was probably fuze function at arming due to a design weakness particular to the M732 fuze.*
- *Two independent assembly errors, occurring in the same fuze, will allow the fuze to detonate on arming. (Note that the M732A1 corrected this problem)*
- *Arming distance in 5” gun is about 295 ft.*

USS Lassen Malfunction Investigation

- *Historical research:*
  - *2.4 million fuzes were fired by Army, USMC, & Navy*
  - *4 incidents of detonation at arming reported by Army, 5 including Navy*
  - *No correlation to manufacturer or to lot number*
  - *No material or personnel injury*
- *Conclusion: Because screening is impractical, and probability of event is so low and probability of injury is so low, investigation was closed with only an advisory to ship captains.*

Summary / Conclusions

- Determination of safe separation distance takes 4 factors, analyzed at worst case operational condition:
  1. Warhead lethality effects
  2. Platform vulnerability
  3. Fly-out conditions which may modify warhead lethality effects
  4. Acceptable hazard for safe separation
- If there is a requirement to engage targets within safe separation distance, a System Safety Risk Assessment (SSRA) is to be developed and signed off by the Developer (PM) and User acknowledge and accepts the risk.