Underwater Bomb Trajectory Prediction for Stand-off Assault Breaching Weapon Fuse Improvement (SOABWFI)

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Sponsored by
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(Program Manager: Brian Almquist)

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Future Assault Breaching System Operational Scenario

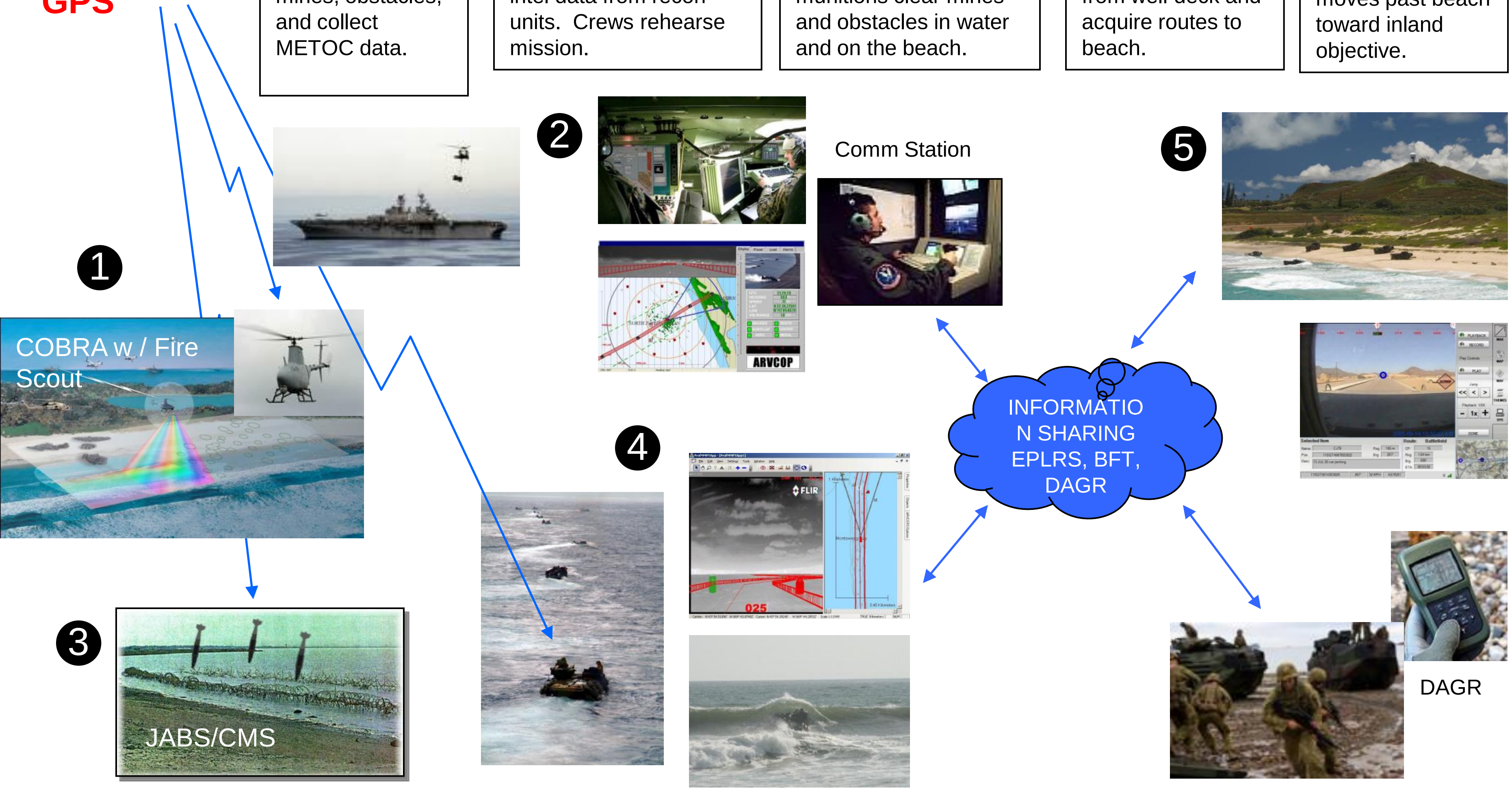
1. Surveillance. Satellites, UUV's and UAV's identify mines, obstacles, and collect METOC data.

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.

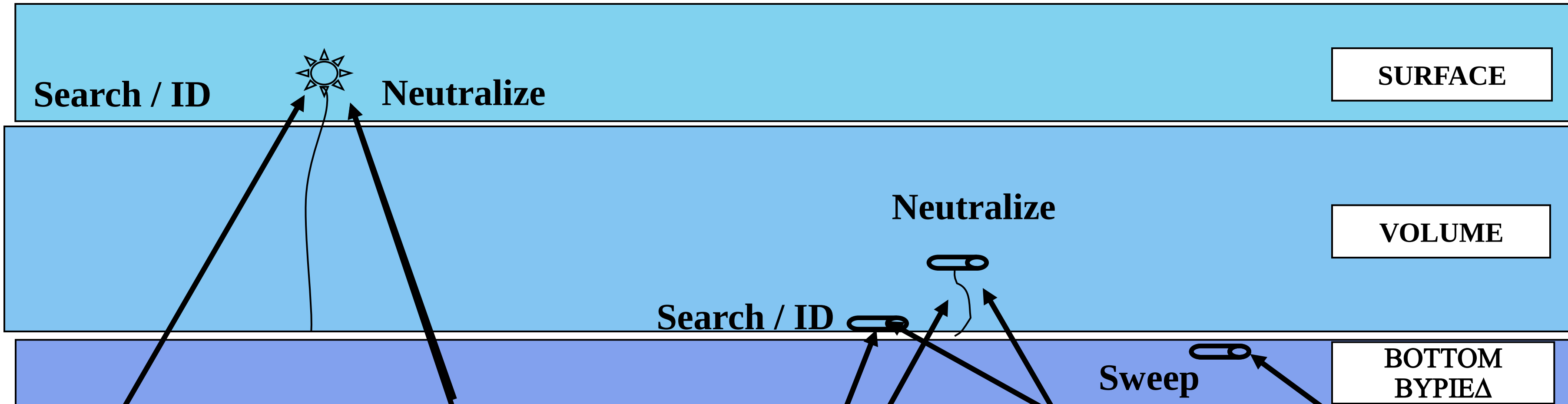


COBRA – Coastal Battlefield Reconnaissance and Analysis
JABS – Joint Direct Attack Munition (JDAM) Assault Breaching System
CMS – Countermine System (darts)

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



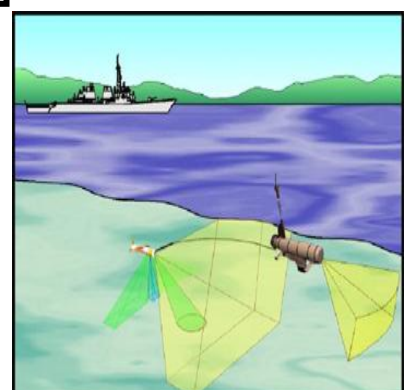
Airborne Laser Mine Detection System (ALMDS)

Laser (search)

Rapid Airborne Mine Clearance System (RAMICS)

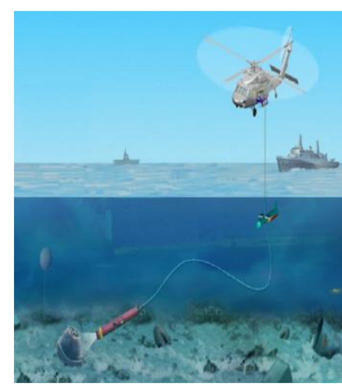
Super-cavitating Projectiles (kill)

Remote Minehunting System (RMS) – AN/AQS20A Sonar



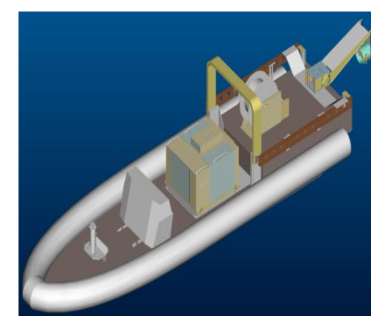
Sonar (search) (and on Helo)

Airborne Mine Neutralization System (AMNS)



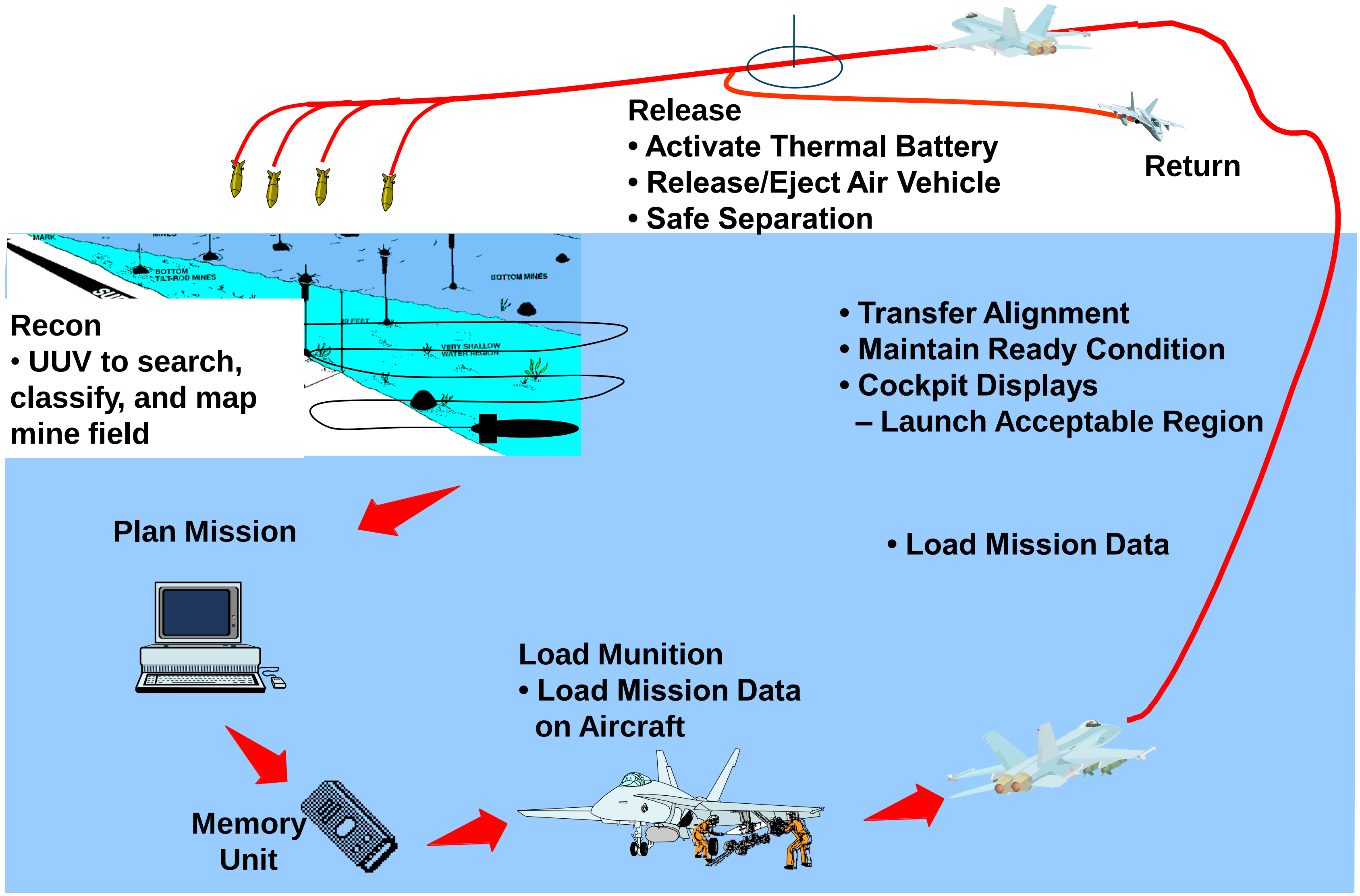
Self propelled explosive charges (kill)

Unmanned Surface Vessel / Organic Airborne and Surface Influence Sweep (USV/OASIS)



Acoustic + magnetic influence sweep and kill

Mission Execution CONOPS



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

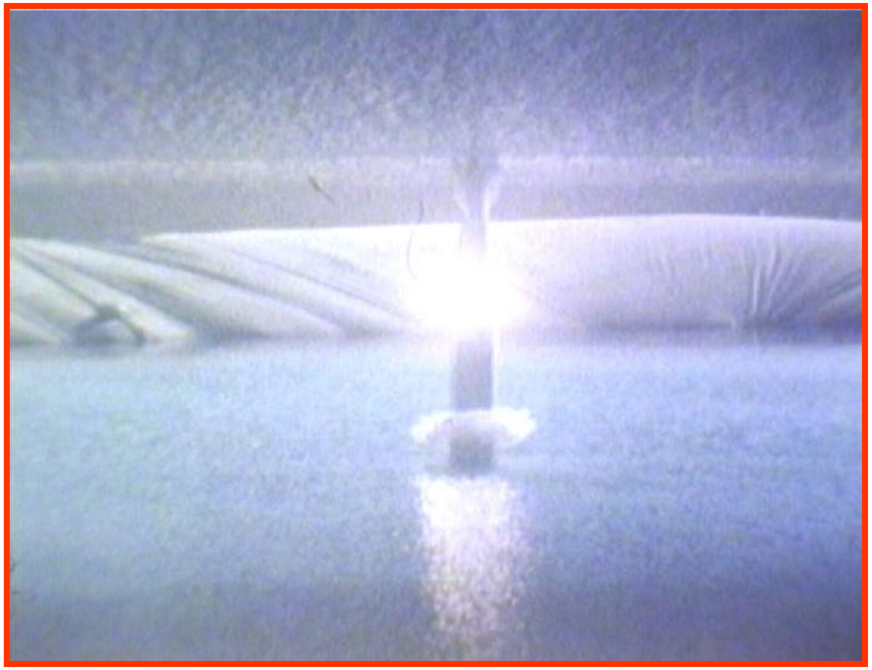
SZ & BZ Countermine & Counterobstacle

- **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**

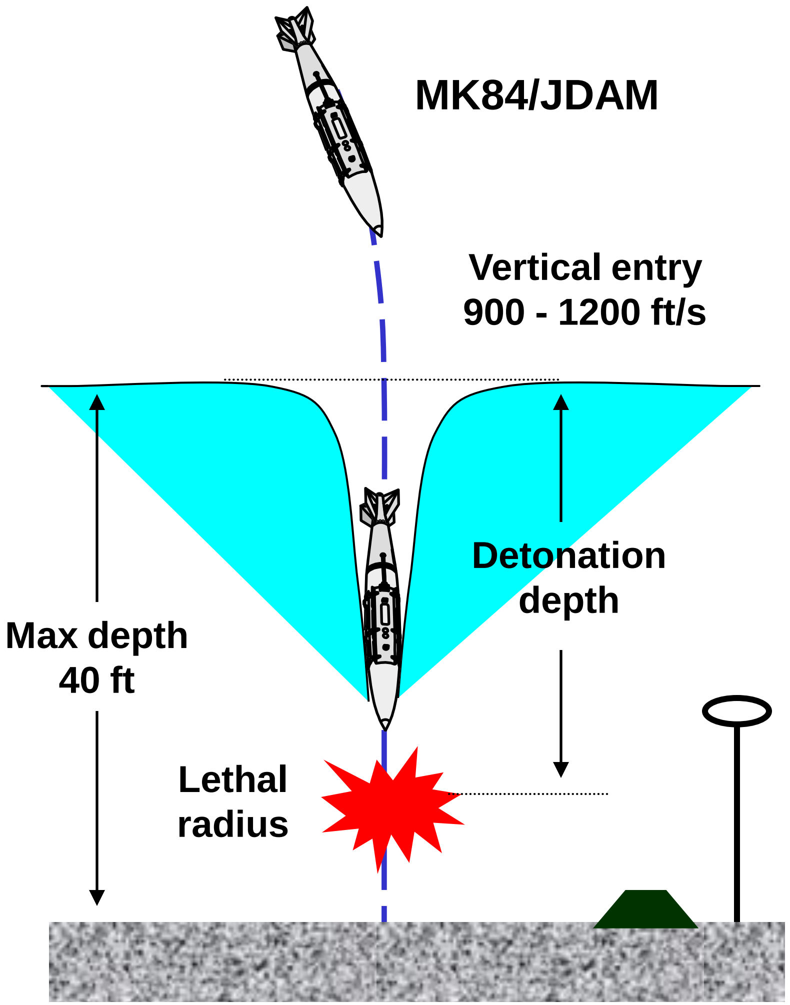
We know JABS performs well to water depths of 10 ft. Can it go deeper?

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

(from Almqist 2006)

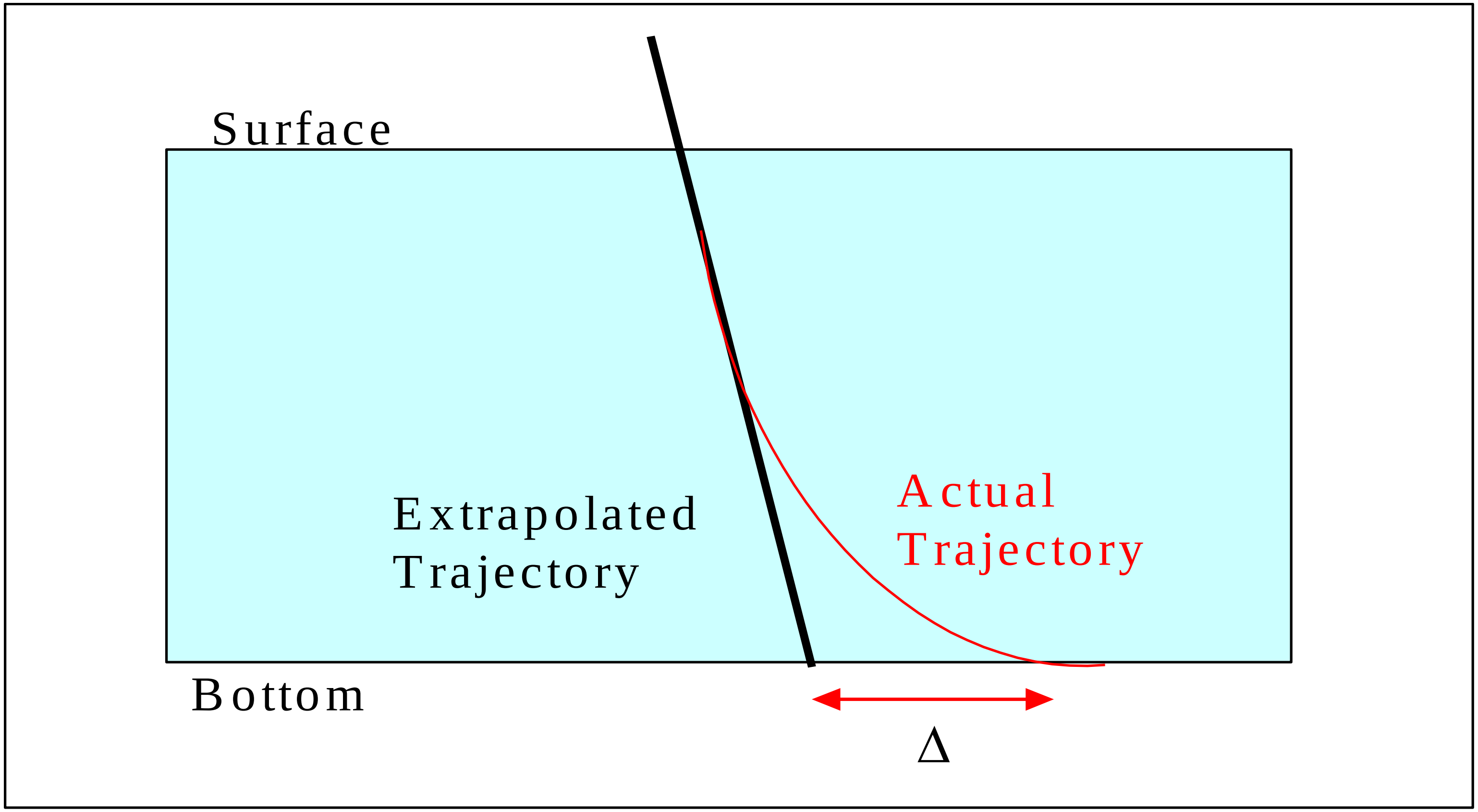


Mine Neutralization by MK84/JDAM



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.

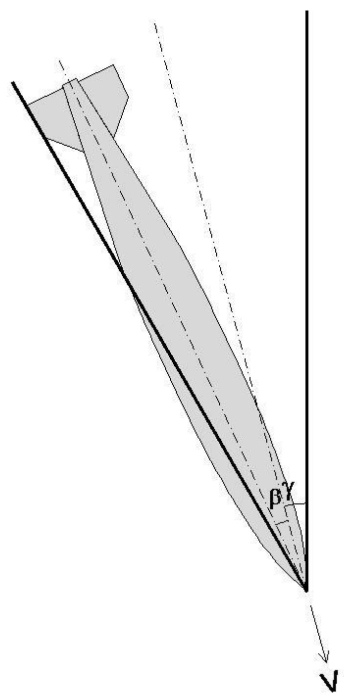


For effective mine clearance

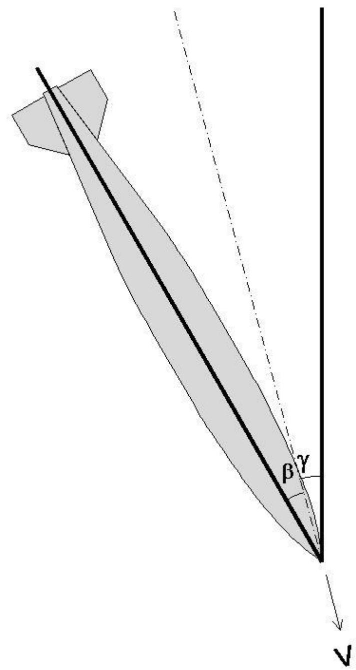
$\Delta < 7$ ft (2.1 m)

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).

Air Cavity

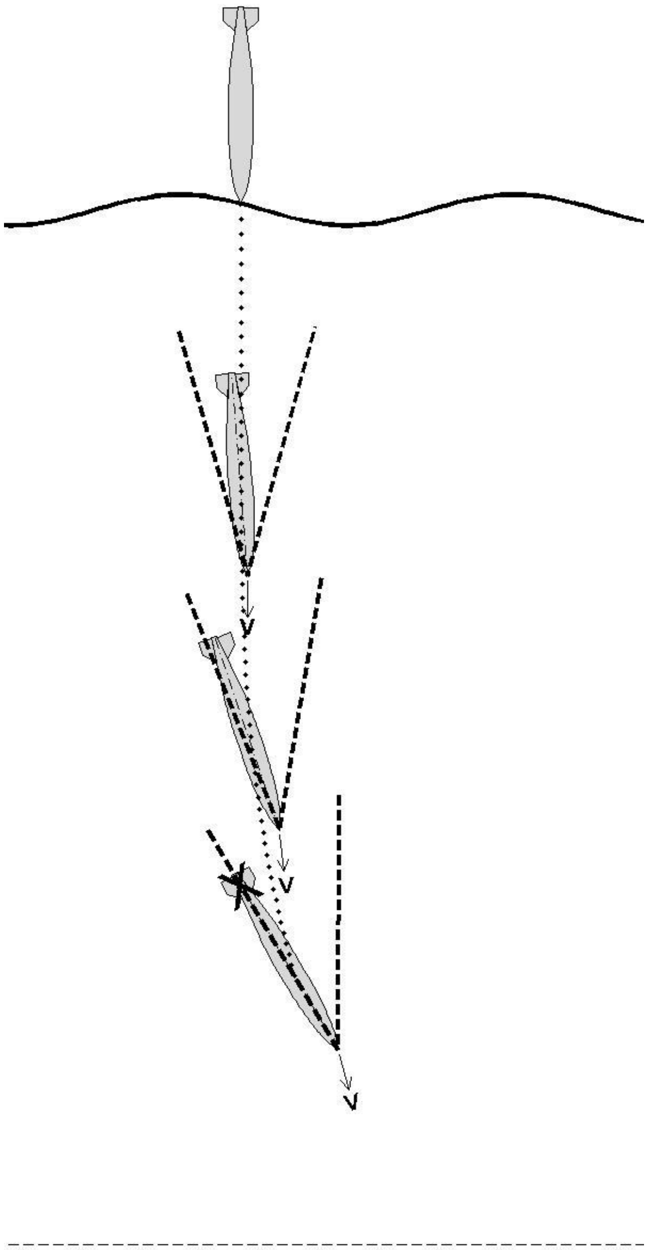


Inside the cavity

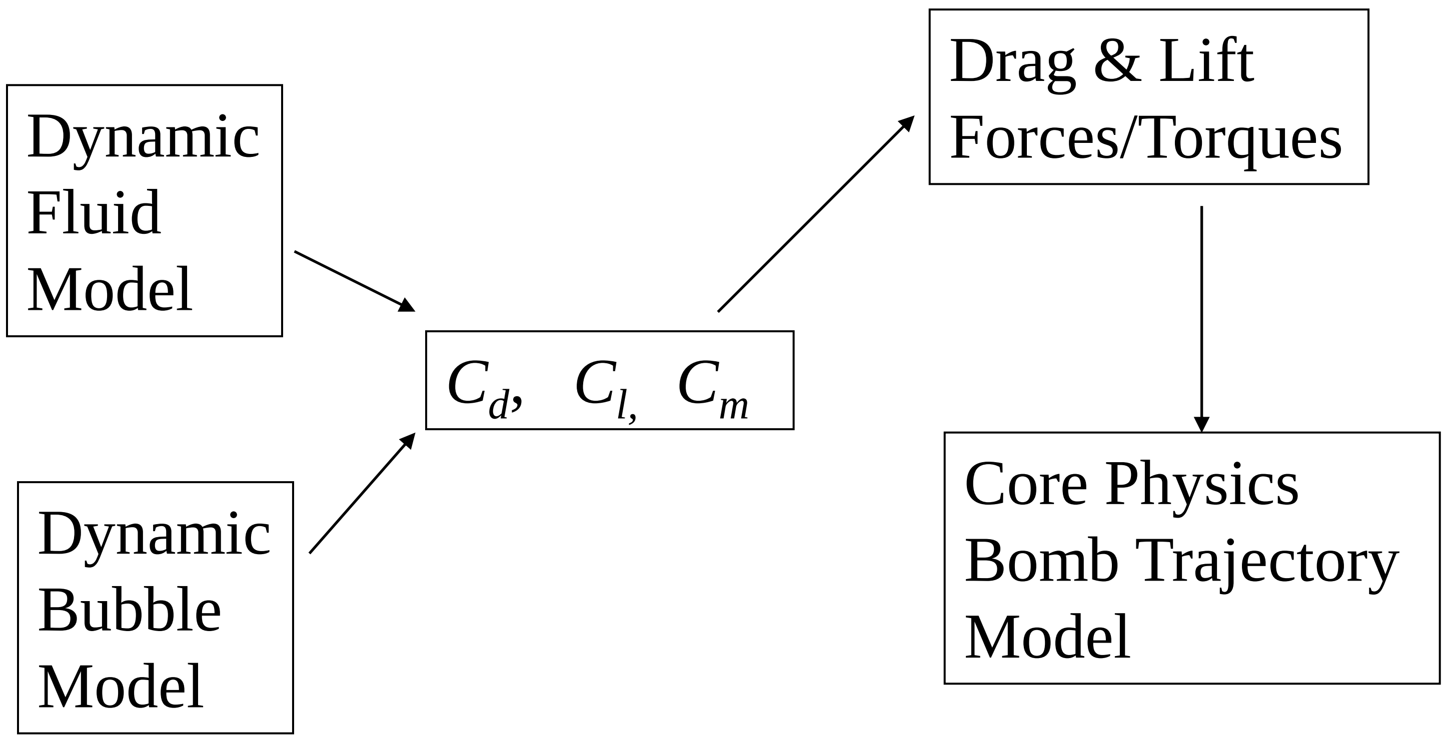


Hitting the cavity wall → Tail Separation

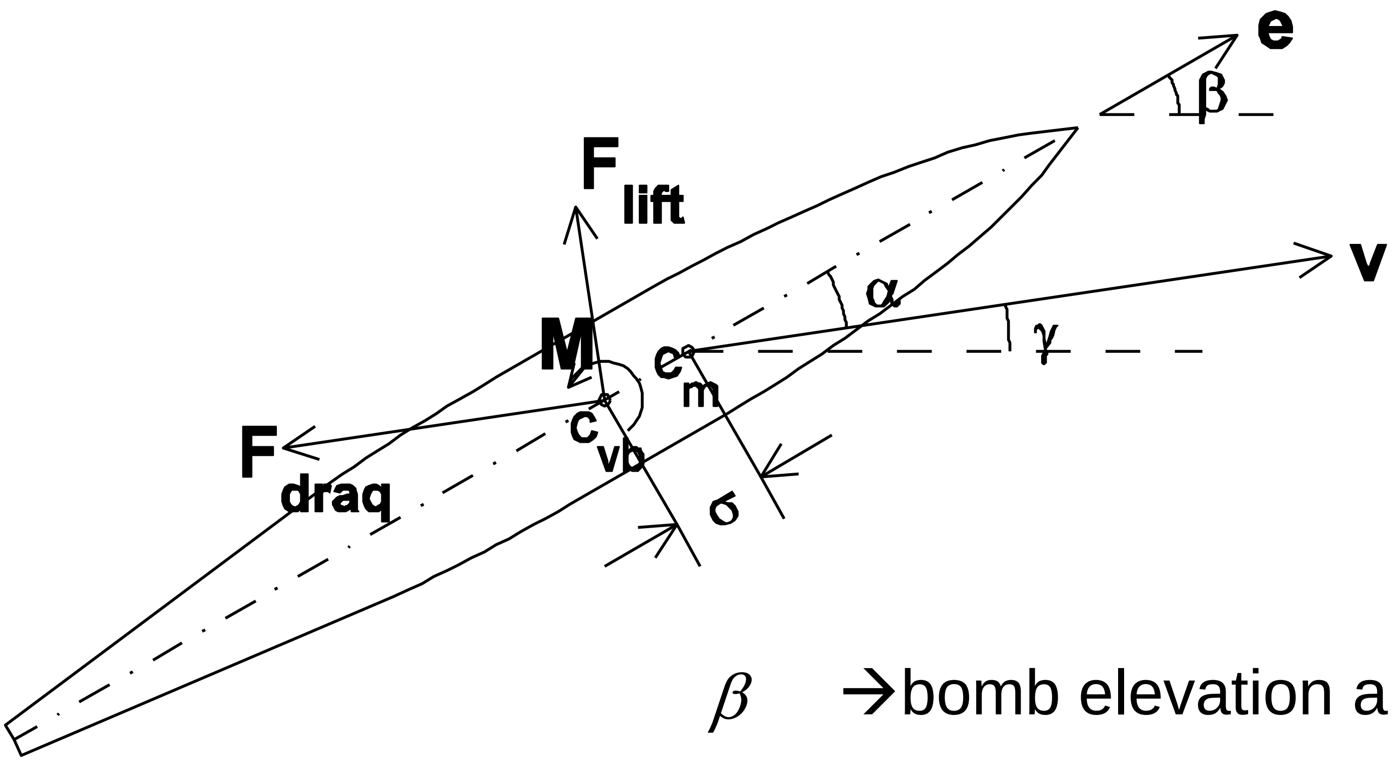
Surface slope affects
the tail separation and the
trajectory



6-FOF Bomb Trajectory Model



Dynamical Determination of Drag/Lift Coefficients



β → bomb elevation angle

γ → bomb velocity angle

α → attack angle

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

Theoretical Base

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

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

Here, **V** is the translation velocity of COM,

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

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

Sub-Scale Model Test Objectives

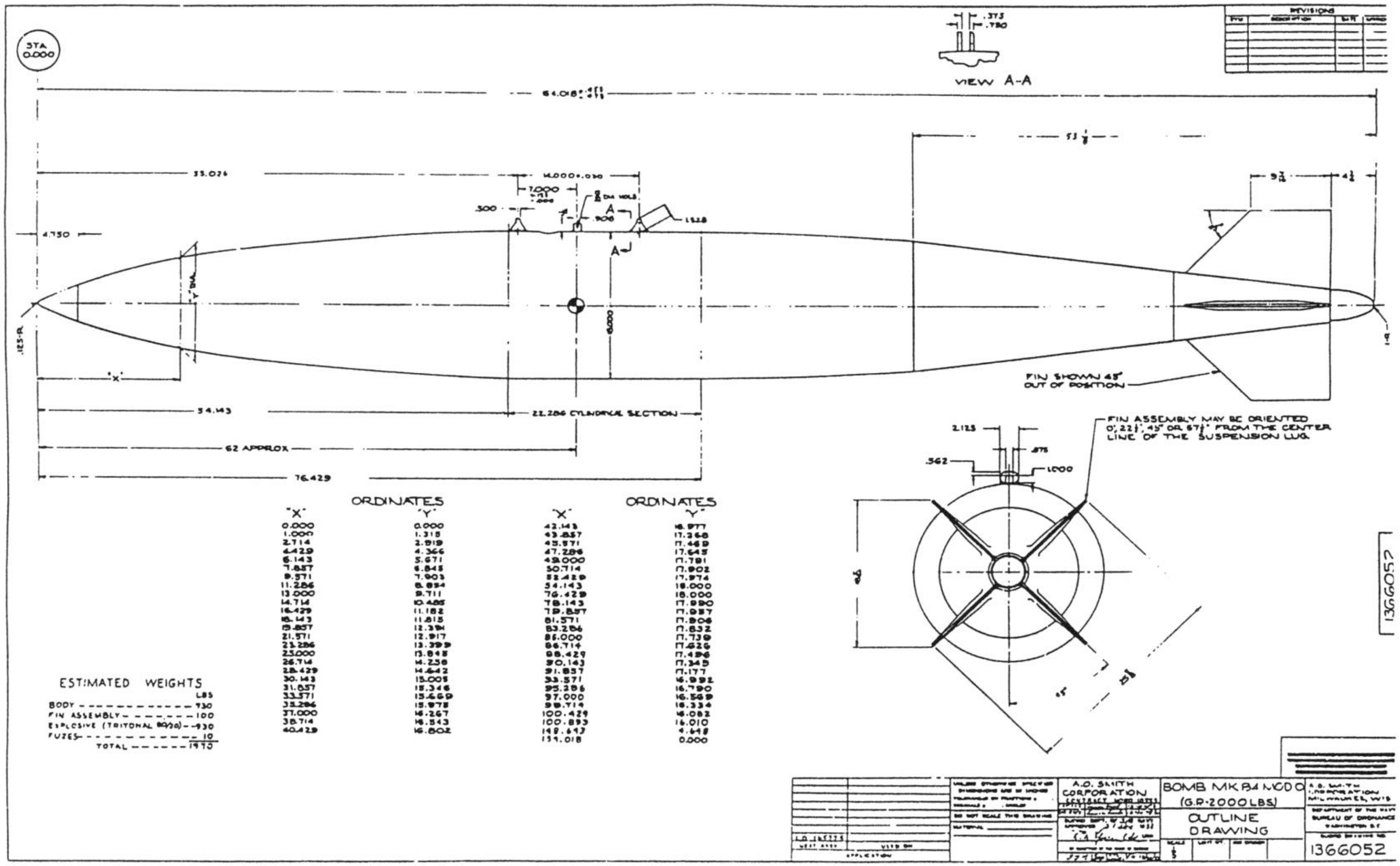
- Use 1/12-scale tests to measure Mk84 bomb trajectory to a shallow water full-scale depth of 160 ft and for a 90 degree water entry angle.

- 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.

Mk84 Bomb Full-Scale Features

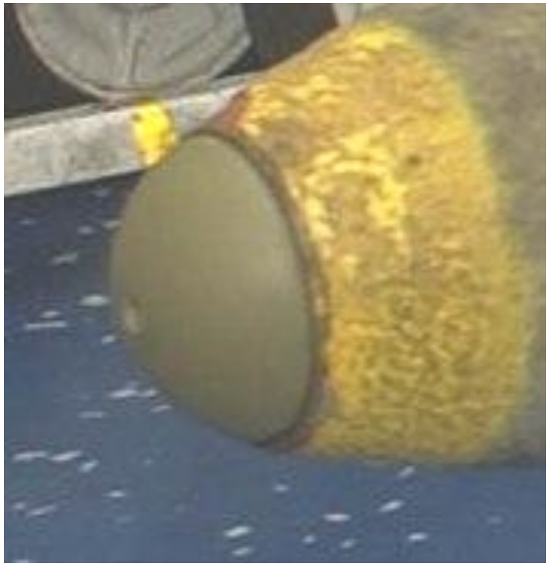
(With USN Ogive Nose)



Current Mk84 Bomb Nose Features

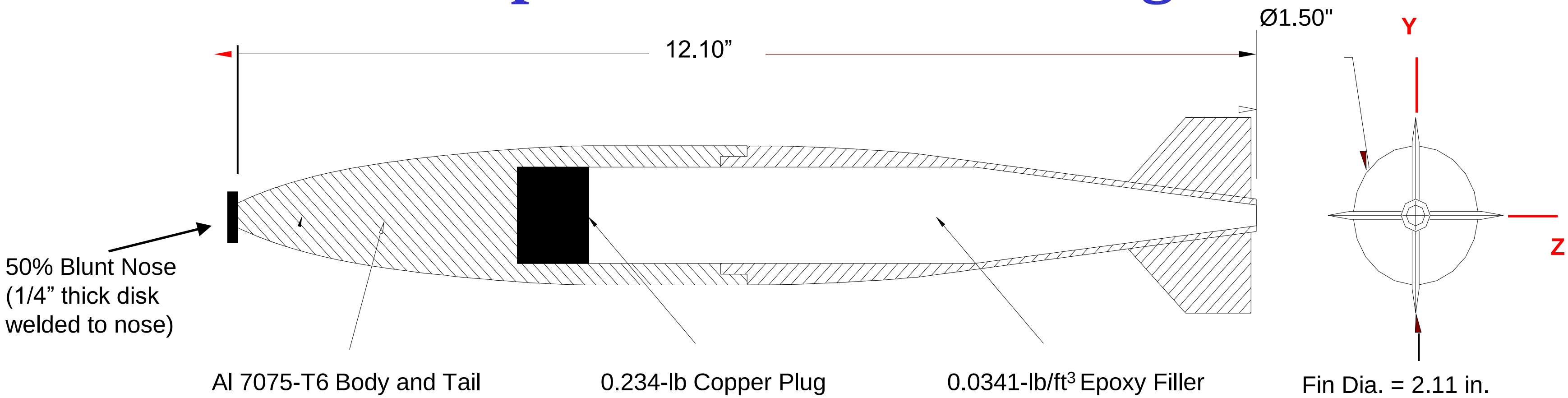
USN Ogive Nose

USAF Nose

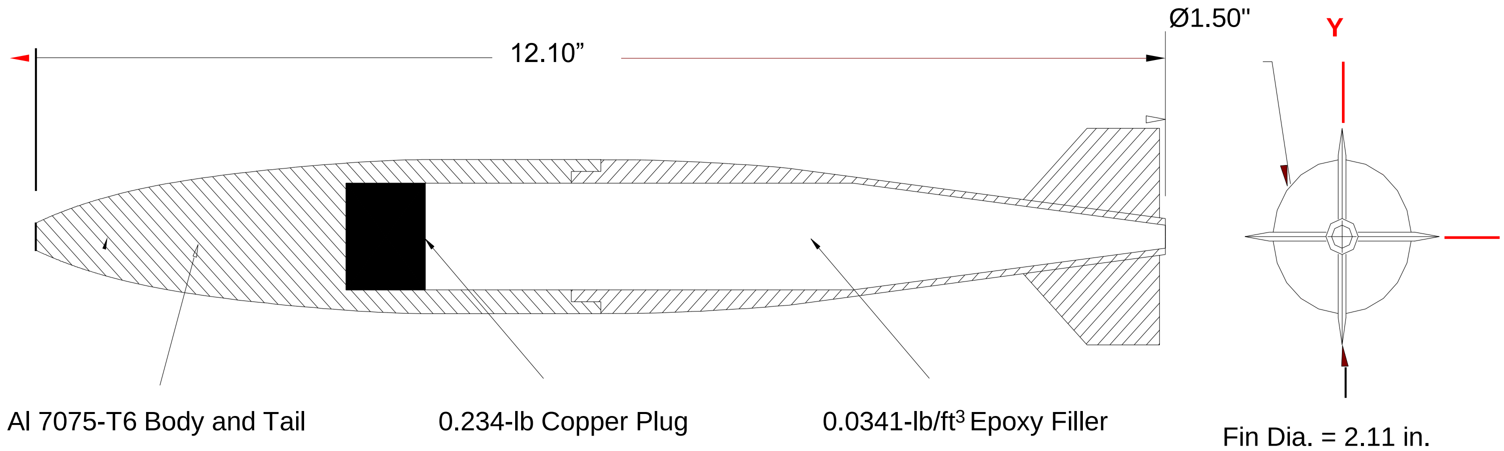


USN MXU-735 Nose

Conceptual Mk84 Nose Designs

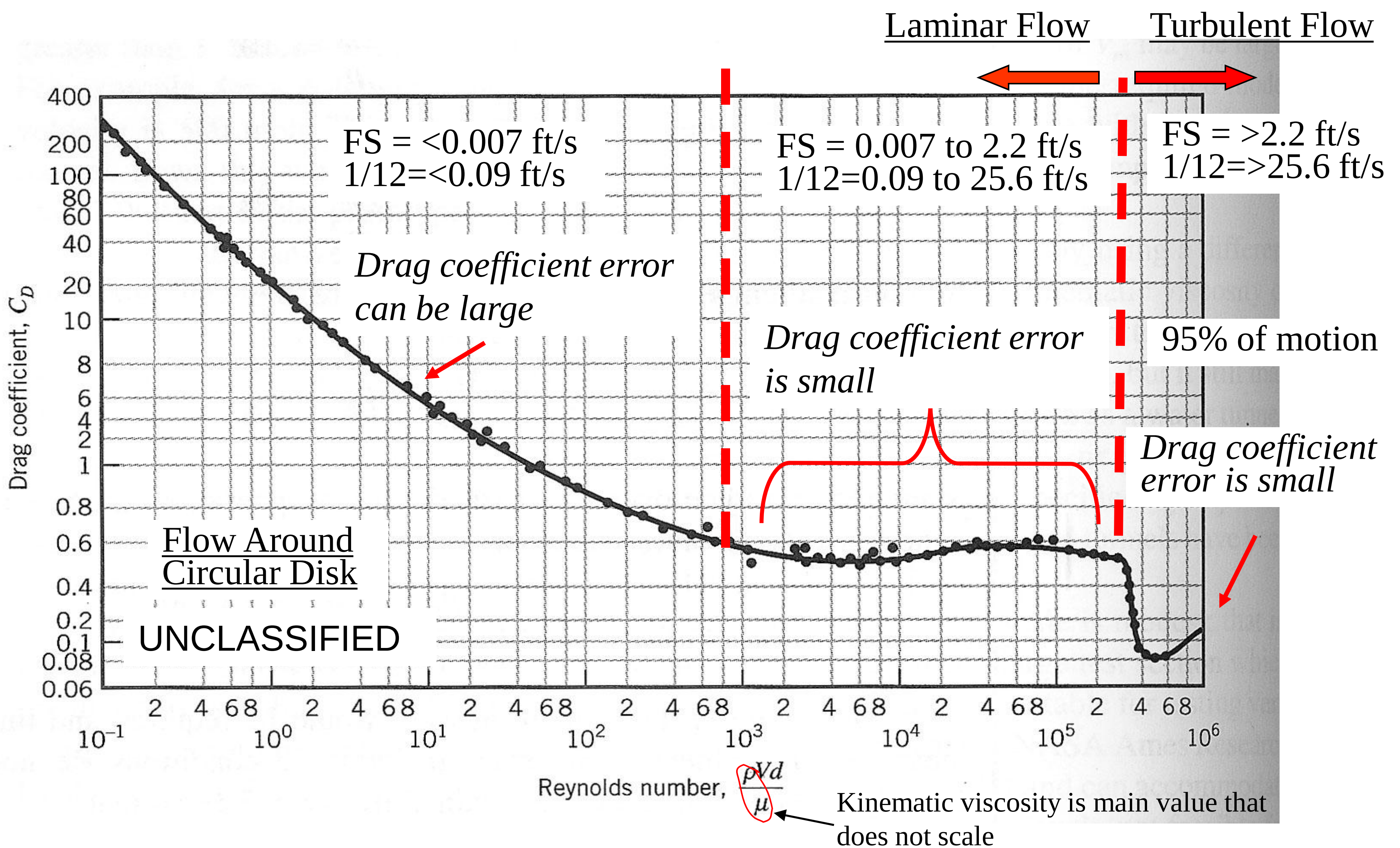


50% Blunt Nose



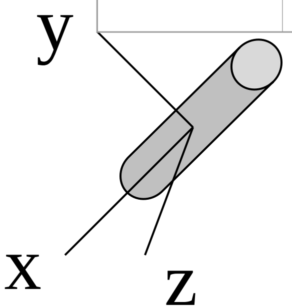
25% Blunt Nose

Trajectory Scaling



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

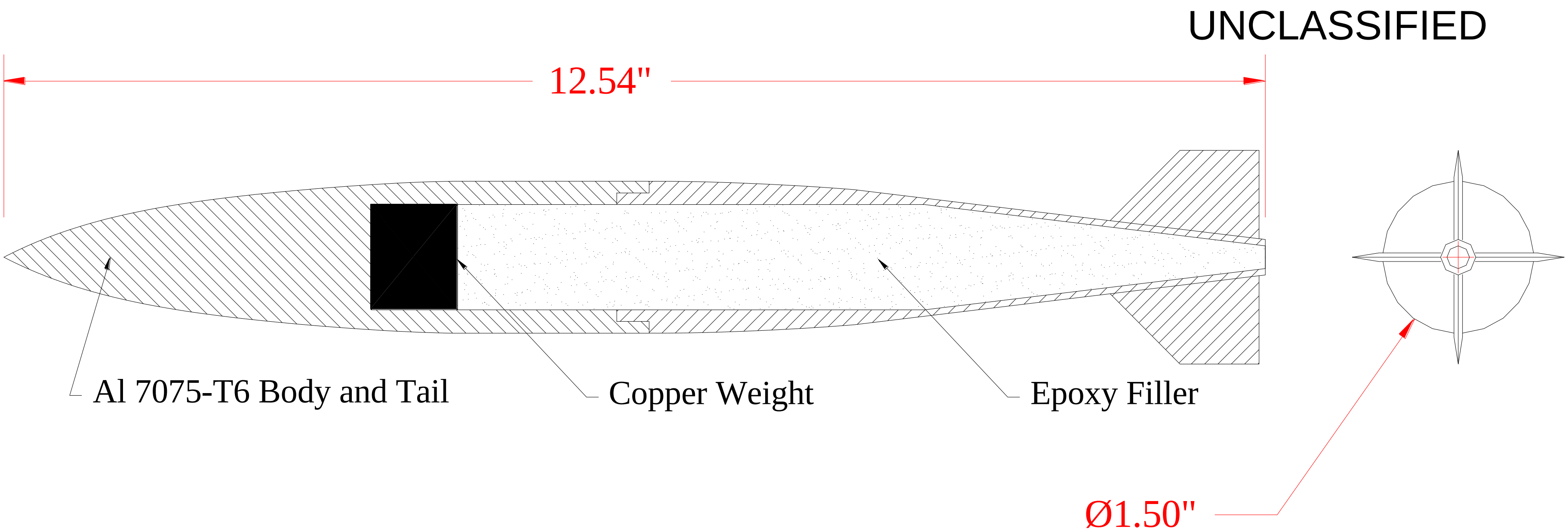
Mk84 Bomb	Length (in.)	Weight (lb)	Center of Gravity (in.)			Radius of Gyration (in.)		
			CGx	CGy	CGz	Kx	Ky	Kz
Full Scale	150.51	2076.64	63.12	0.130	0.100	6.660	30.640	30.640
True 1/12 Scale	12.54	1.202	5.260	0.010	0.010	0.555	2.553	2.553
As-Built 1/12 Scale	12.54	1.201	5.362	0.000	0.000	0.319	2.557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

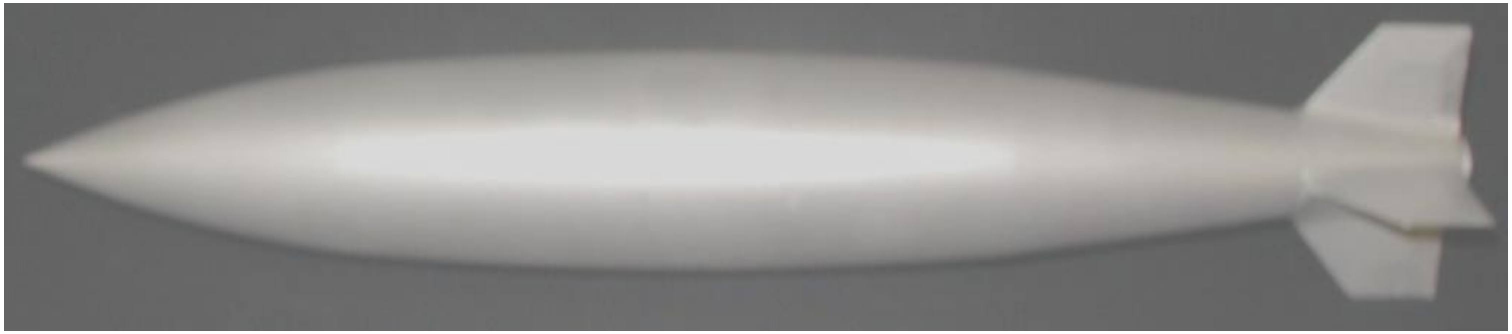


Due to neglecting casing lugs and strakes

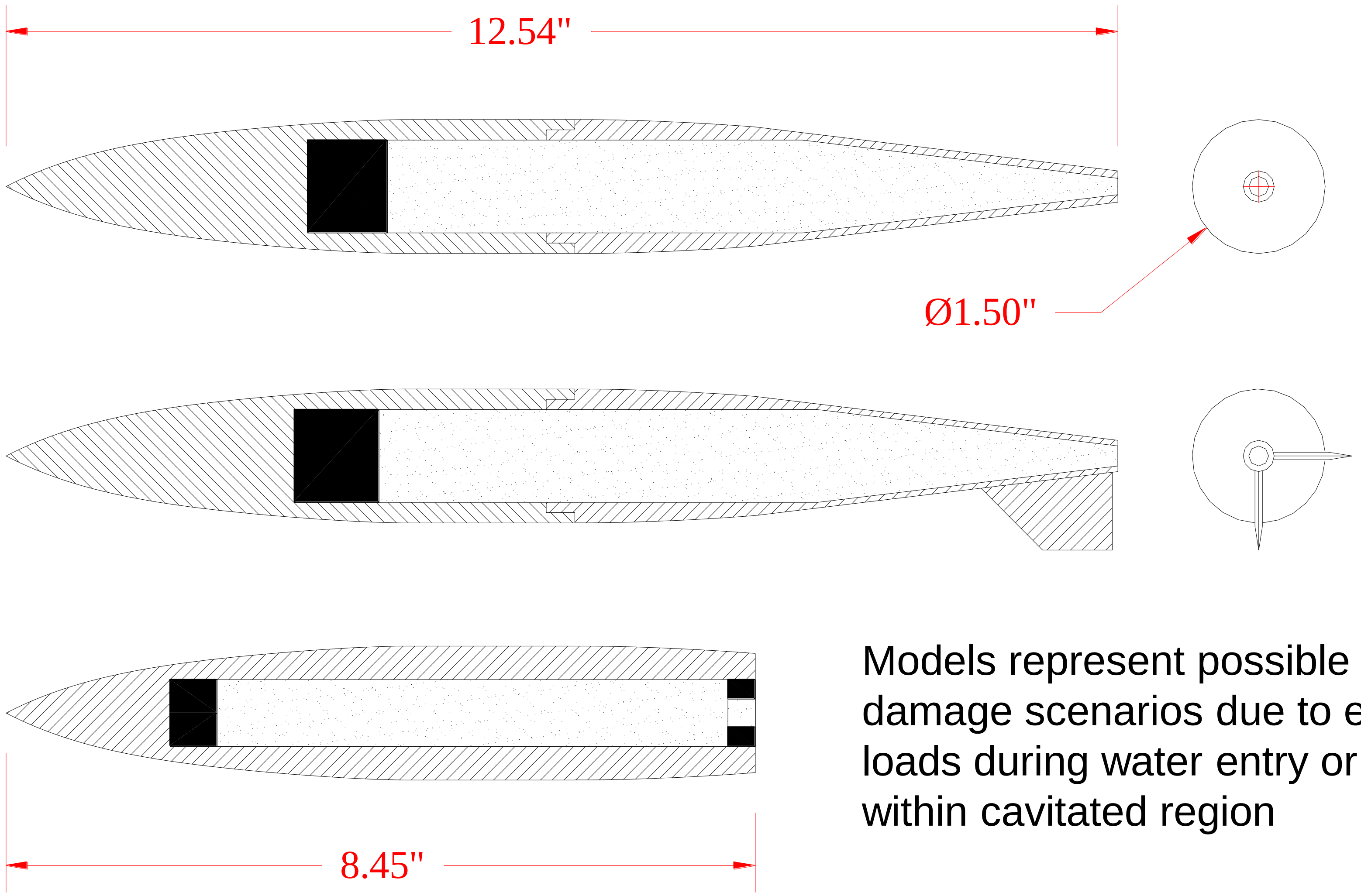
Neglected because the bomb does not rotate about x-axis

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





Tests With Simulated Fin or Tail Removal

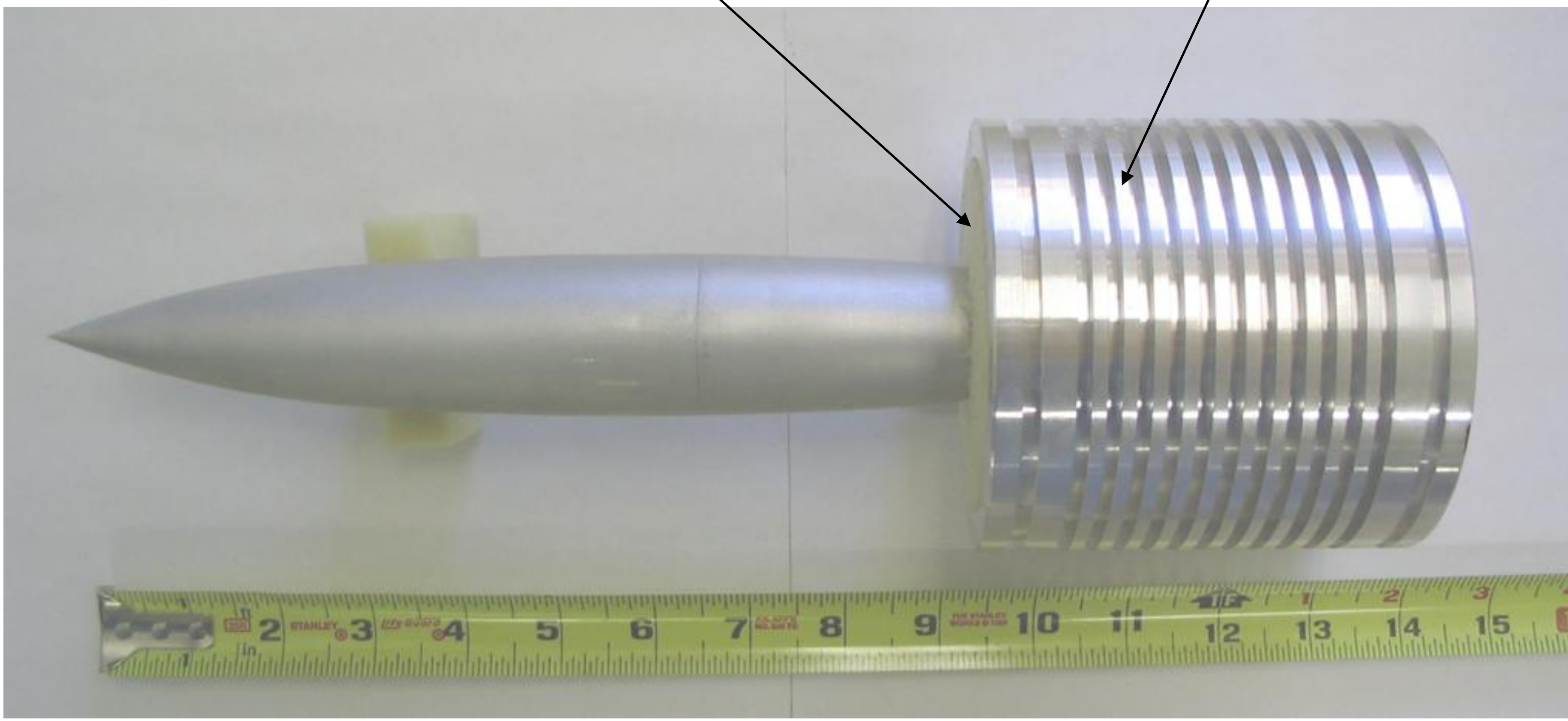


Models represent possible different damage scenarios due to excessive loads during water entry or tail slap within cavitated region

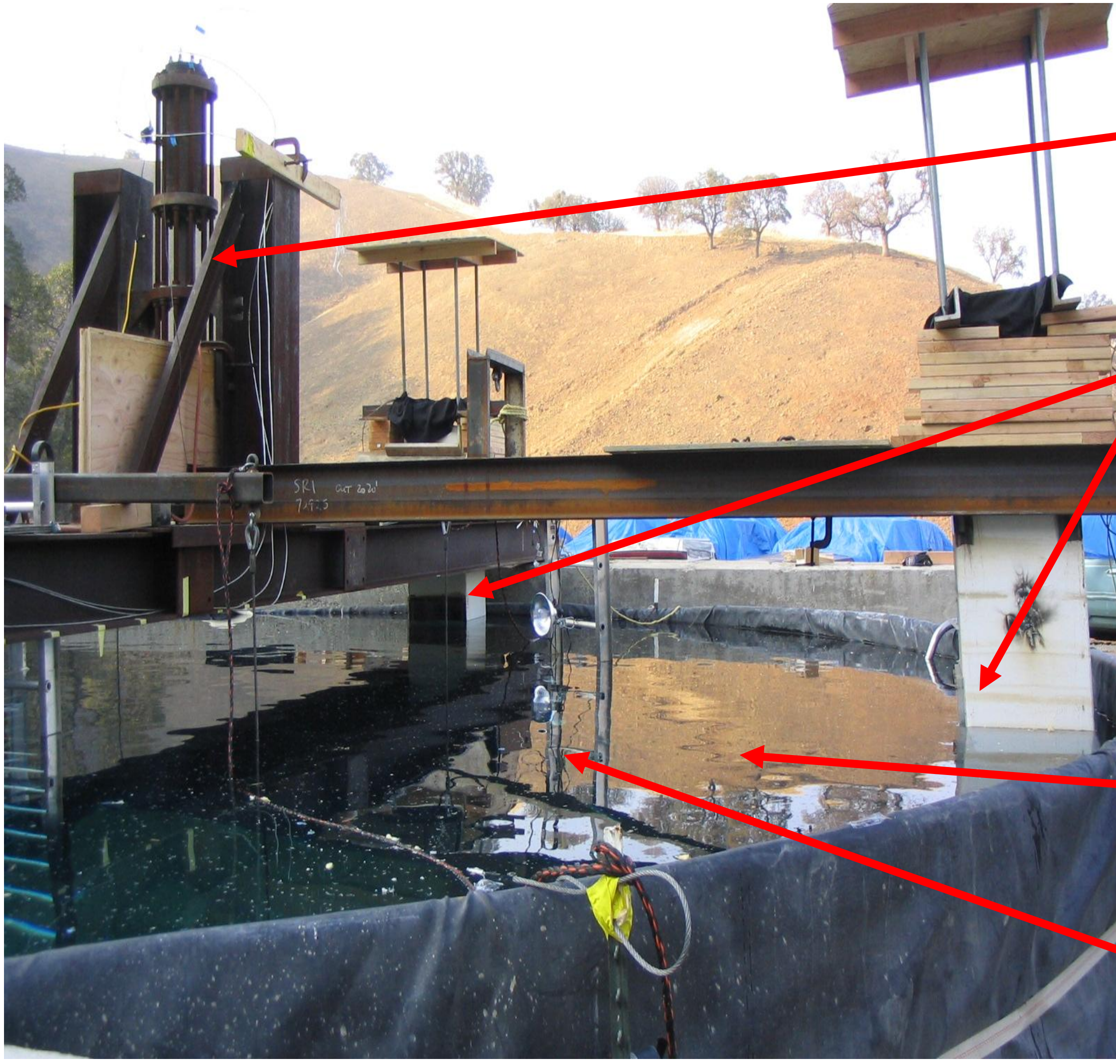
Sabot Design

Low-Density Foam

Aluminum Crushable Sabot



SRI Test Arrangement



4” dia. Gas Gun

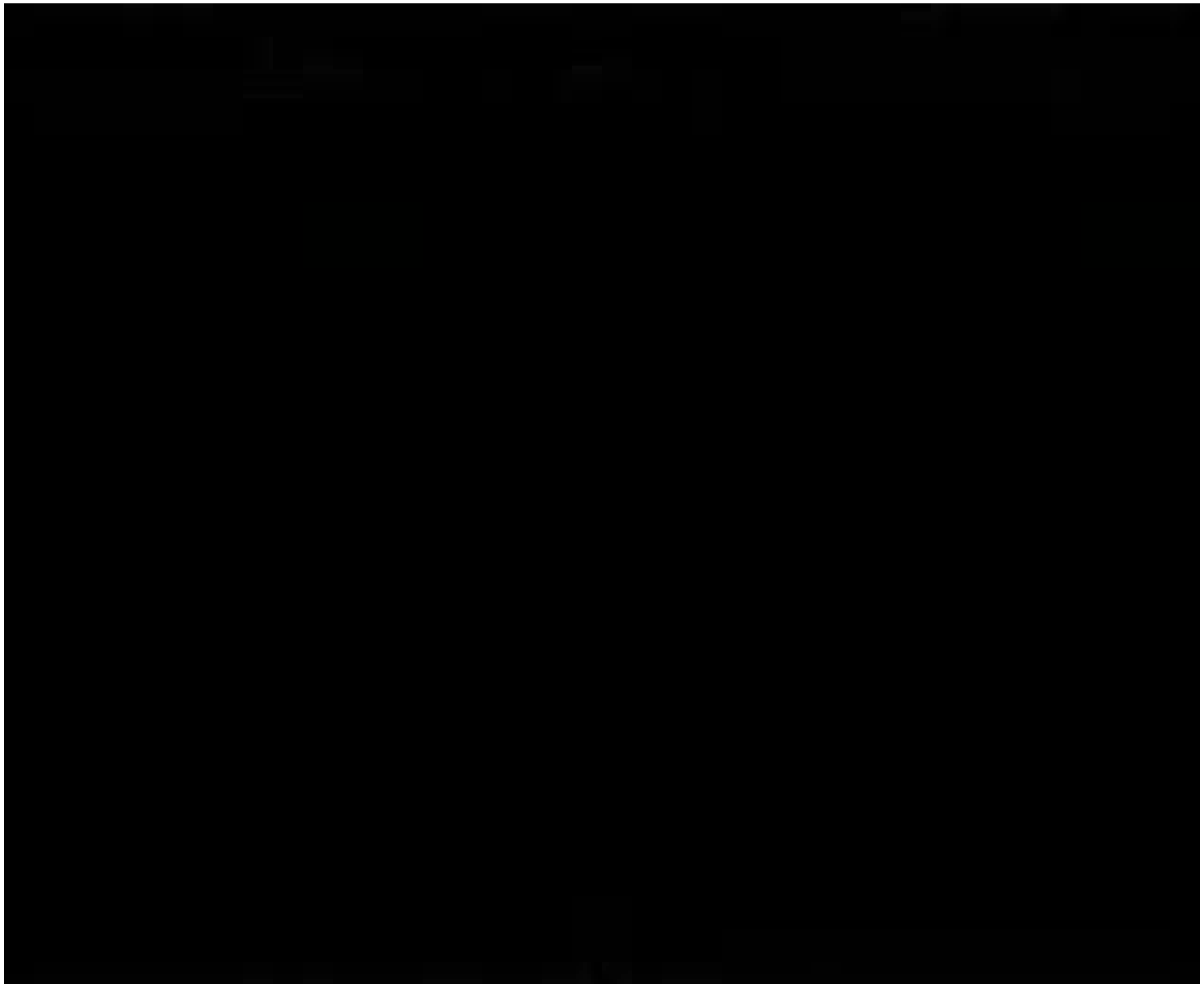
2 Phantom 7 Cameras
(10,000 fps) in Periscope

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

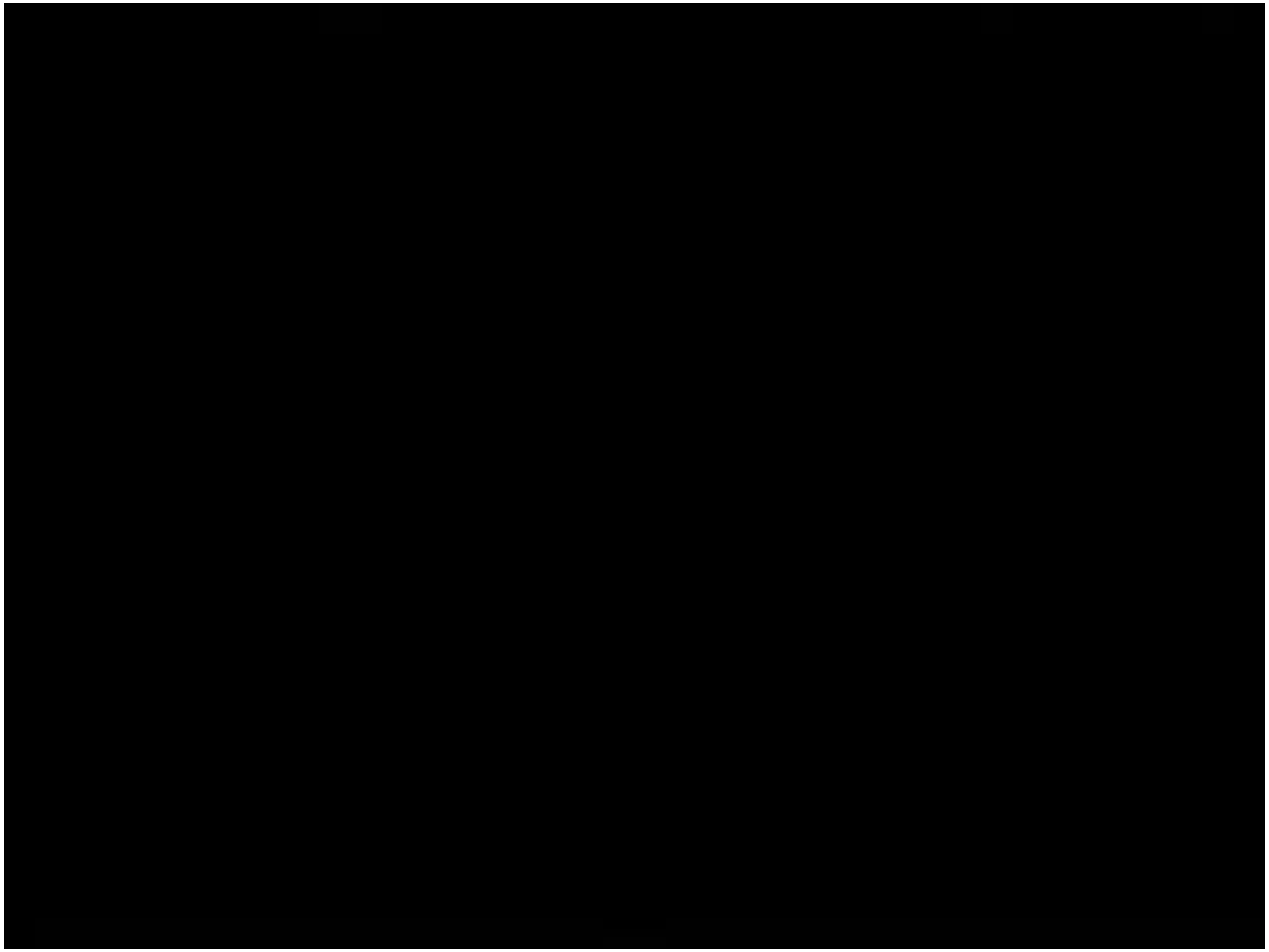
Underwater Lights

Tail with 4 Fins

Tail with 2 Fins

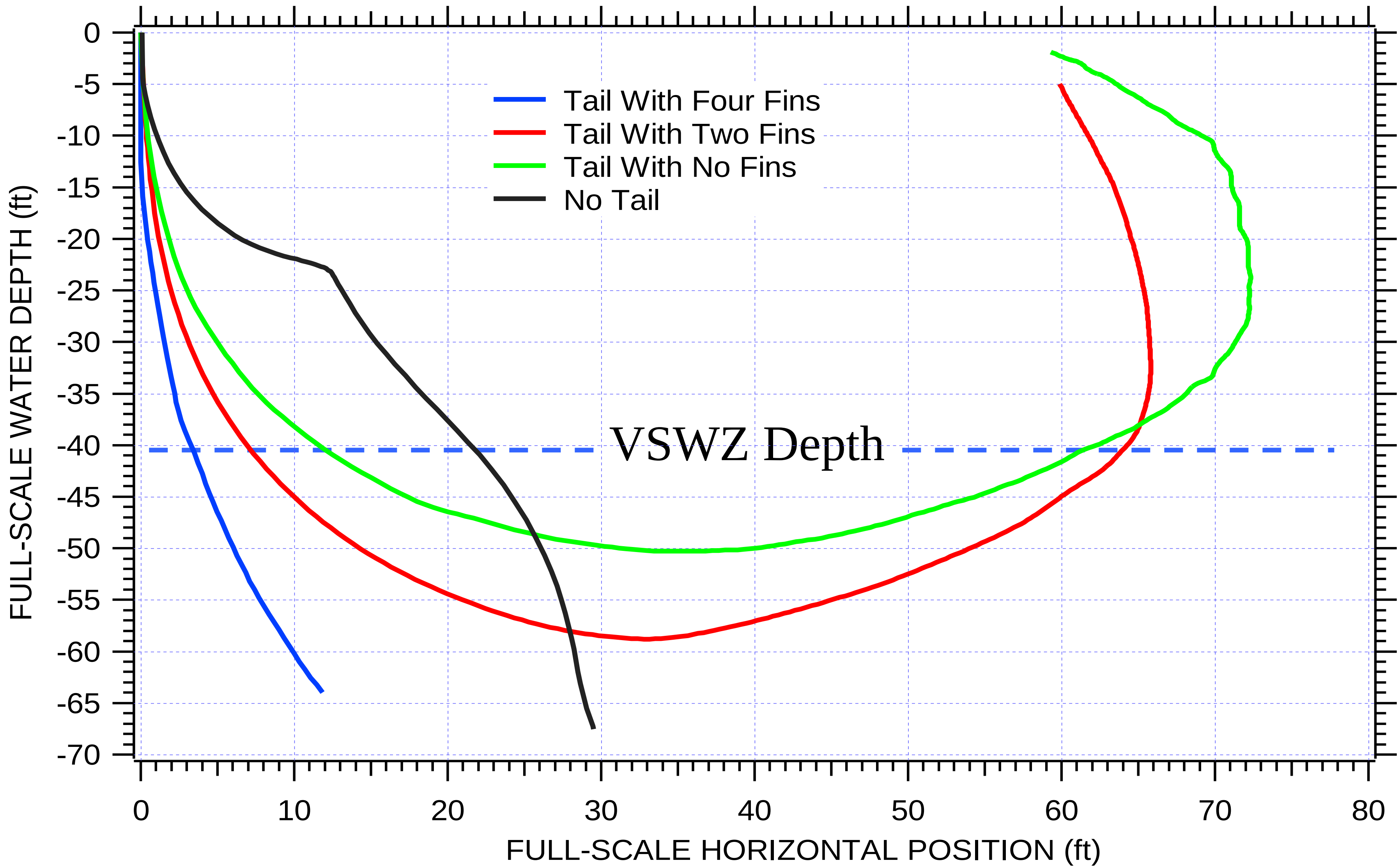


Tail with No Fins



No Tail

1/12th Scaled Model Test Results



Determination of C_d C_l C_m from Experimental Data

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

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

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

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

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

Semi-Empirical Formulas for (C_d C_l)

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

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

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

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

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

Semi-Empirical Formulas for C_m

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

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

NPS Model and SRI Data Inter-Comparison
Trajectory-1

NPS Model and SRI Data Inter-Comparison
Trajectory-14

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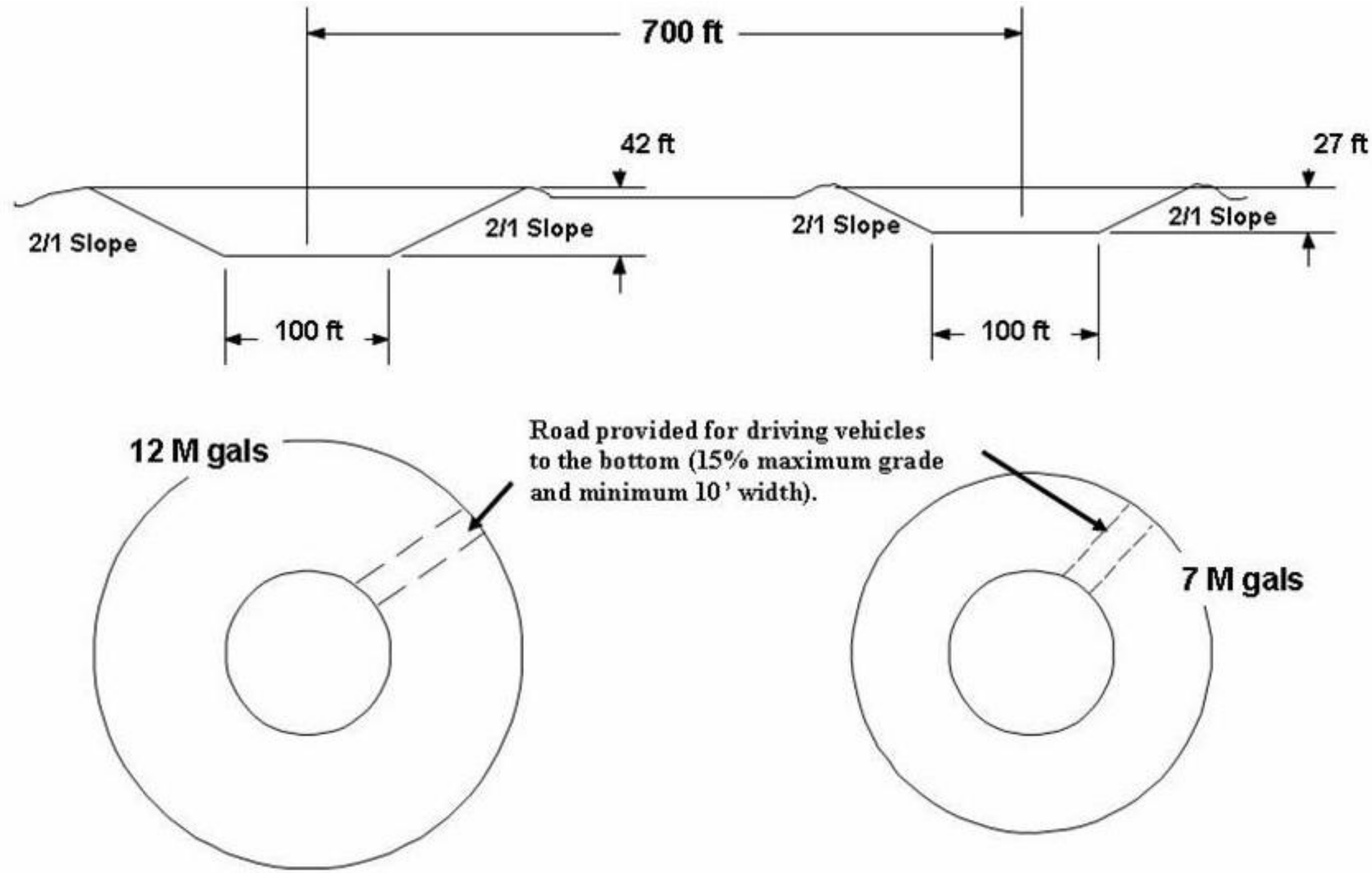
NPS Model and SRI Data Inter-Comparison
Trajectory-15

Full Size Test → China Lake

Experiments

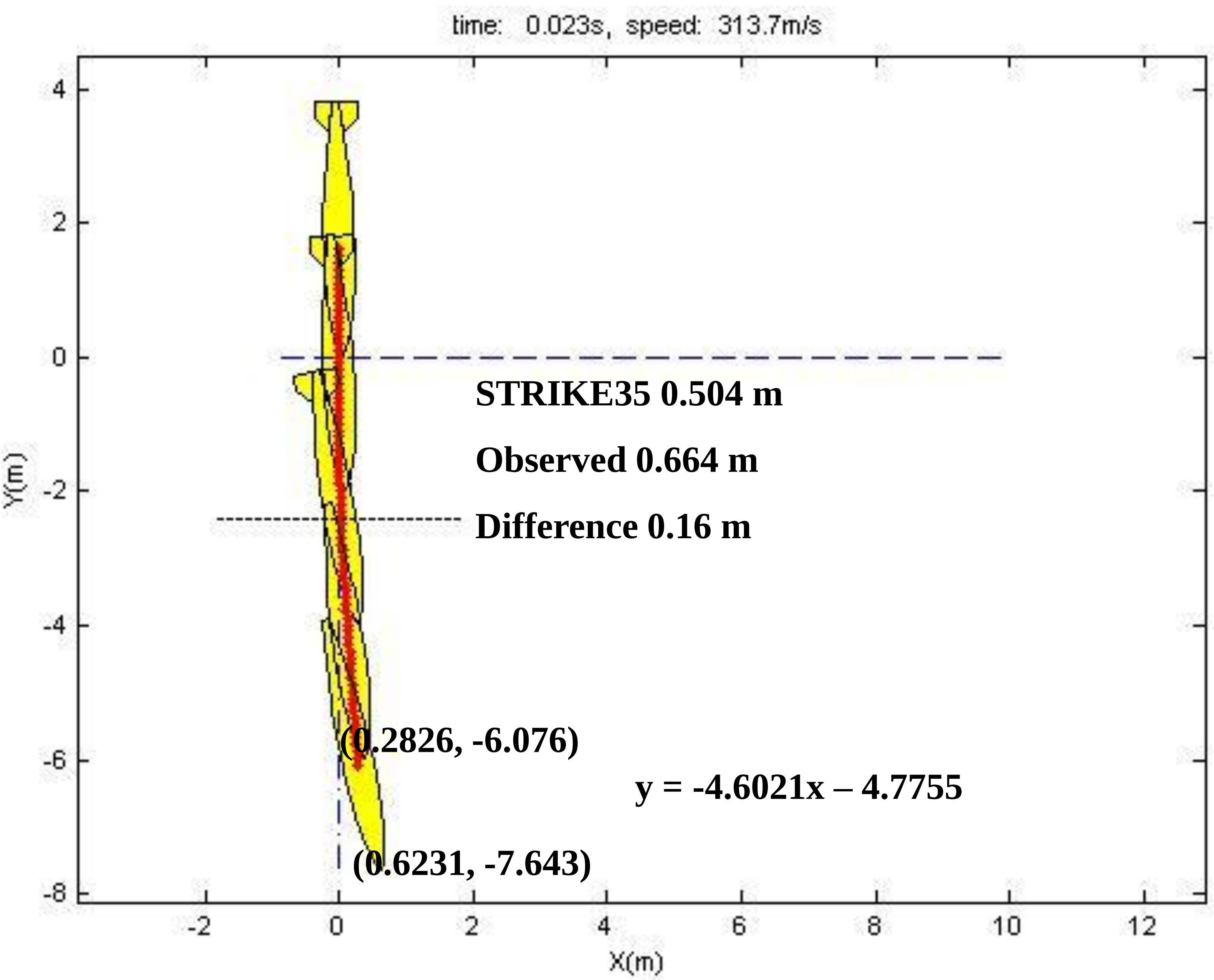
Stand Off Assault Breaching Weapons Fuze Improvement (SOABWFI)



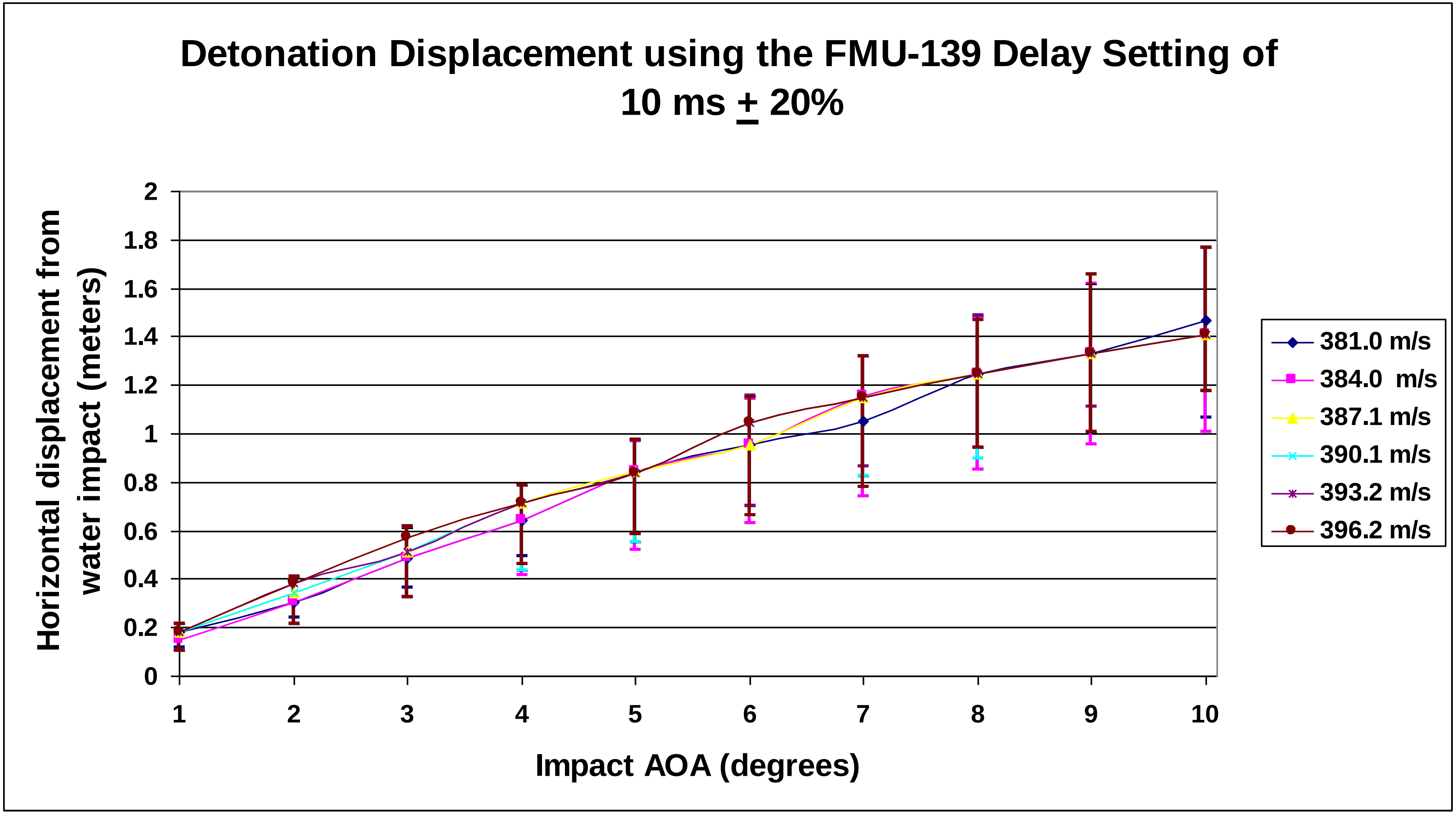
Test pond at China Lake with JDAM near impact (25 ft deep)

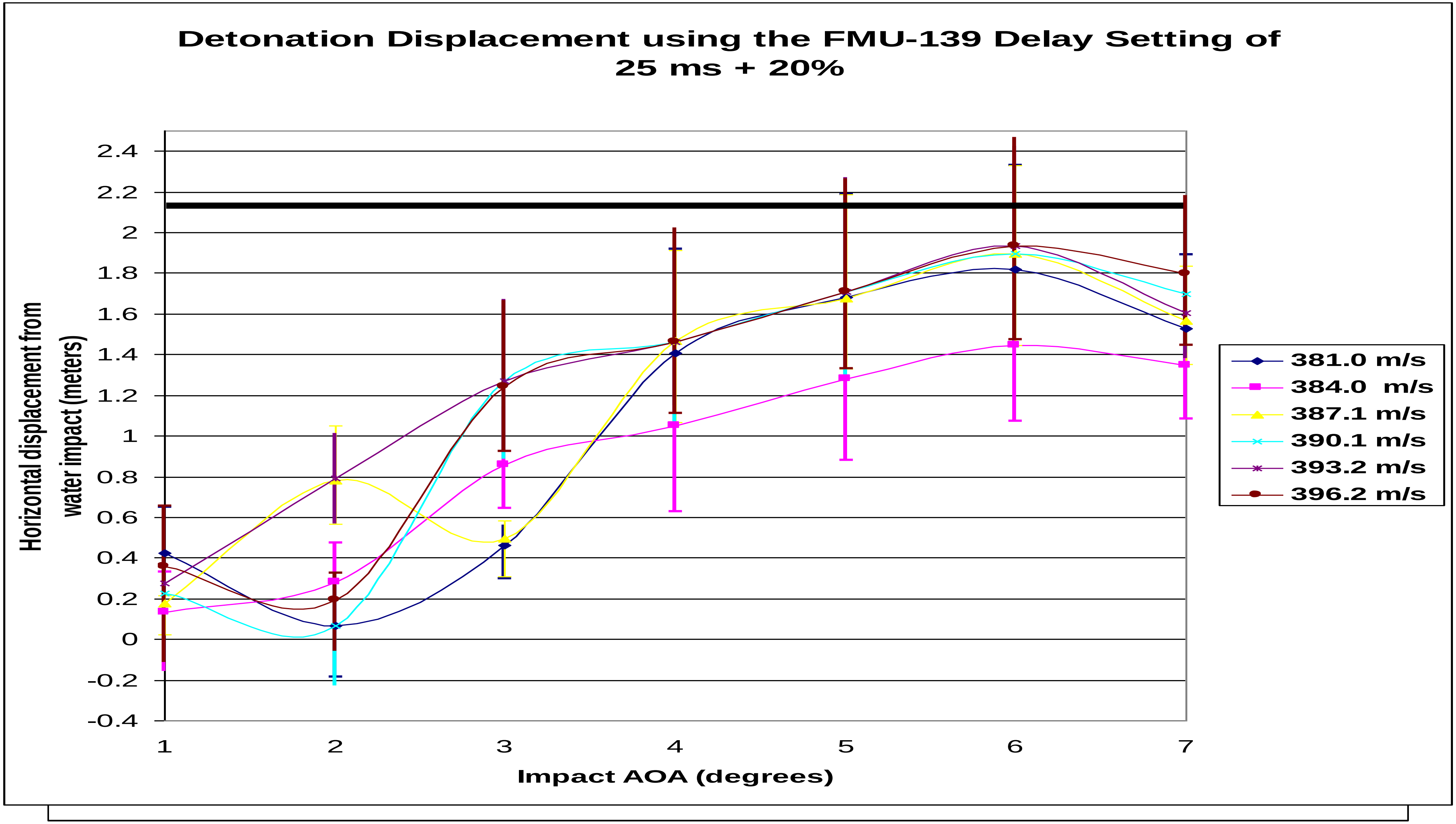
Provided by Boeing/ATR Corp

[redacted]


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

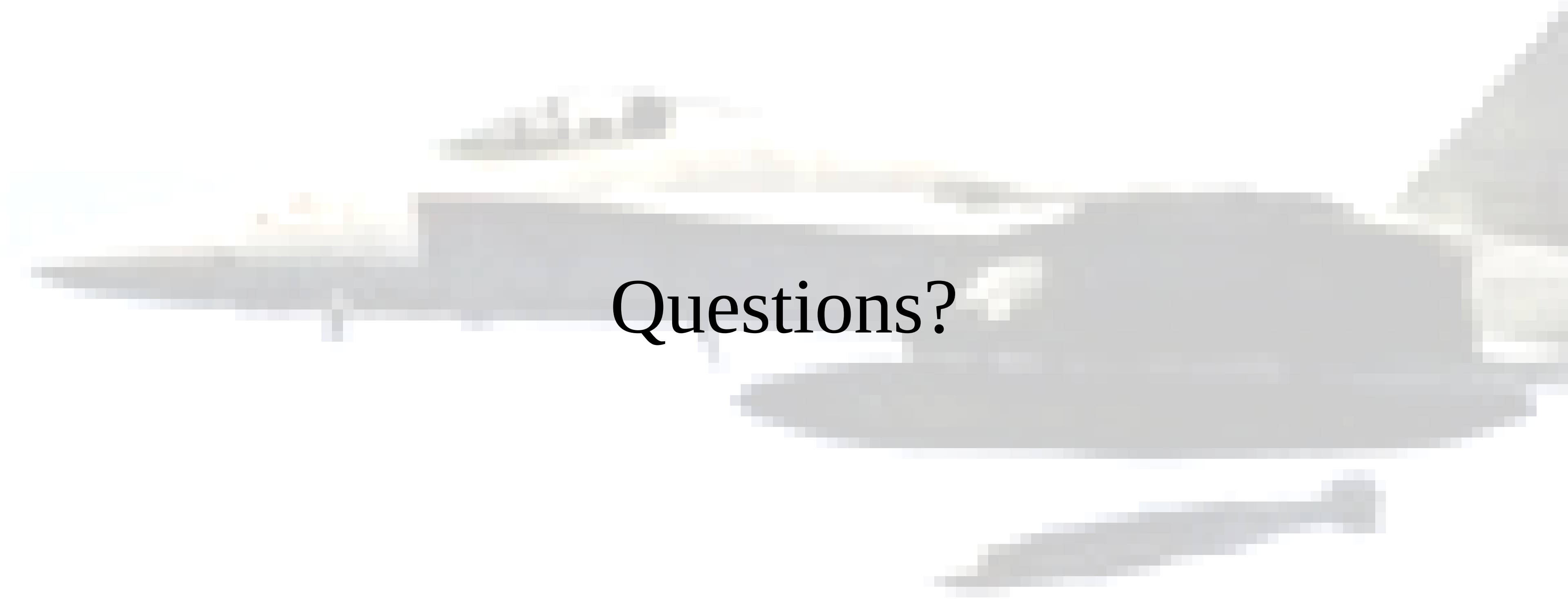
Experiment	Tail Separation Depth (m)	Model Displacement (m)	Observed to Model Distance (m)
UTT-1(2)	NA	0.43	0.24
UTT-1(2)	4.6	0.44	0.23
UTT-1(2)	3.0	0.50	0.17
UTT-1(2)	2.4	0.62	0.05
UTT-1(3)	NA	0.48	0.09
UTT-1(3)	4.6	0.48	0.08
UTT-1(3)	3.0	0.56	0.01
UTT-1(3)	2.9	0.57	0.00
UTT-2(2)	NA	1.23	-0.80
UTT-2(2)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


Detonation Displacement using the FMU-139 Delay Setting of
10 ms ± 20%
Horizontal displacement from water impact (meters)
Impact AOA (degrees)
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
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

Conclusions

- Trajectory/deviation is sensitive to changes in impact AOA, especially when it is above 2^{o}
- 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^{o}
  - 10 ms delay → no limitation on impact AOA
  - 25 ms delay → remain below 4^{o} impact AOA



Questions?