UNCLASSIFIED











Three-dimensional underwater bomb trajectory prediction for mine neutralization (Stand-off Assault Breaching Weapon Fuse Improvement)

Peter C. Chu
Naval Postgraduate School, USA

Sponsored by
Office of Naval Research
(Program Manager: Brian Almquist)

Temasek Defense System Institute, National University of Singapore, Singapore, 11 August 2009.

UNCLASSIFIED

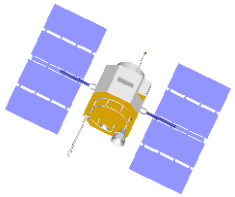
UNCLASSIFIED

Collaborators & Contributors

- Kennard Watson, Naval Surface Warfare Center-Panama City, USA
- Ronald Betsch, Naval Oceanographic Office, Stennis Space Center, Mississippi
- Jack Goeller, ATR Corp
- Jim Markarski, Boeing
- Paul Gefken, SRI International, USA
- LCDR Charles Allen, Naval Postgraduate School
- LCDR Jillene Bushnell, Naval Postgraduate School
- LCDR Greg Ray, Naval Postgraduate School
- C.W. Fan, Naval Postgraduate School

UNCLASSIFIED

Future Assault Breaching System Operational Scenario



GPS

1. Surveillance. Satellites, UUV's and UAV's identify mines, obstacles, and collect METOC data.

2. Mission Planning. MEDAL/JMPS plan routes and incorporate intel data from recon units. Crews rehearse mission.

3. Breaching Operation. JABS/CMS precision guided munitions clear mines and obstacles in water and on the beach.

4. Assault Force Deployment. EFV/AAV's launch from well deck and acquire routes to beach.

5. Inland Objective. Assault force moves past beach toward inland objective.

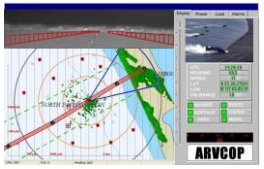


2



Comm Station





5



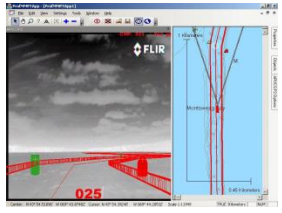
1



INFORMATIO N SHARING EPLRS, BFT, DAGR



4









DAGR



3

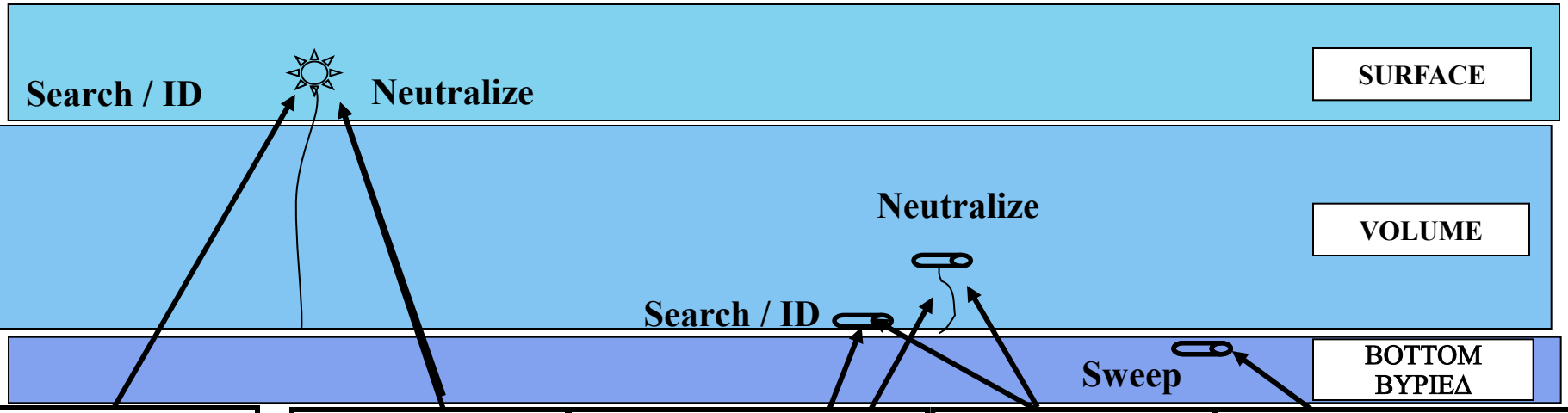


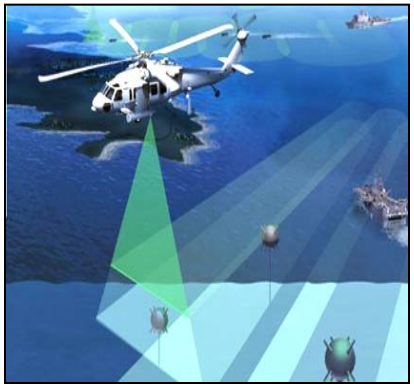
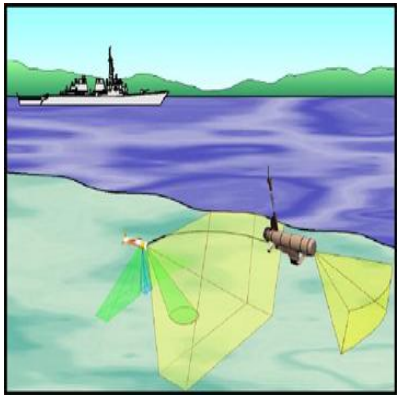
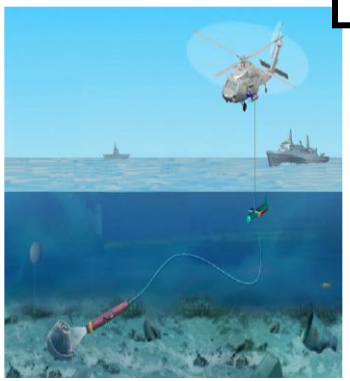
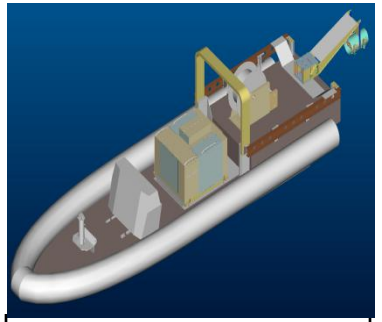
COBRA – Coastal Battlefield Reconnaissance and Analysis
JABS – Joint Direct Attack Munition (JDAM) Assault Breaching System
CMS – Countermine System (darts)

MEDAL – Mine Warfare and Environmental Decision Aids Library
JMPS – Joint Mission Planning System, DAGR – Defense Advanced GPS Receiver
BFT – Blue Force Tracker, EPLRS – Enhanced Position Location Reporting System

Littoral Combat Ship...

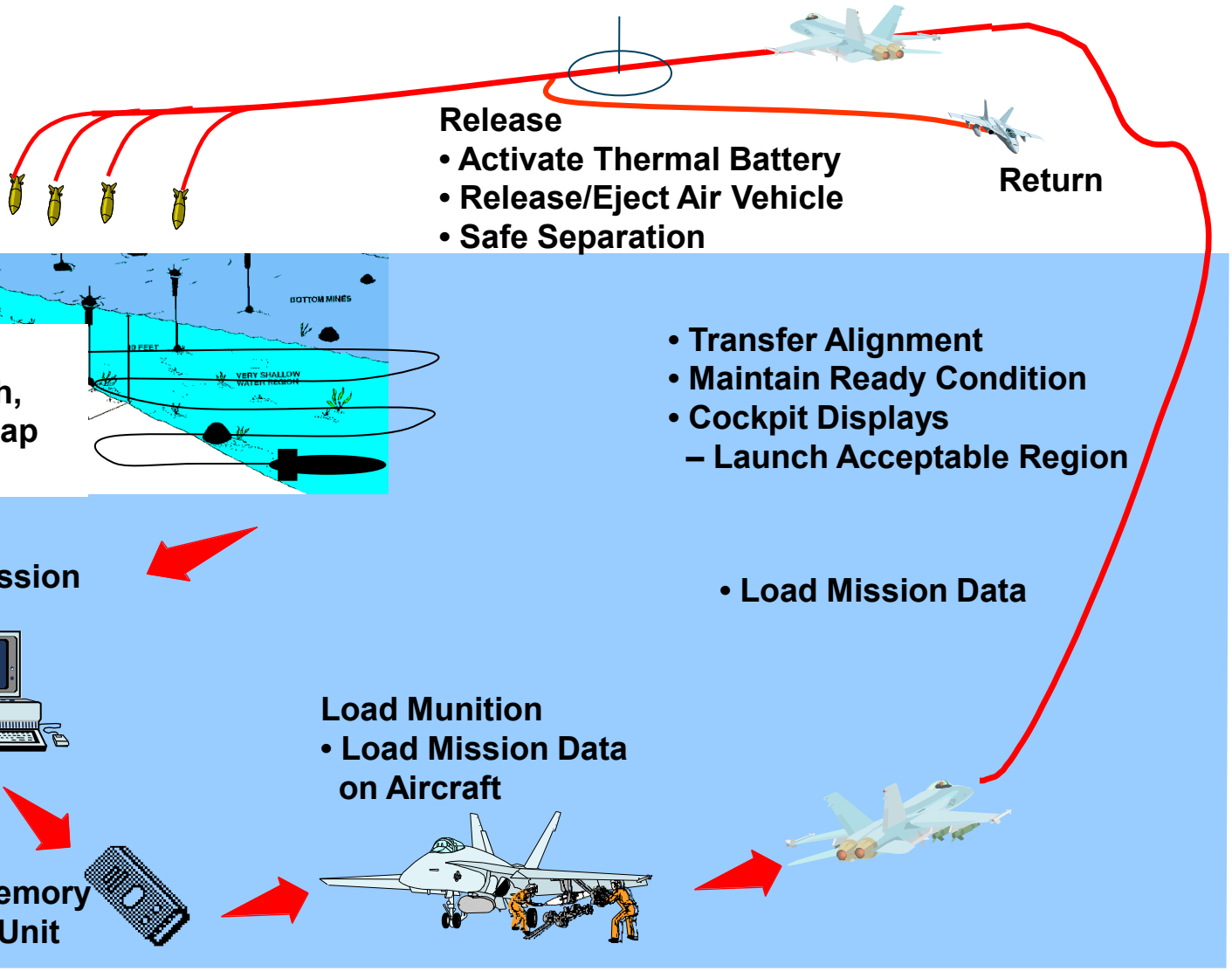
MIW Capabilities throughout the battlespace



Airborne Laser Mine Detection System (ALMDS)	Rapid Airborne Mine Clearance System (RAMICS)	Remote Minehunting System (RMS) – AN/AQS20A Sonar	Airborne Mine Neutralization System (AMNS)	Unmanned Surface Vessel / Organic Airborne and Surface Influence Sweep (USV/OASIS)
				
Laser (search)	Super-cavitating Projectiles (kill)	Sonar (search) (and on Helo)	Self propelled explosive charges (kill)	Acoustic + magnetic influence sweep and kill

UNCLASSIFIED

Mission Execution CONOPS



UNCLASSIFIED

Organic Mine Warfare

Because of a lack of immediately available mine counter measures in any large quantities, the Navy is evaluating the JDAM for its capability in countermine and assault breaching. The JDAM accuracy, repeatability (guaranteed delivery patterns for multiple deliveries), and fusing options make it a prime contender for an interim capability.

- Brian Almquist, ONR, 2008

Joint Direct Attack Munition (JDAM) Assault Breaching System (JABS)





Standoff Delivery Platform



SZ & BZ Countermine & Counterobstacle

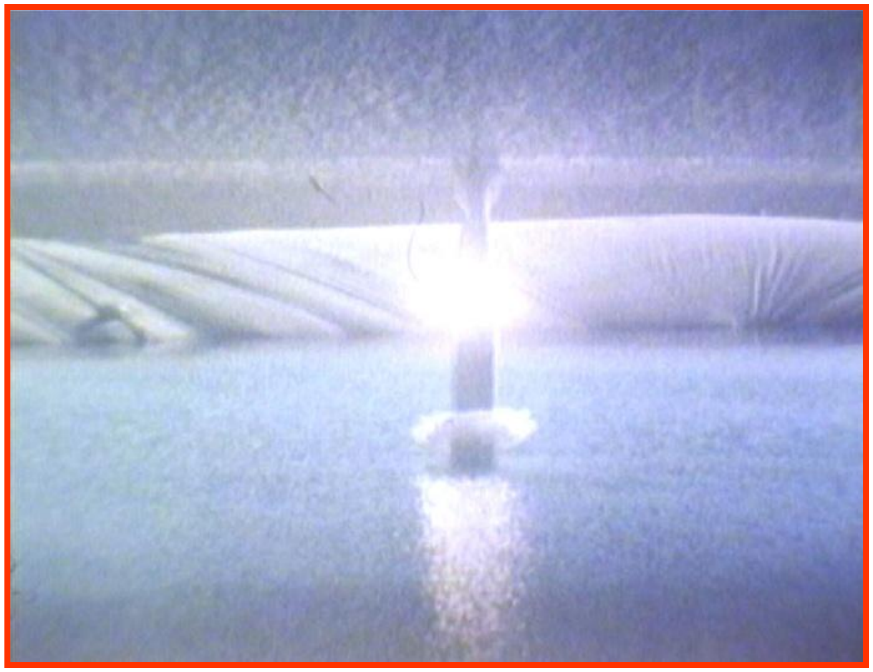
- Current capability to clear SZ/BZ mines and light obstacles on the beach
- USN and/or USAF Delivered, Signed MOA between USN & USAF for Assault Breaching Munitions Delivery
  - B1, B2, B52, F/A18, JSF
- New mission for an existing weapon system

We know JABS performs well to water depths of 10 ft. Can it go deeper?

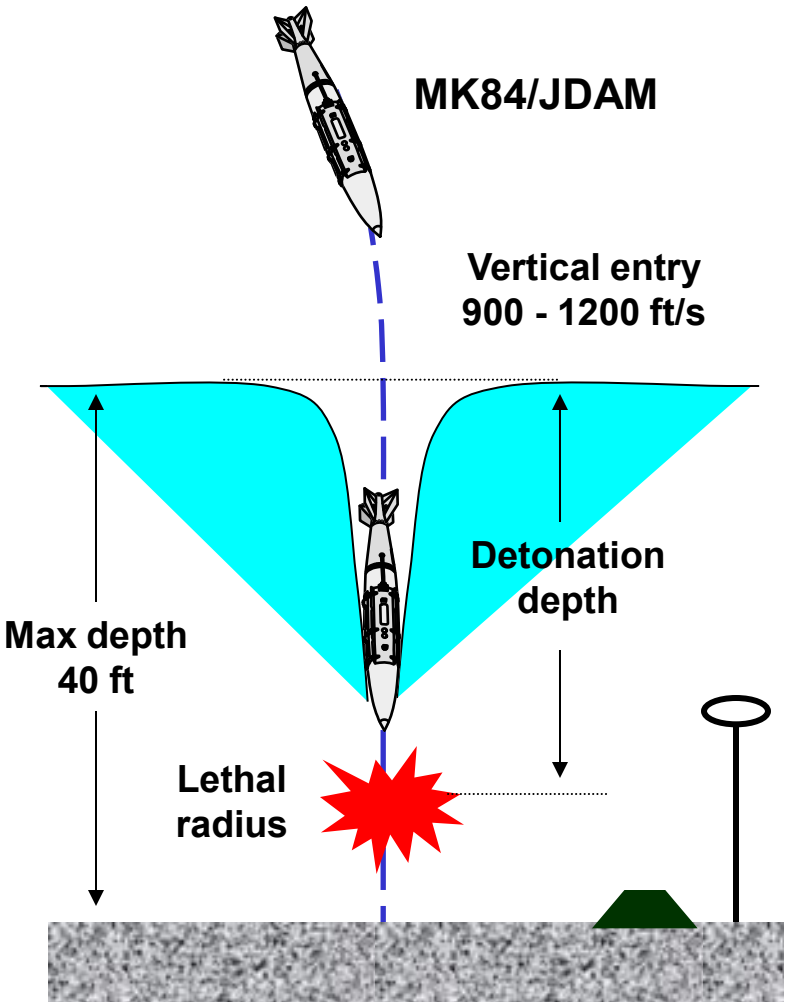
Successful breaching in beaches/surf zones by Joint Direct Attack Munition (JDAM) Assault Breaching System (JABS)

(from Almqist 2006)





Mine Neutralization by MK84/JDAM

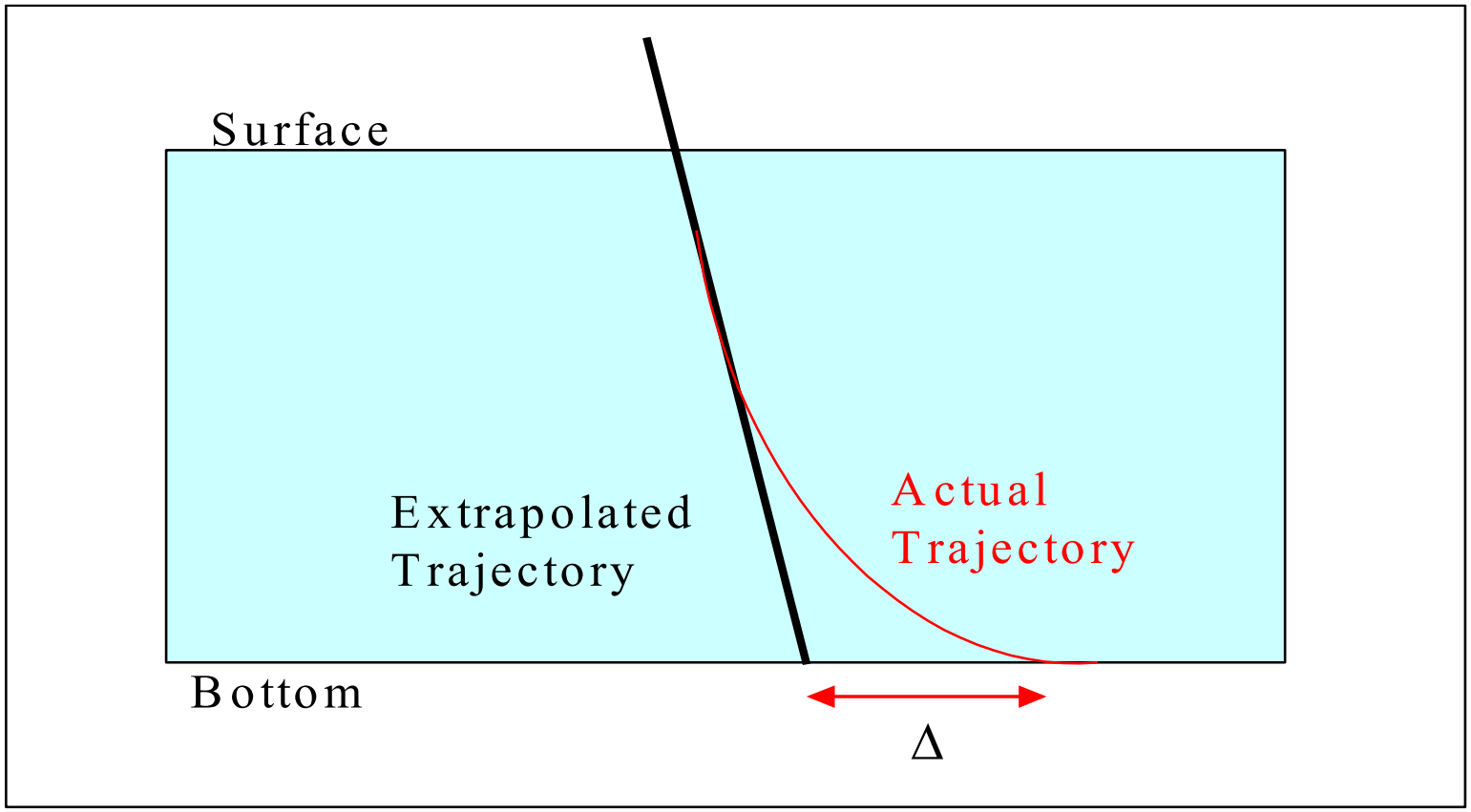


Objective

- Investigate lethality of precision guided bombs against mines in 10-40 ft water depths (VSW).

- Investigate bomb stability after water impact, lethal radius, and optimum detonation depth for fuse design.

UNCLASSIFIED



For effective mine clearance

$\Delta < 7$ ft (2.1 m)

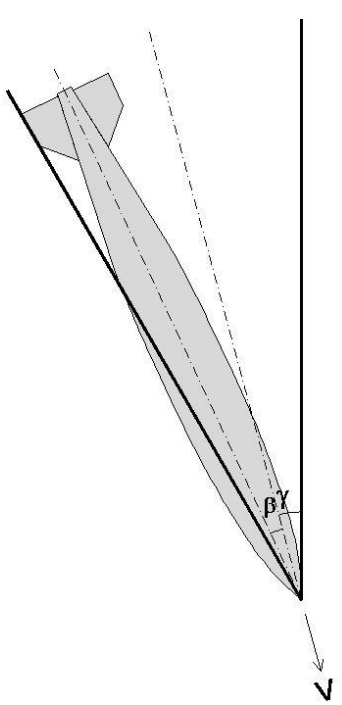
UNCLASSIFIED

UNCLASSIFIED

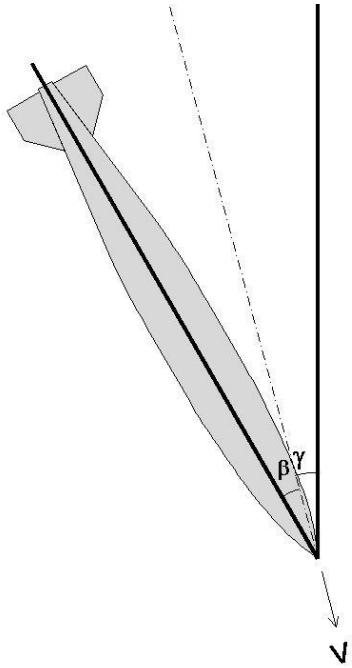
The Technology Transition Agreement (TTA) between the Office of Naval Research and the Navy states that the "trajectory deviation from the flight path (velocity vector) should not exceed 7 ft (2.1 m) (approximate) for water depths of 10-40 ft (3-12.2 m)" (Humes 2007).

UNCLASSIFIED

Air Cavity

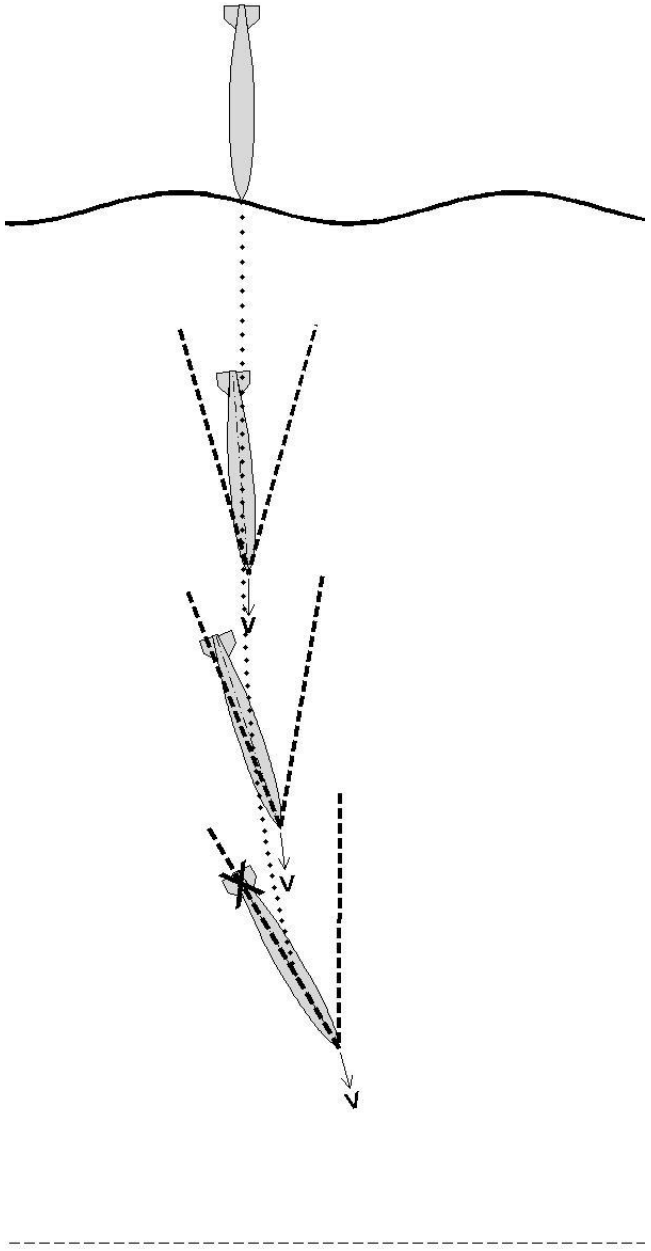


Inside the cavity



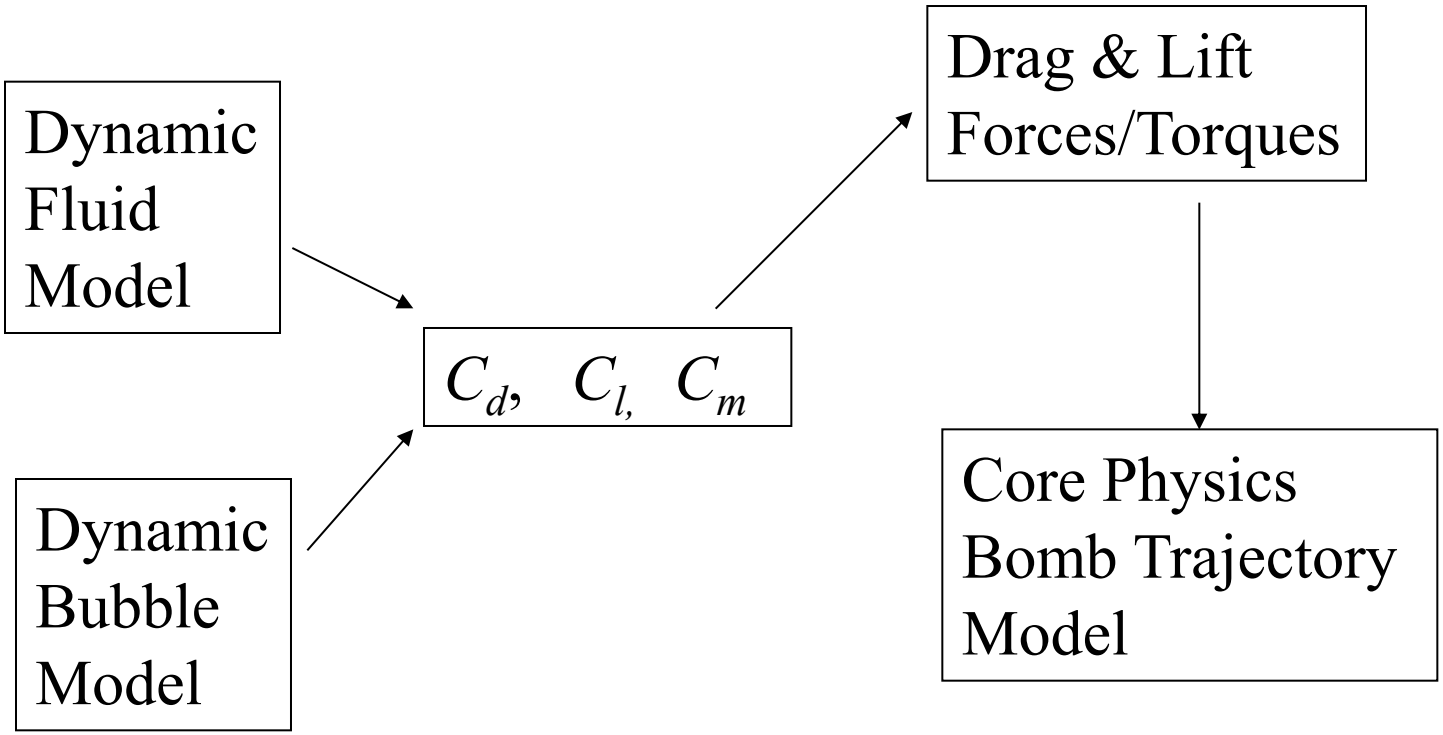
Hitting the cavity wall → Tail Separation

Surface slope affects
the tail separation and the
trajectory



UNCLASSIFIED

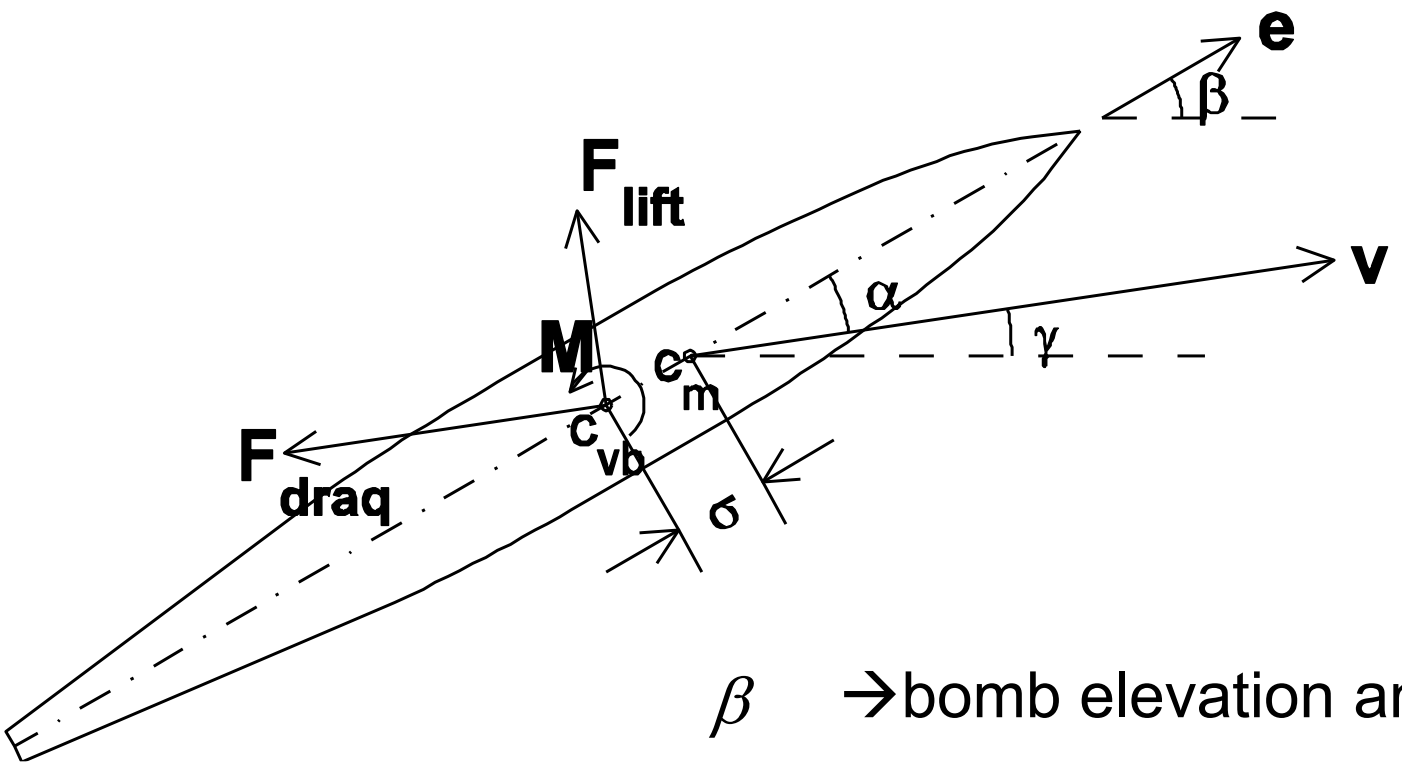
6-FOF Bomb Trajectory Model



UNCLASSIFIED

UNCLASSIFIED

Dynamical Determination of Drag/Lift Coefficients



β → bomb elevation angle

γ → bomb velocity angle

α → attack angle

UNCLASSIFIED

UNCLASSIFIED

Definitions of $(C_d \;\; C_l \;\; C_m)$

$$f_{drag} = \frac{1}{2} C_d \rho A_w V^2$$

$$f_{lift} = \frac{1}{2} C_l \rho A_w V^2$$

$$M_{trav} = \frac{1}{2} C_m \rho \Pi_w V^2$$

Π_w → Underwater volume

A_w → Underwater area

UNCLASSIFIED

UNCLASSIFIED

Theoretical Base

$$m\frac{d\mathbf{V}}{dt} = \left(\rho\Pi - m\right)g\mathbf{k} + f_{drag}\mathbf{e}_d + f_{lift}\mathbf{e}_l$$

$$\mathbf{I}\bullet\frac{d\boldsymbol{\Omega}}{dt} = \mathbf{r}_v \times \mathbf{f}_b + \mathbf{r}_f \times \left(\mathbf{f}_{drag} + \mathbf{f}_{lift}\right) + \mathbf{M}_r$$

Here, $\mathbf{V}$ is the translation velocity of COM,

$\boldsymbol{\Omega}$ is the angular velocity.

UNCLASSIFIED

There is no existing formulae for calculating C_d C_l C_m for underwater bomb.

UNCLASSIFIED

Sub-Scale Model Test Objectives

- Use 1/12-scale tests to measure Mk84 bomb trajectory to a shallow water full-scale depth of 160 ft and for a 90 degree water entry angle.

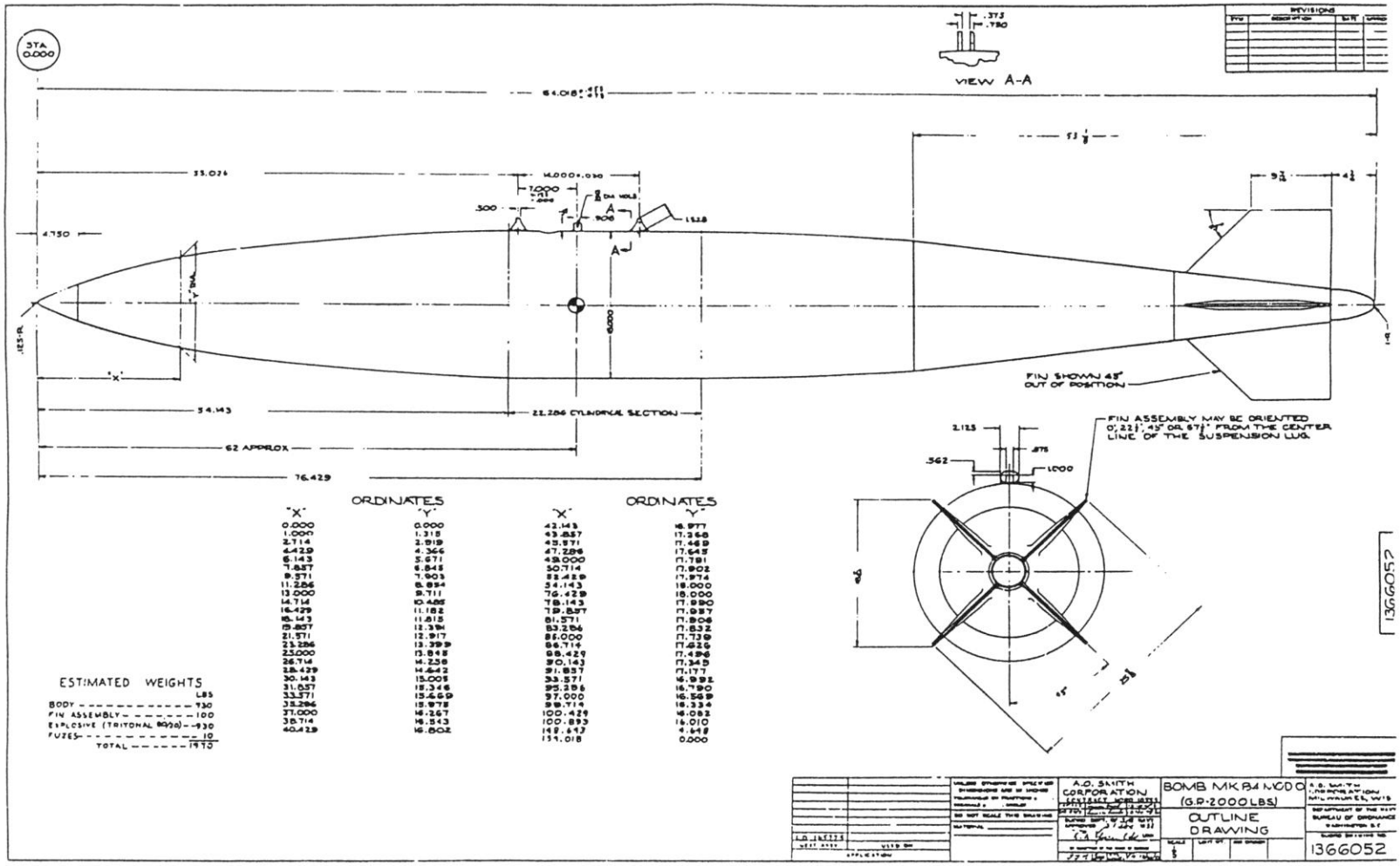
- Evaluate stability performance associated with current USN Ogive, USN MXU-735, and USAF noses and conceptual 25% and 50% blunt nose designs.

- Evaluate trajectory performance for possible tactical water entry angles of 65 and 77 degrees and determine how possible fin or tail section removal during water entry or tail slap within cavity influences trajectory behavior.

UNCLASSIFIED

Mk84 Bomb Full-Scale Features

(With USN Ogive Nose)



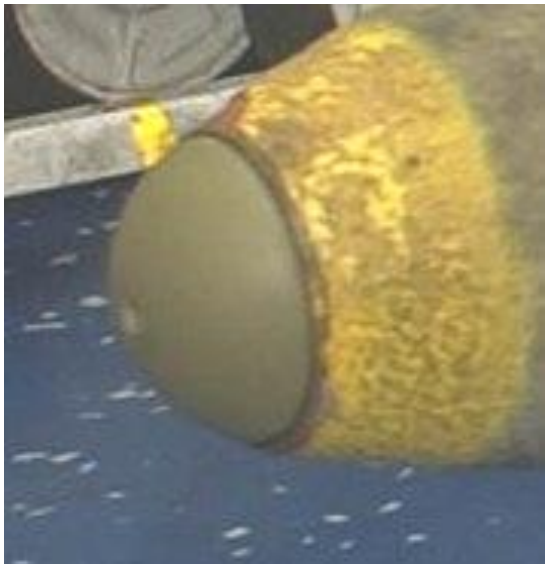
Current Mk84 Bomb Nose Features



USN Ogive Nose



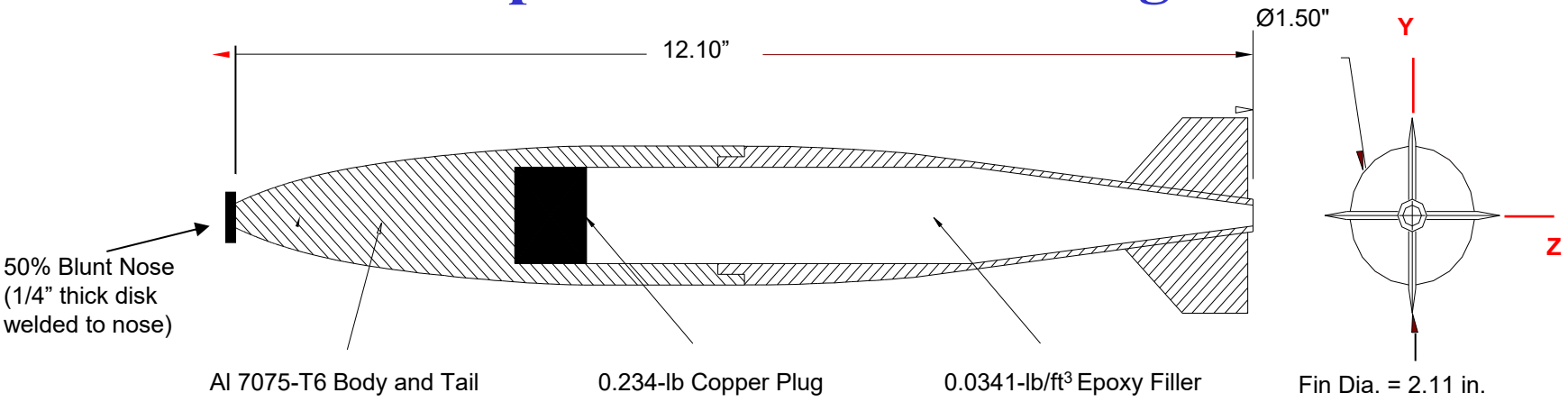
USAF Nose



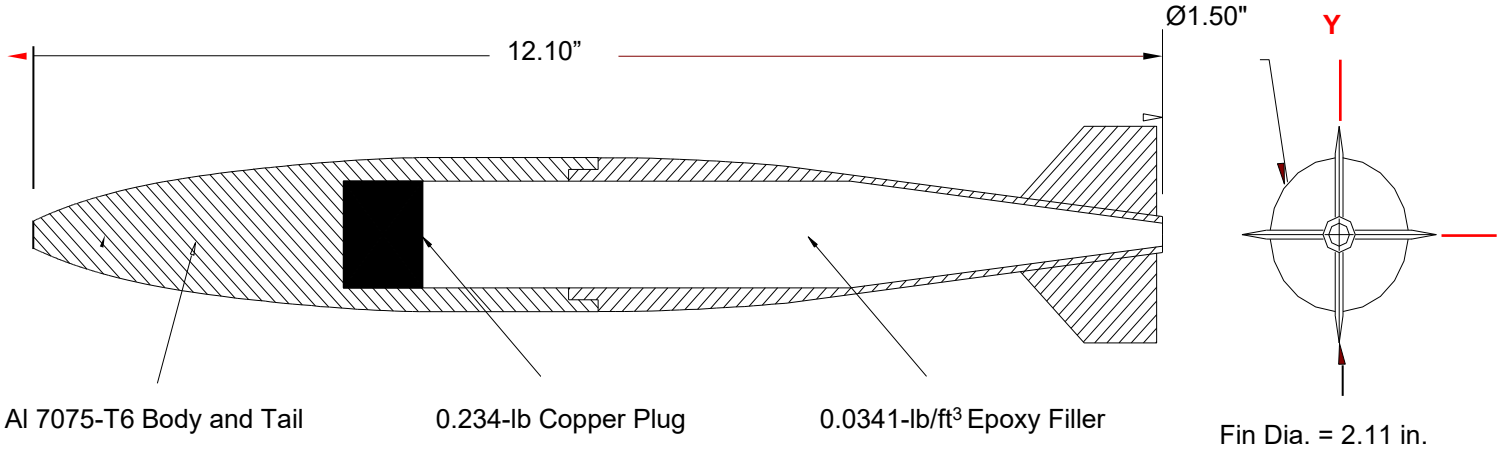
USN MXU-735 Nose

UNCLASSIFIED

Conceptual Mk84 Nose Designs



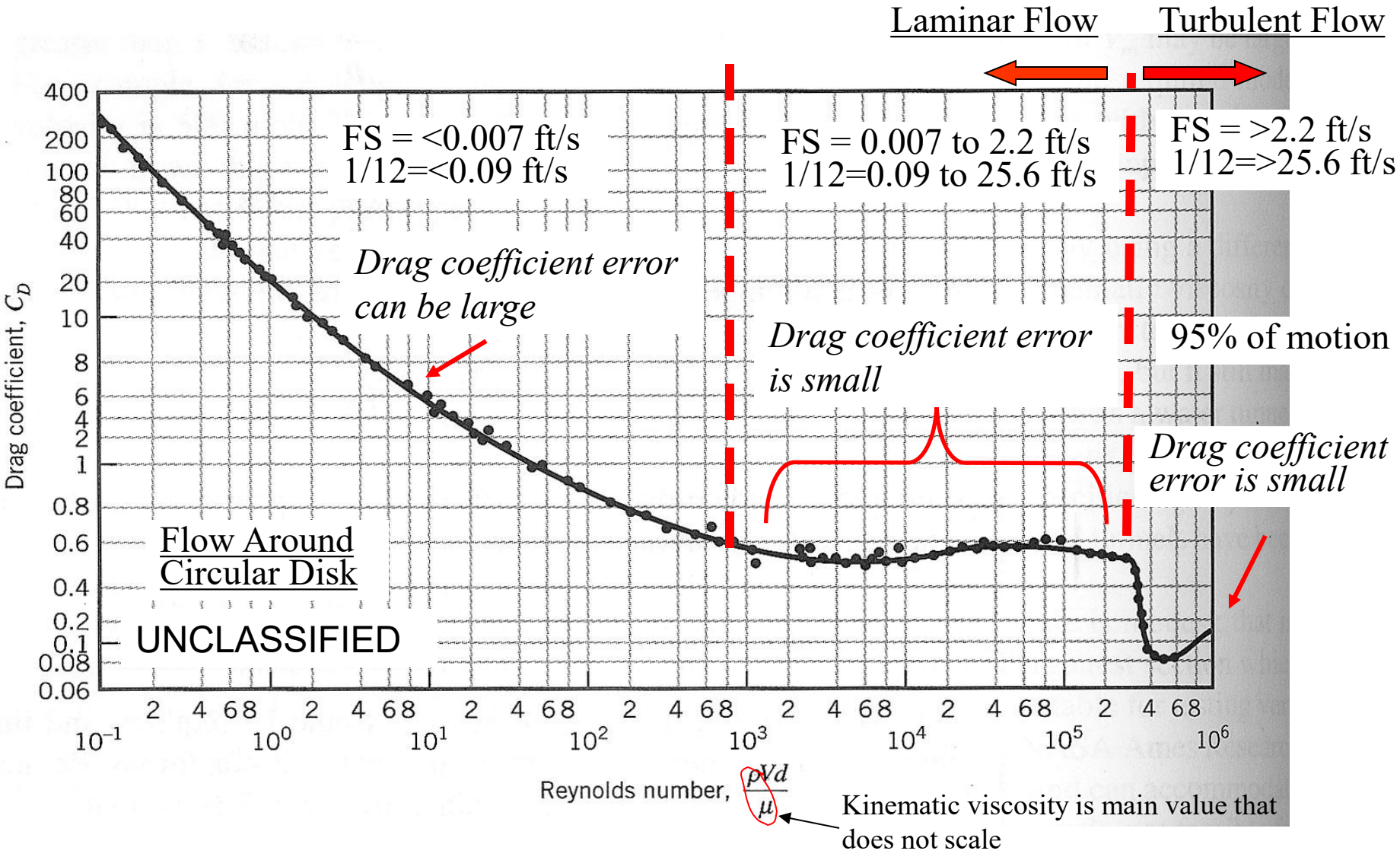
50% Blunt Nose



25% Blunt Nose

UNCLASSIFIED

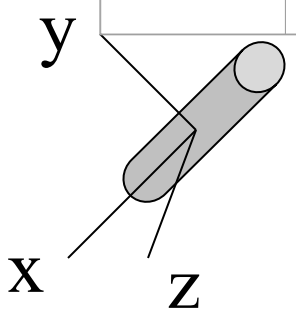
Trajectory Scaling



UNCLASSIFIED

High-Fidelity 1/12-Scale Mk84 Scale Model - 4 Fins

Mk84 Bomb	Length (in.)	Weight (lb)	Center of Gravity (in.)			Radius of Gyration (in.)		
			CGx	CGy	CGz	Kx	Ky	Kz
Full Scale	150.51	2076.64	63.12	0.130	0.100	6.660	30.640	30.640
True 1/12 Scale	12.54	1.202	5.260	0.010	0.010	0.555	2.553	2.553
As-Built 1/12 Scale	12.54	1.201	5.362	0.000	0.000	0.319	2.557	2.557
% Error	0.0	-0.1	0.2	—	—	—	0.1	0.1



Due to neglecting casing lugs and strakes

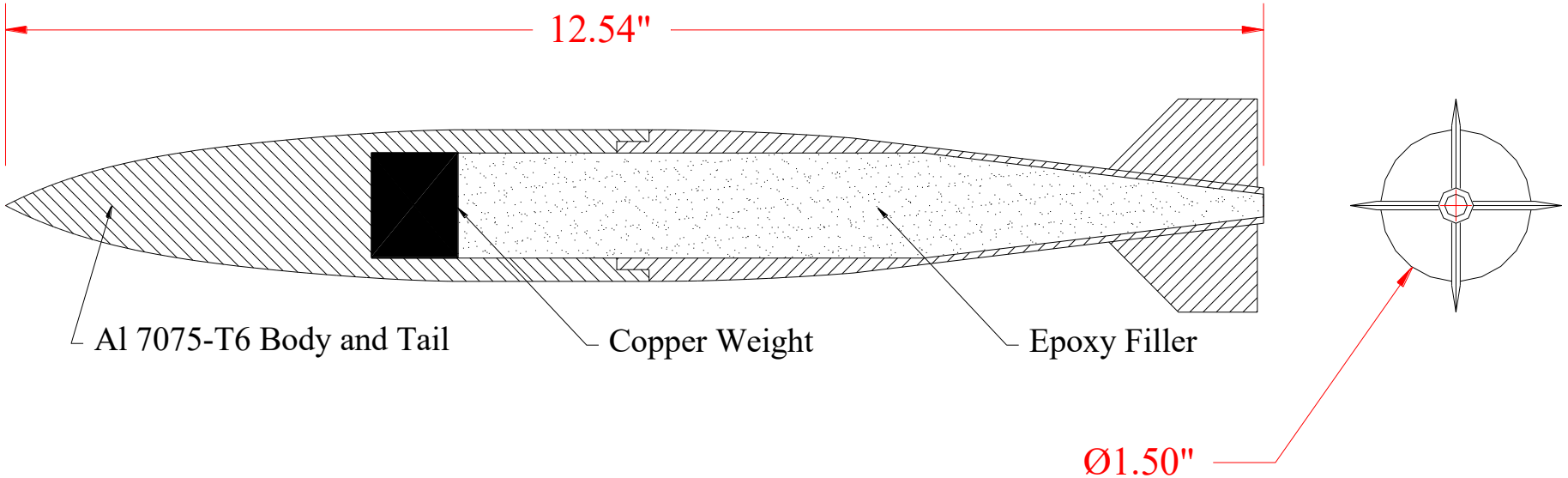
Neglected because the bomb does not rotate about x-axis

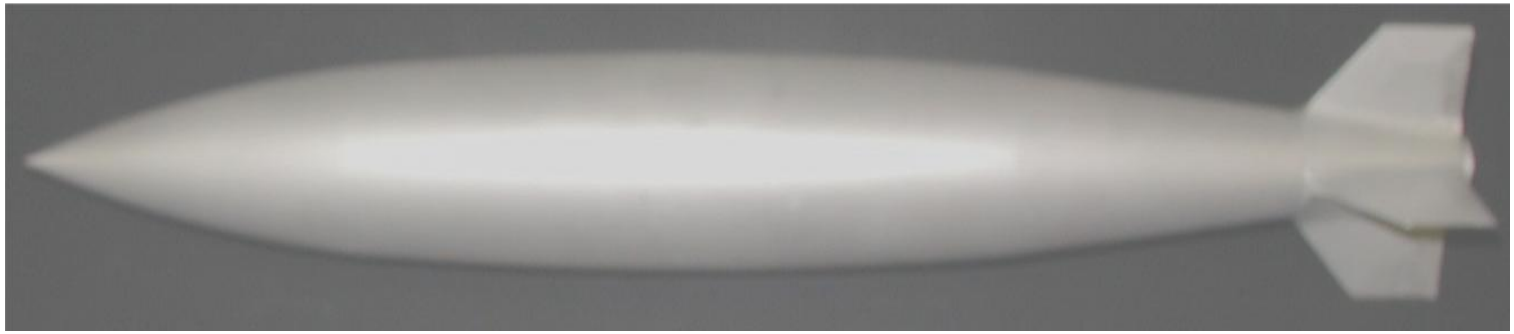
UNCLASSIFIED

UNCLASSIFIED

High-Fidelity 1/12-Scale Mk84 Scale Model - 4 Fins

UNCLASSIFIED

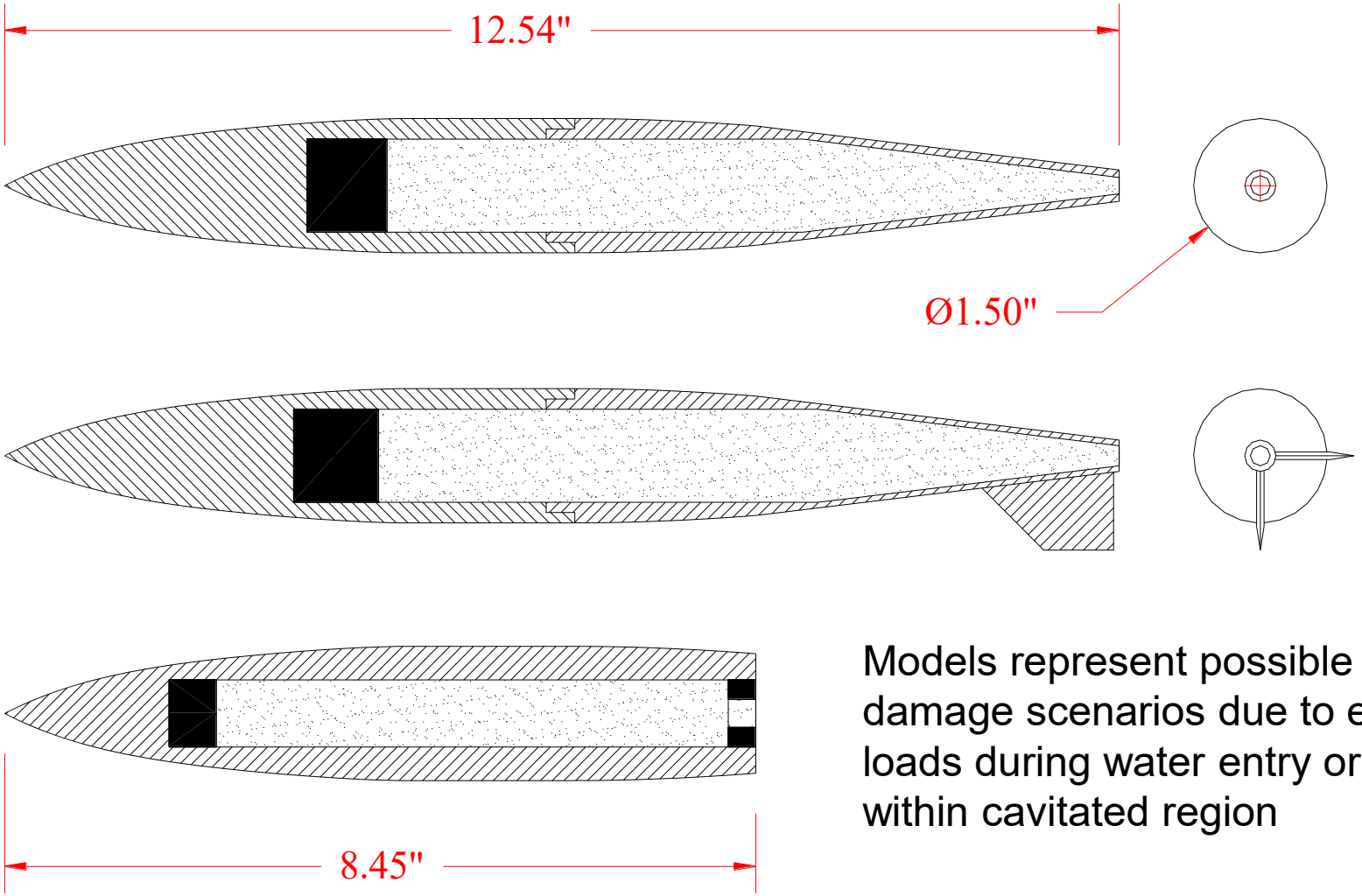




UNCLASSIFIED

UNCLASSIFIED

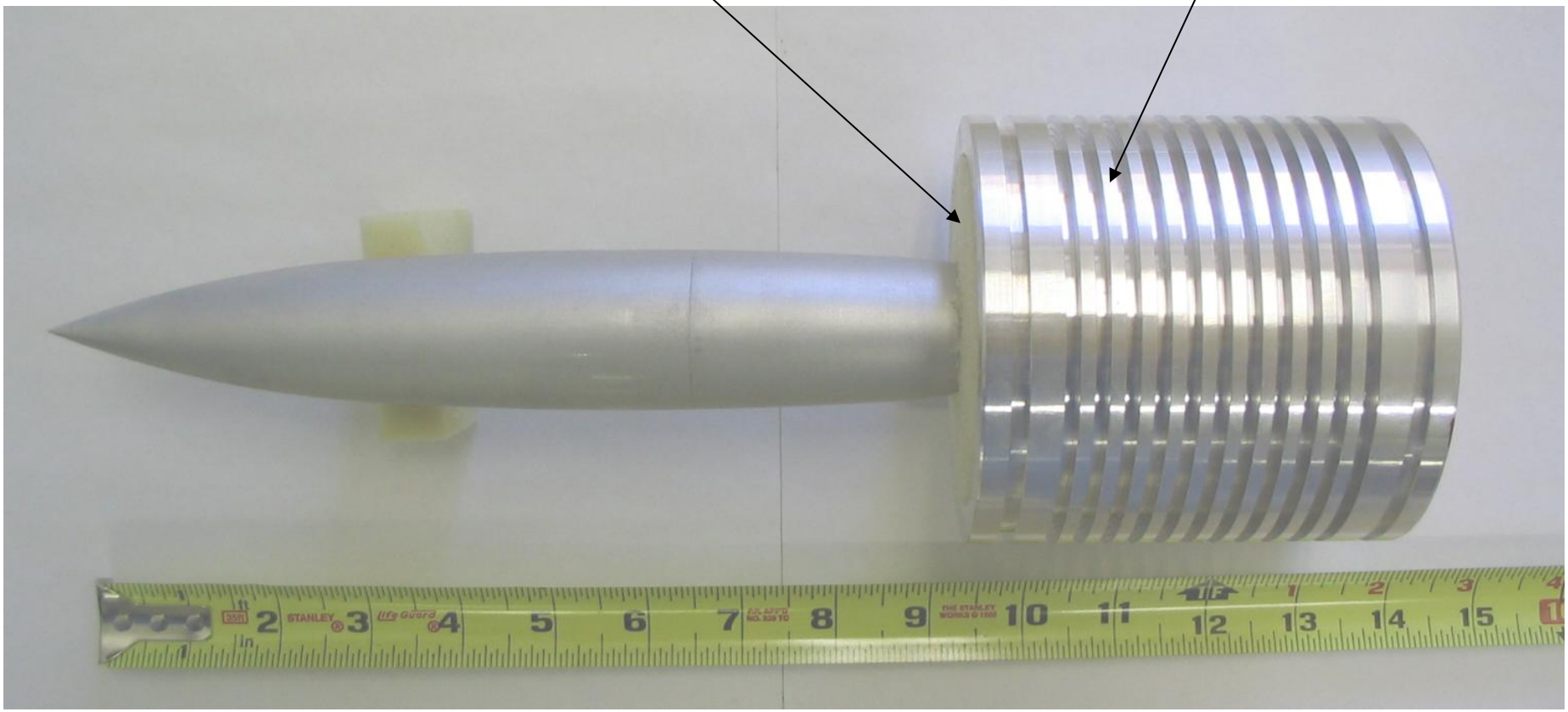
Tests With Simulated Fin or Tail Removal



Models represent possible different damage scenarios due to excessive loads during water entry or tail slap within cavitated region

UNCLASSIFIED

Sabot Design



SRI Test Arrangement



4” dia. Gas Gun

2 Phantom 7 Cameras
(10,000 fps) in Periscope

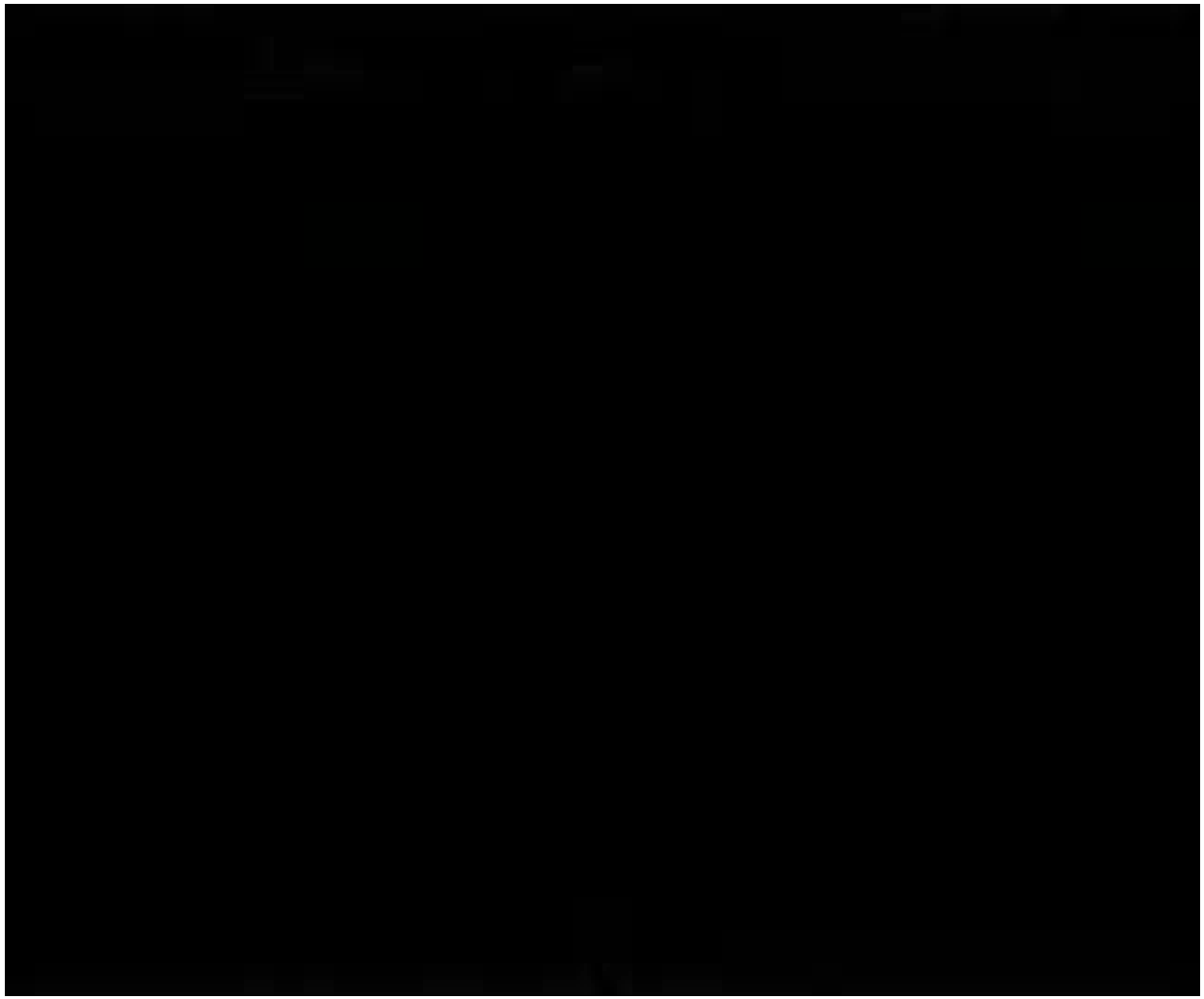
30-ft-dia. by 20-ft-deep
Water Shock Pool

Underwater Lights

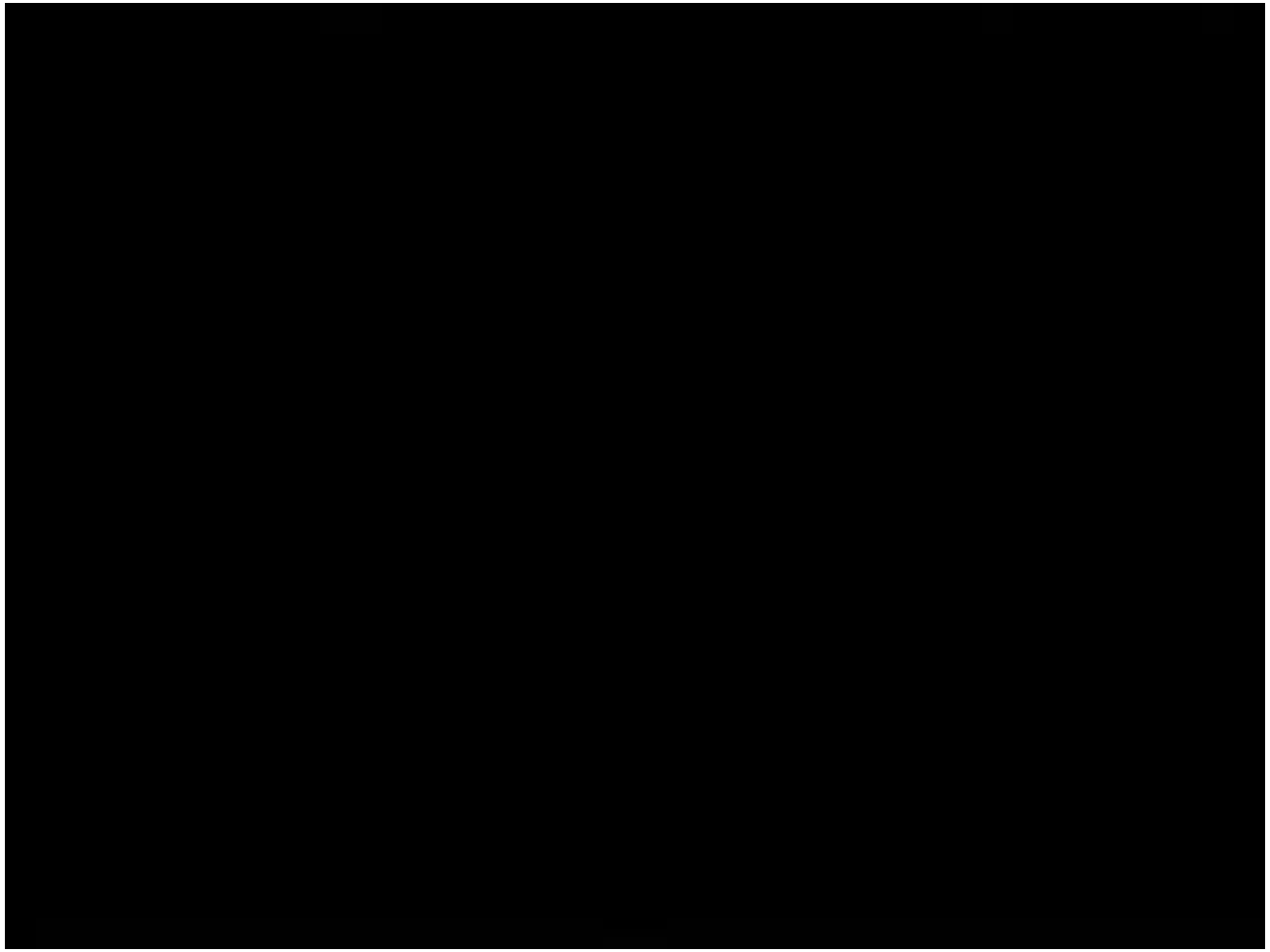
Tail with 4 Fins



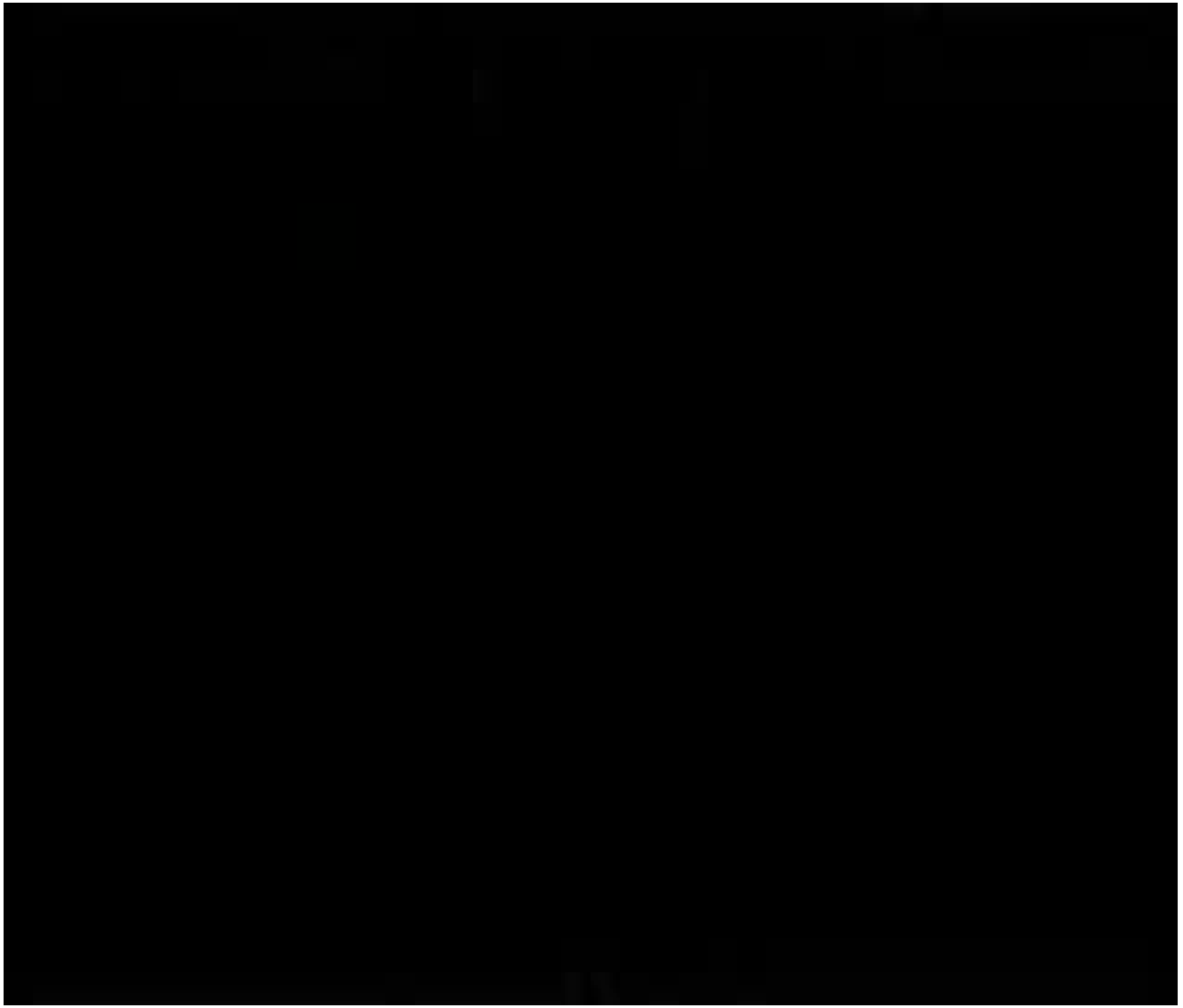
Tail with 2 Fins



Tail with No Fins

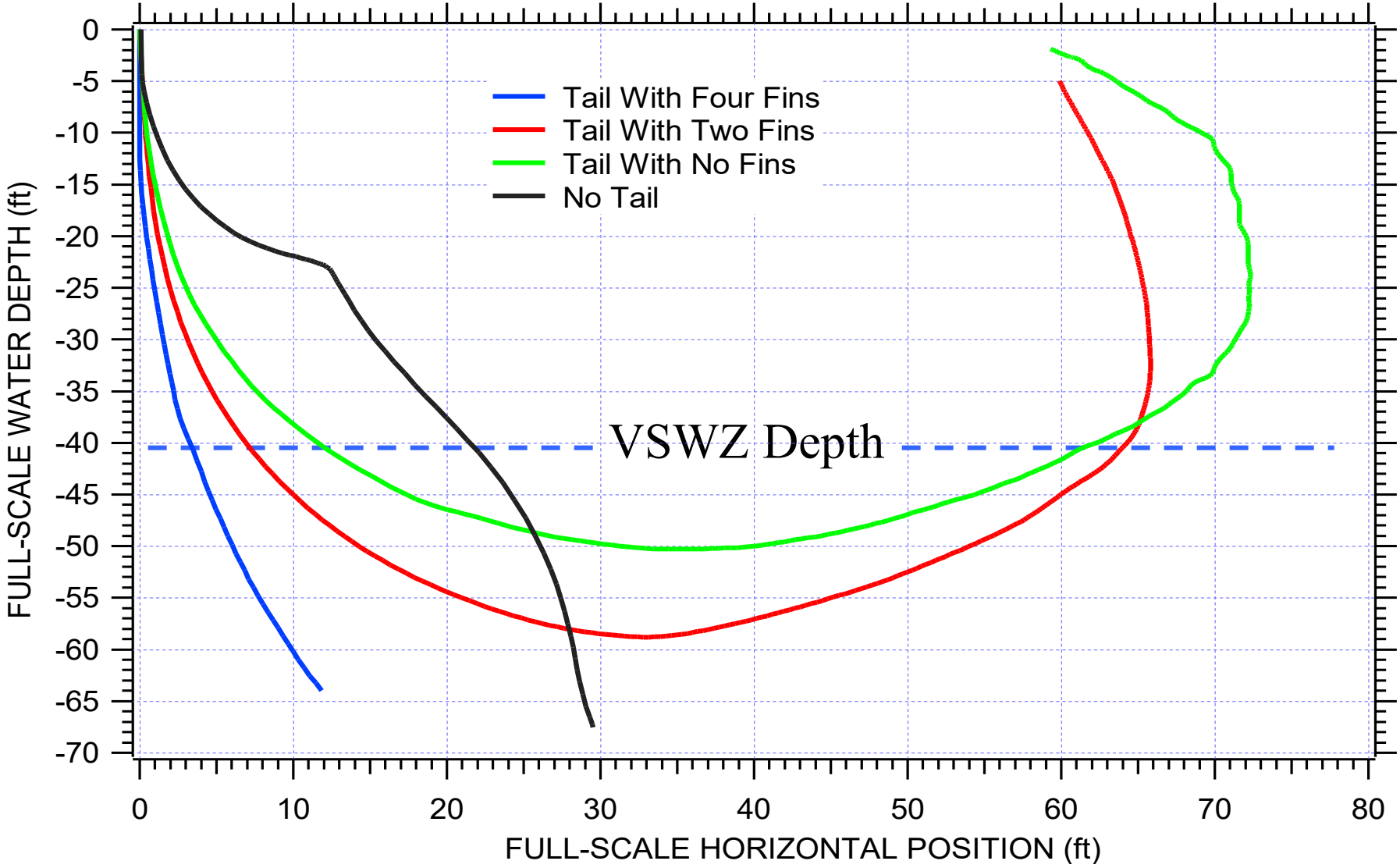


No Tail



UNCLASSIFIED

1/12th Scaled Model Test Results



UNCLASSIFIED

UNCLASSIFIED

Determination of C_d C_l C_m from Experimental Data

$$C_d = \frac{\left(\rho\Pi - m\right) g\mathbf{k} \bullet \mathbf{e}_d - md\mathbf{v}/dt \bullet \mathbf{e}_d}{\frac{1}{2}\rho DLV^2}$$

$$C_l = \frac{\left(\rho\Pi - m\right) g\mathbf{k} \bullet \mathbf{e}_l - md\mathbf{v}/dt \bullet \mathbf{e}_l}{\frac{1}{2}\rho DLV^2}$$

$$C_m = \frac{\mathbf{J} \cdot \frac{d\boldsymbol{\Omega}}{dt} \bullet \mathbf{e}_m^h + \sigma\rho\Pi g\left(\mathbf{e} \times \mathbf{k}\right) \bullet \mathbf{e}_m^h - \frac{n}{2}\sigma_f \left(\mathbf{e} \times \mathbf{F}_r^f\right) \bullet \mathbf{e}_m^h}{\frac{1}{2}\rho A_w L_w v^2}$$

$$+ \frac{\sigma}{L_w}\left(C_d\left(\mathbf{e} \times \mathbf{e}_m^h\right) \bullet \mathbf{e}_m^h + C_l\left(\mathbf{e} \times \mathbf{e}_l\right) \bullet \mathbf{e}_m^h\right)$$

UNCLASSIFIED

UNCLASSIFIED

Separation of SRI Bomb Trajectory Data

- The total 15 trajectories are separated into two groups:
  - (1) 11 trajectories → (C_d C_l C_m) semi-empirical formulas
  - (2) 4 trajectories → model verification

UNCLASSIFIED

UNCLASSIFIED

Semi-Empirical Formulas for (C_d C_l)

$$C_d = 0.02 + 0.35e^{-2\left(\alpha - \pi/2\right)^2}\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{0.2} + 0.008\Omega\sin\theta$$

$$\theta = sign\left(\pi - 2\alpha\right)\left(\pi^{2.2} - \left(\pi - \left|\pi - 2\alpha\right|\right)^{2.2}\right)^{\frac{1}{2.2}}$$

$$C_l = \begin{cases} 0.35\sin\left(\theta_1\right)\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{0.2} & if\ \alpha \le \frac{\pi}{2} \\ 0.1\sin\left(\theta_2\right) - 0.015\Omega\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{2}\sin\left(\theta_2{}^{0.85}\right) & if\ \alpha > \frac{\pi}{2} \end{cases}$$

Where $\theta_1 = \pi\left(\frac{2\alpha}{\pi}\right)^{1.8}$ and $\theta_2 = 2\pi\left(\frac{2\alpha}{\pi} - 1\right)^{0.7}$.

$\mathrm{Re}^* = 1.8 \times 10^7$

UNCLASSIFIED

UNCLASSIFIED

Semi-Empirical Formulas for C_m

$$C_m = \begin{cases} 0.07\sin(2\alpha)\left(\dfrac{\mathrm{Re}^*}{\mathrm{Re}}\right)^{0.2} & \text{if } \alpha \le \dfrac{\pi}{2} \\ 0.02\sin(2\alpha)\sqrt{\left(\dfrac{\mathrm{Re}}{\mathrm{Re}^*}\right)} & \text{if } \alpha > \dfrac{\pi}{2} \end{cases}$$

$\mathrm{Re}^* = 1.8 \times 10^7$

UNCLASSIFIED

NPS Model and SRI Data Inter-Comparison Trajectory-1



NPS Model and SRI Data Inter-Comparison
Trajectory-14



NPS Model and SRI Data Inter-Comparison
Trajectory-15

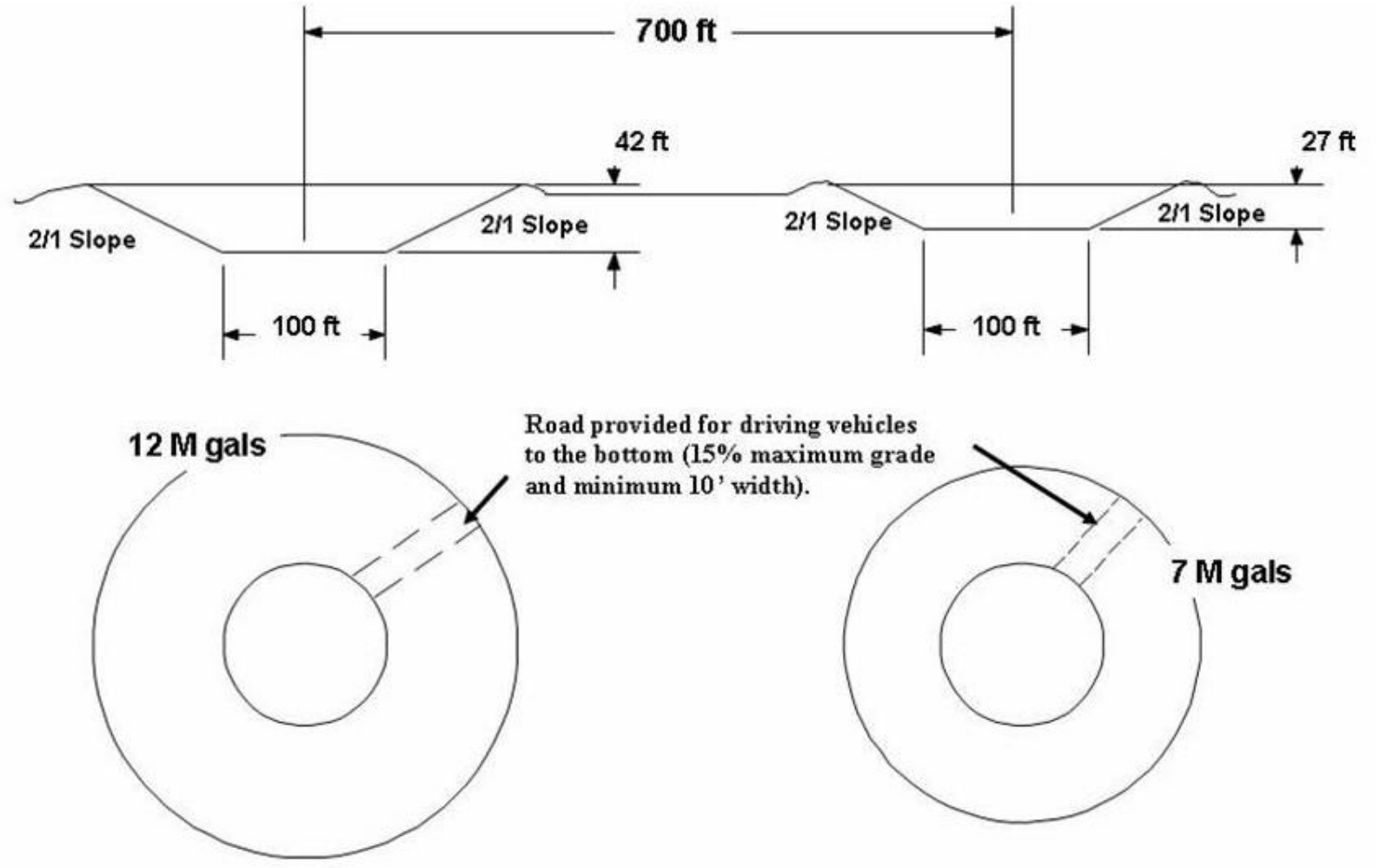


Full Size Test → China Lake

UNCLASSIFIED

Experiments

Stand Off Assault Breaching Weapons Fuze Improvement (SOABWFI)

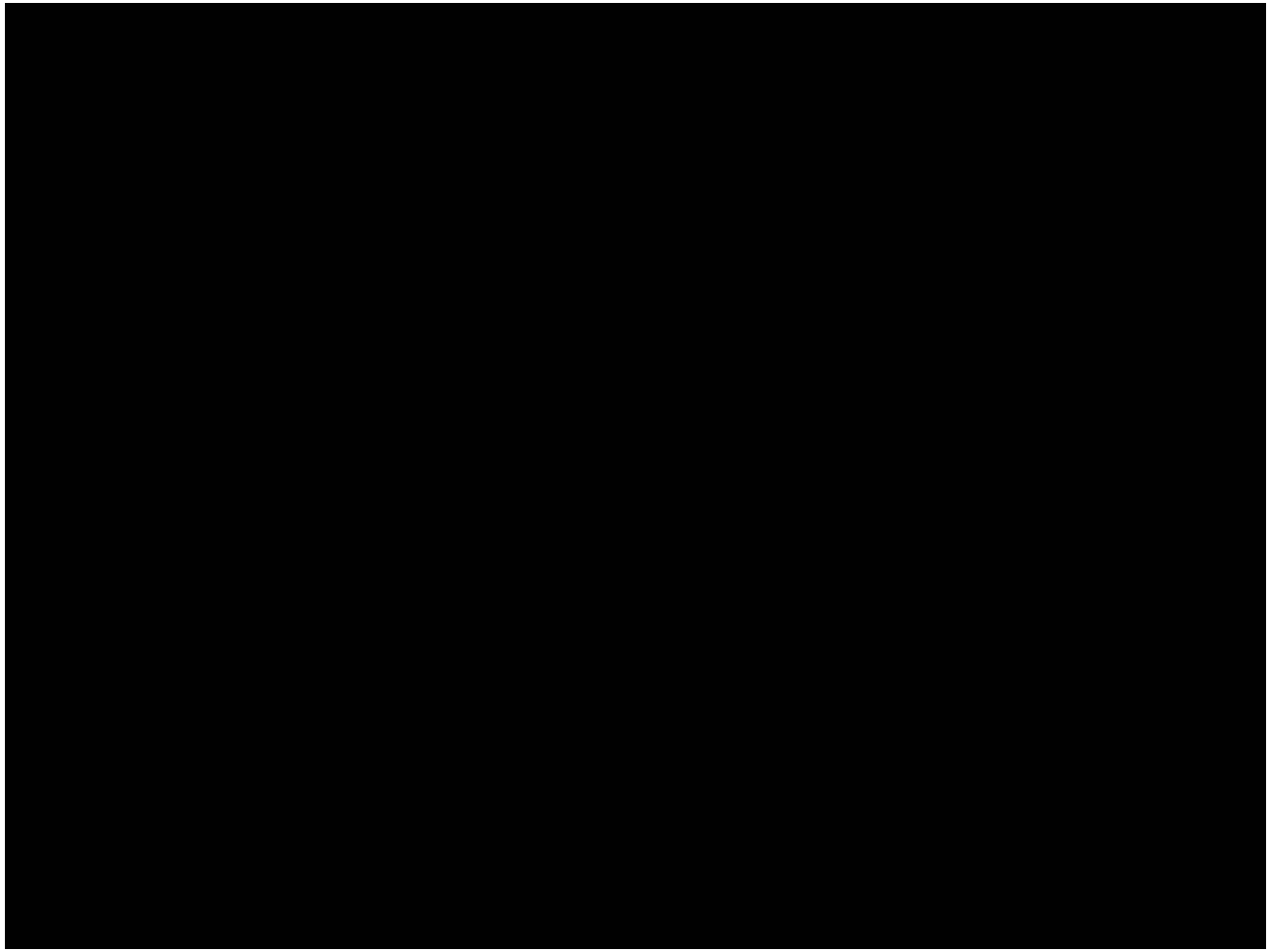


UNCLASSIFIED

Test pond at China Lake with JDAM near impact (25 ft deep)



Provided by Boeing/ATR Corp



UNCLASSIFIED

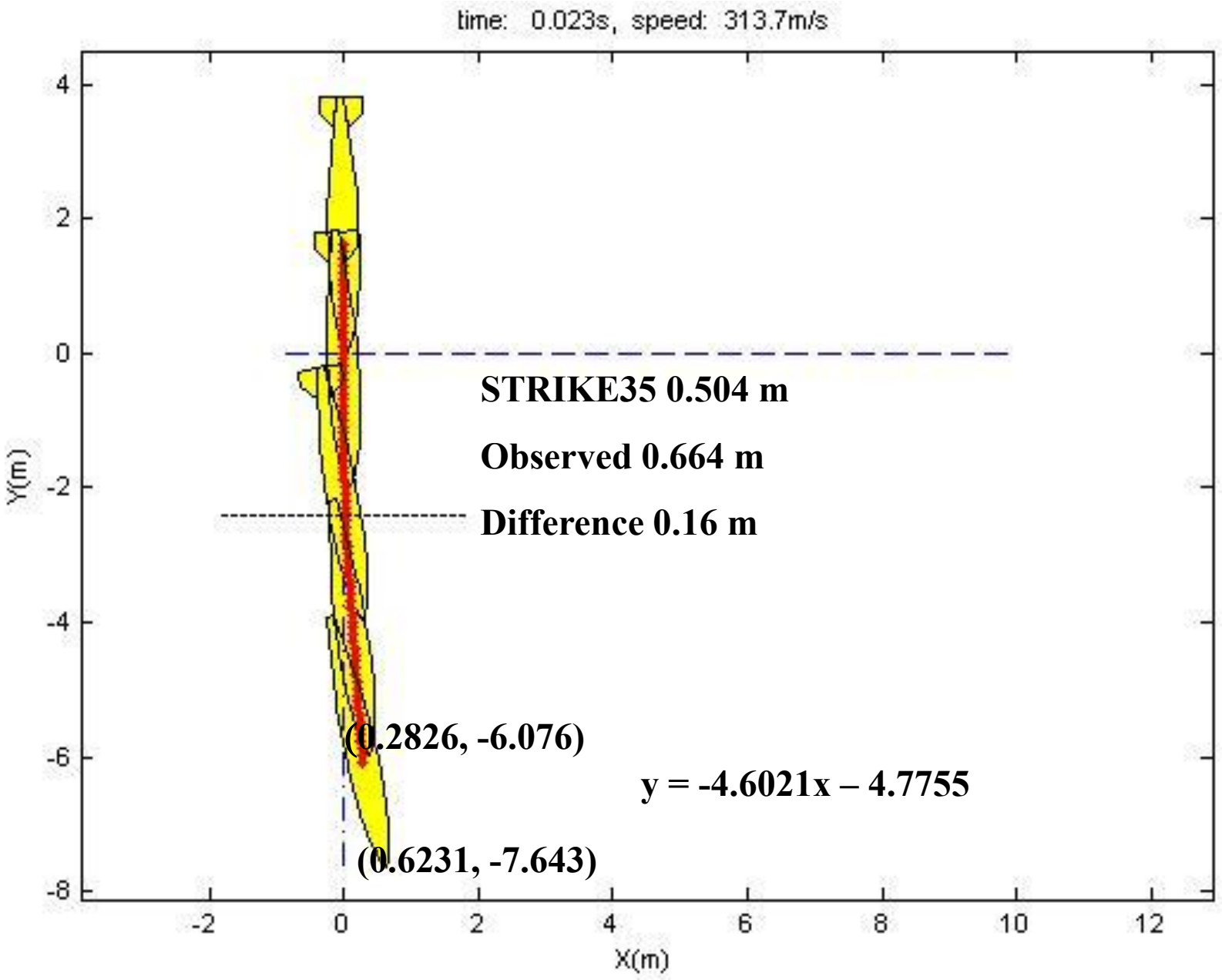


UNCLASSIFIED





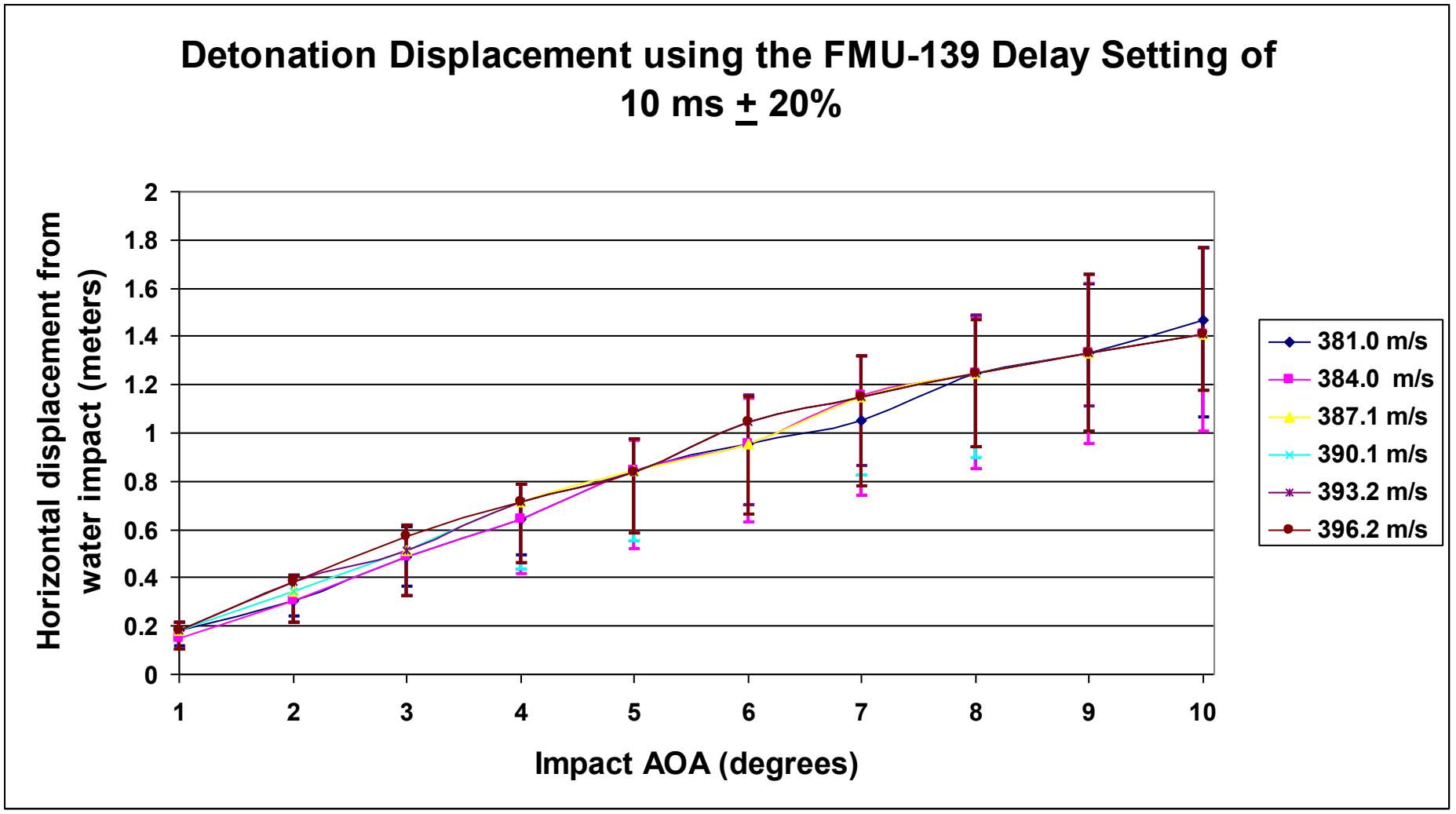


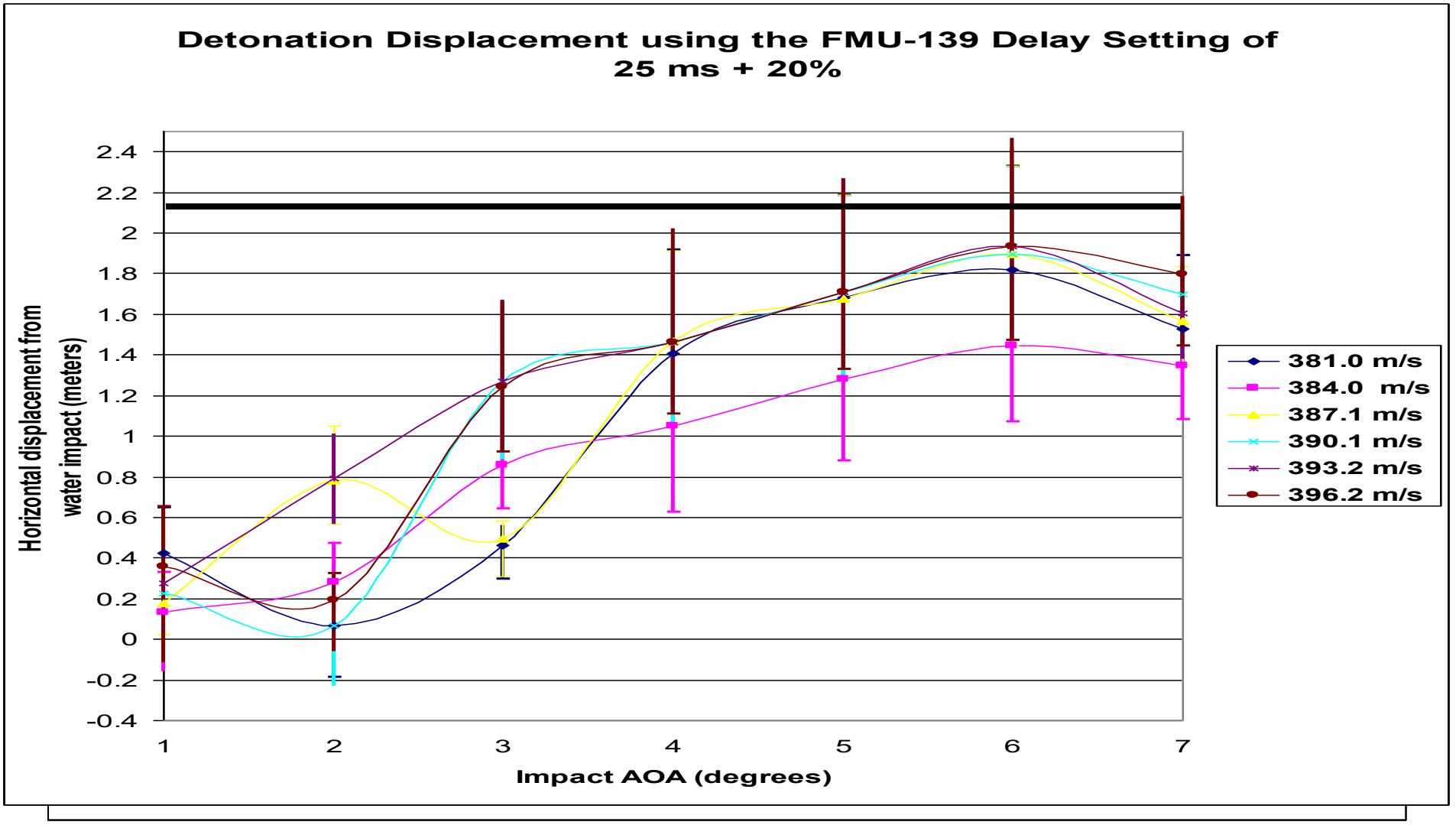

time: 0.023s, speed: 313.7m/s
STRIKE35 0.504 m
Observed 0.664 m
Difference 0.16 m
(0.2826, -6.076)
y = -4.6021x – 4.7755
(0.6231, -7.643)
Y(m)
X(m)
4
2
0
-2
-4
-6
-8
-2
0
2
4
6
8
10
12

UNCLASSIFIED

Experiment	Tail Separation Depth (m)	Model Displacement (m)	Observed to Model Distance (m)
UTT-1(2)	NA	0.43	0.24
UTT-1(2)	4.6	0.44	0.23
UTT-1(2)	3.0	0.50	0.17
UTT-1(2)	2.4	0.62	0.05
UTT-1(3)	NA	0.48	0.09
UTT-1(3)	4.6	0.48	0.08
UTT-1(3)	3.0	0.56	0.01
UTT-1(3)	2.9	0.57	0.00
UTT-2(2)	NA	1.23	-0.80
UTT-2(2)	4.6	1.33	-0.90
UTT-2(2)	3.0	2.30	-1.87

UNCLASSIFIED


Detonation Displacement using the FMU-139 Delay Setting of 10 ms ± 20%
Horizontal displacement from water impact (meters)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1
2
3
4
5
6
7
8
9
10
Impact AOA (degrees)
381.0 m/s
384.0 m/s
387.1 m/s
390.1 m/s
393.2 m/s
396.2 m/s


Detonation Displacement using the FMU-139 Delay Setting of 25 ms + 20%
Horizontal displacement from water impact (meters)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1
2
3
4
5
6
7
Impact AOA (degrees)
381.0 m/s
384.0 m/s
387.1 m/s
390.1 m/s
393.2 m/s
396.2 m/s

UNCLASSIFIED

Conclusions

- Trajectory/deviation is sensitive to changes in impact AOA, especially when it is above 2°
- Impact airspeed and water density change the trajectory, but have small effect on Technology Transfer Agreement (TTA) (i.e., horizontal drift < 2.1 m, i.e., 7 ft).
- For TTA
  - Surface impact AOA to stay below about 2.1°
  - 10 ms delay → no limitation on impact AOA
  - 25 ms delay → remain below 4° impact AOA

UNCLASSIFIED

Questions?