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

Peter C. Chu
Naval Postgraduate School, USA

Brian Almquist
Office of Naval Research and Naval Postgraduate School, USA

Paul Gefken
SRI International, USA

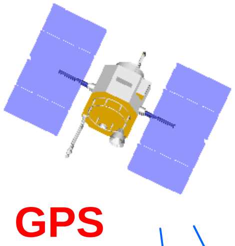
Kennard Watson
Naval Surface Warfare Center-Panama City, USA

European Undersea Defense Technology, Carnes, France, 9-11 June 2009

Collaborators & Contributors

- Jack Goeller, ATR Corp
- Jim Markarski, Boeing
- LCDR Charles Allen, Naval Postgraduate School
- LCDR Jillene Bushnell, Naval Postgraduate School
- LCDR Greg Ray, Naval Postgraduate School
- C.W. Fan, Naval Postgraduate School
- Ronald Betsch, Naval Oceanographic Office, Stennis Space Center, Mississippi

Future Assault Breaching System Operational Scenario



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

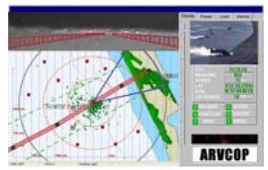
2. Mission Planning. MEDAL/JMPS plan routes and incorporate intel data from recon units. Crews rehearse mission.

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.

2



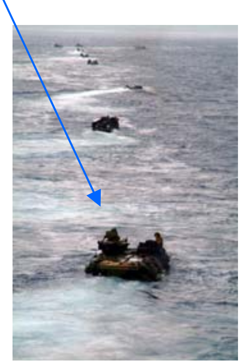
Comm Station

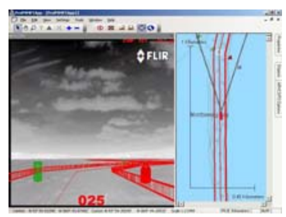
5

1

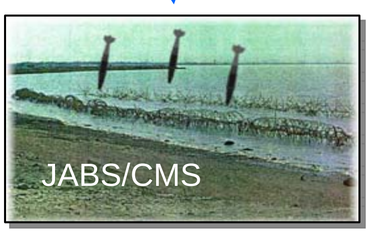
INFORMATION SHARING EPLRS, BFT, DAGR

4





3



DAGR

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

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

GBU-31(V)2/B Precision Guidance

JDAM Tail Kit

Standoff Delivery Platform

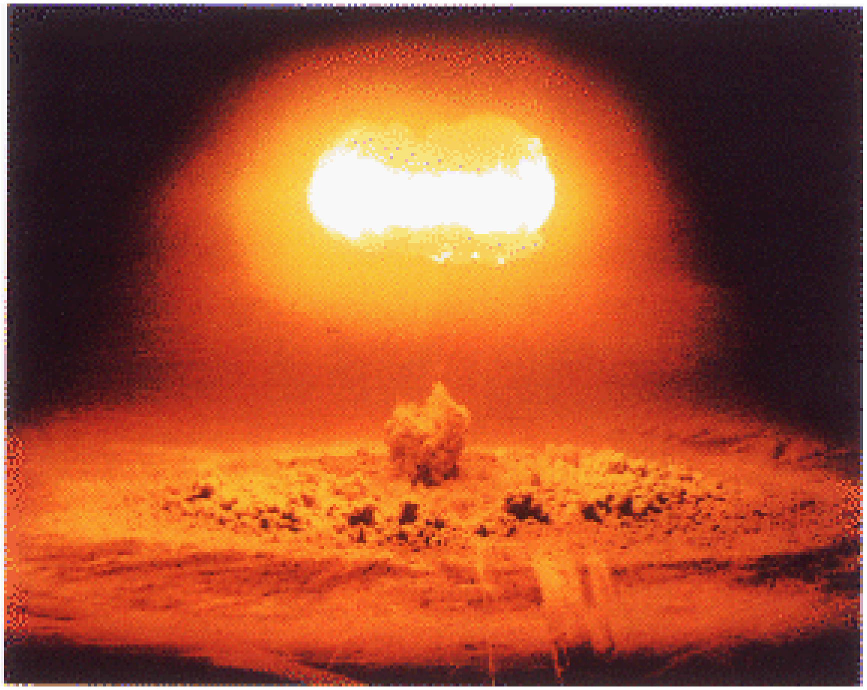
SZ & BZ Countermine & Counterobstacle

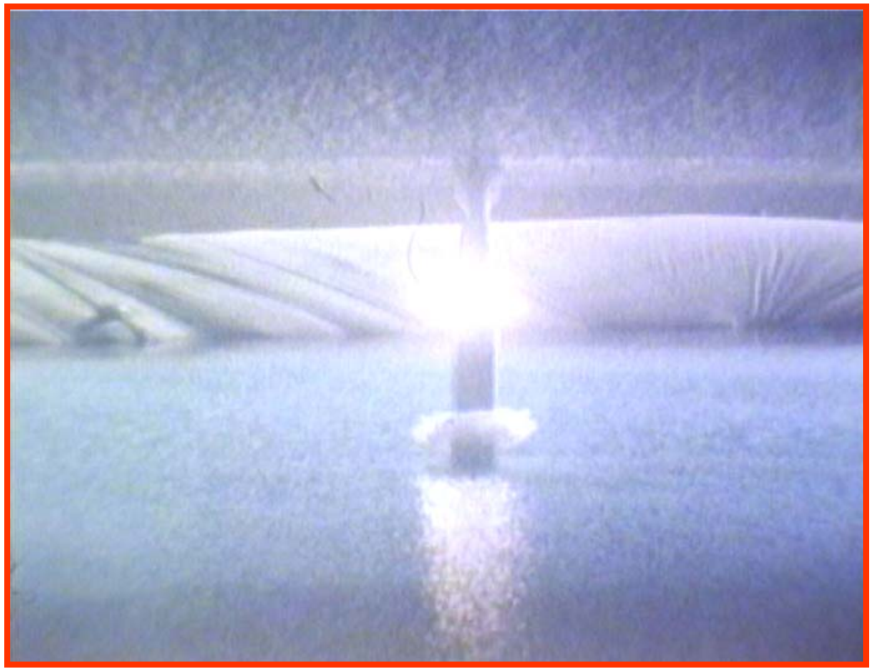
- **Current capability to clear SZ/BZ mines and light obstacles on the beach**
- **USN and/or USAF Delivered, Signed MOA between USN & USAF for Assault Breaching Munitions Delivery**
  - **B1, B2, B52, F/A18, JSF**
- **New mission for an existing weapon system**

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

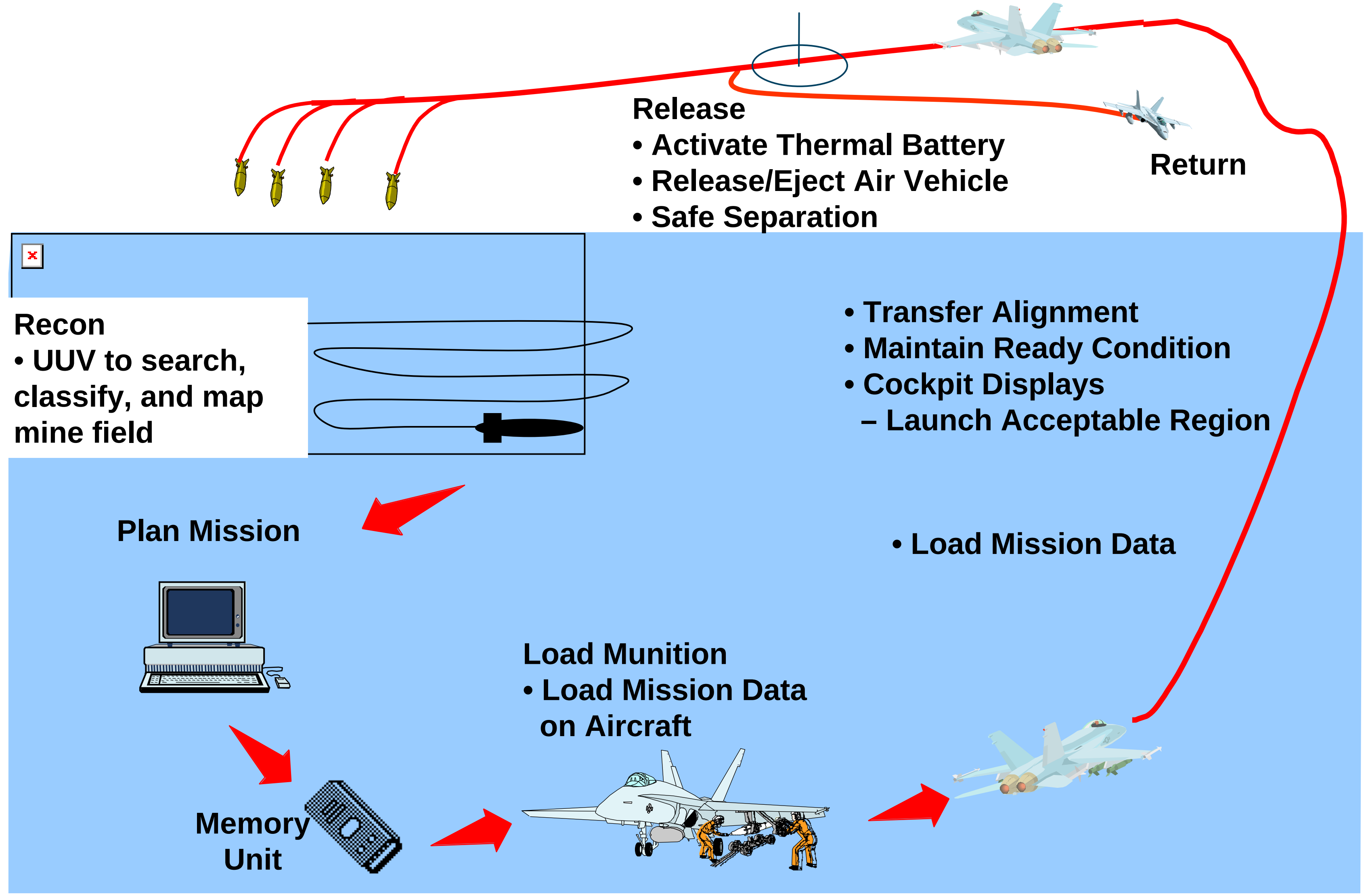
Successful breaching in beaches/surf zones by Joint Direct Attack Munition (JDAM) Assault Breaching System (JABS)

(from Almqist 2006)



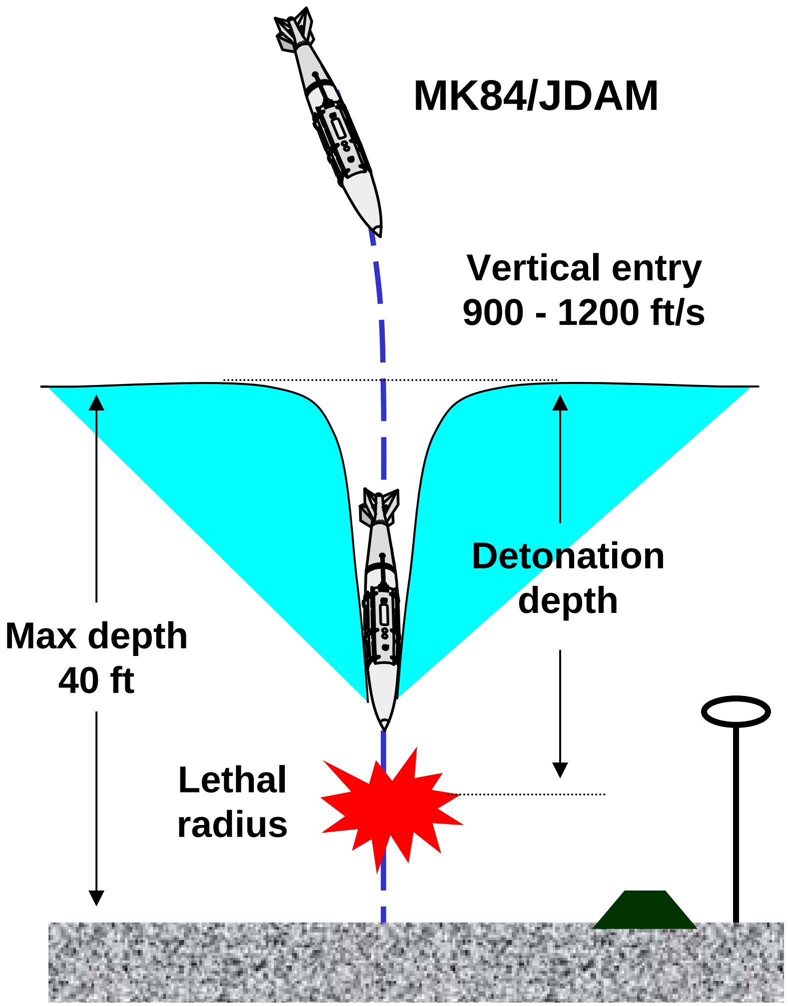


Mission Execution CONOPS



No Change to JDAM Mission Execution

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.

Sub-Scale Model Test Objectives

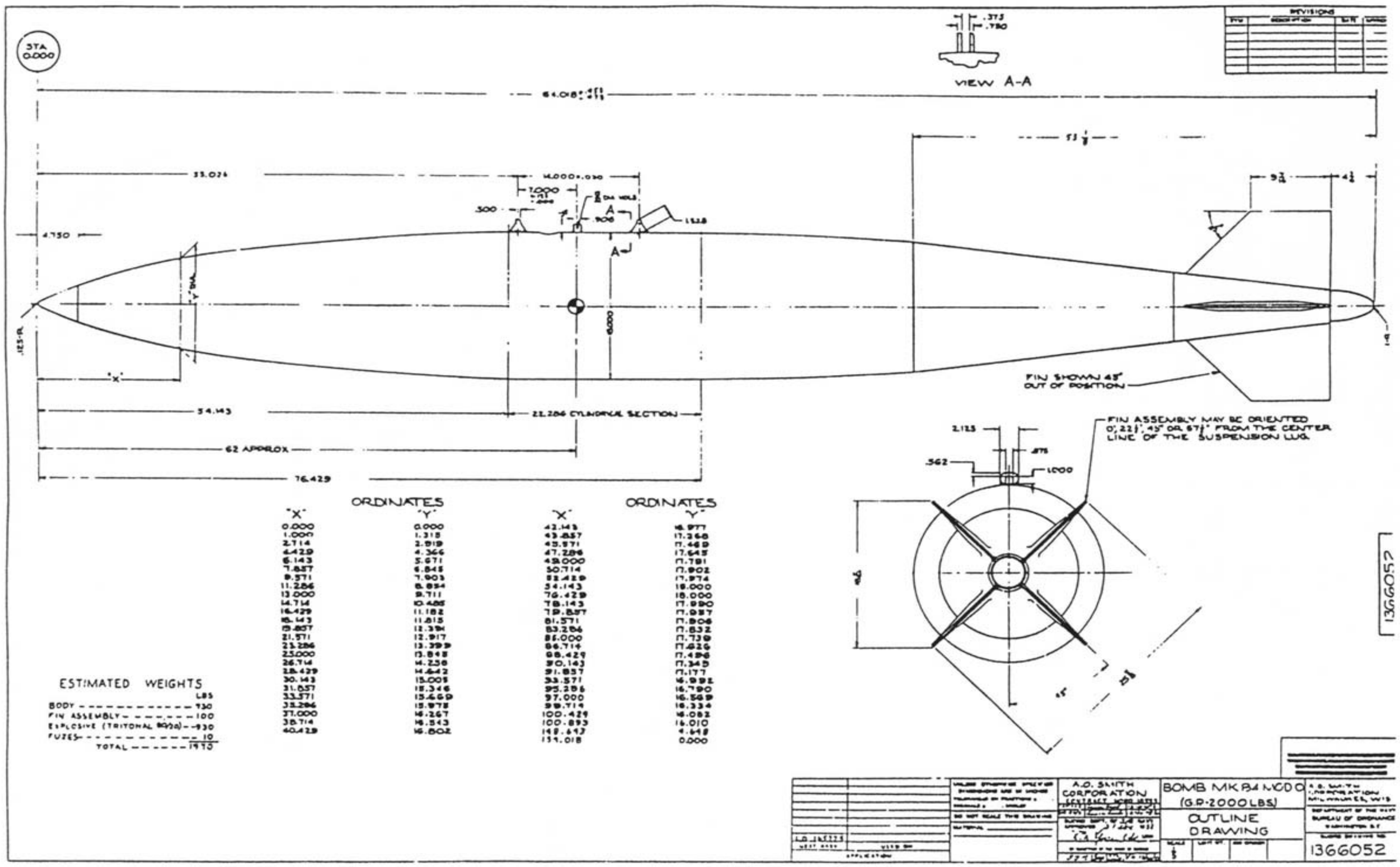
- Use 1/12-scale tests to measure Mk84 bomb trajectory to a shallow water full-scale depth of 160 ft and for a 90 degree water entry angle.

- 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

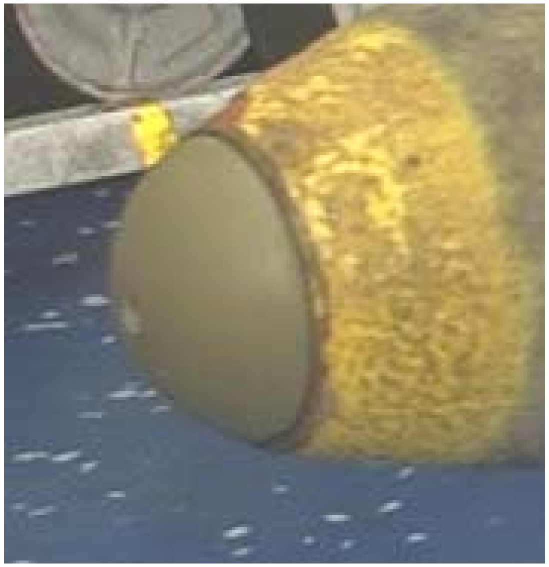
(With USN Ogive Nose)



Current Mk84 Bomb Nose Features

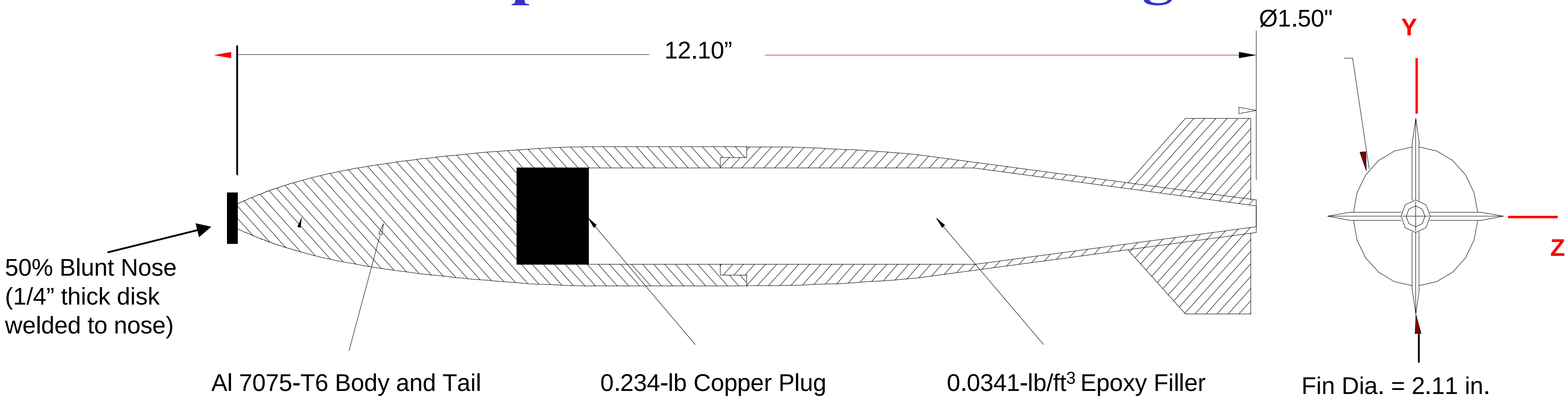
USN Ogive Nose

USAF Nose

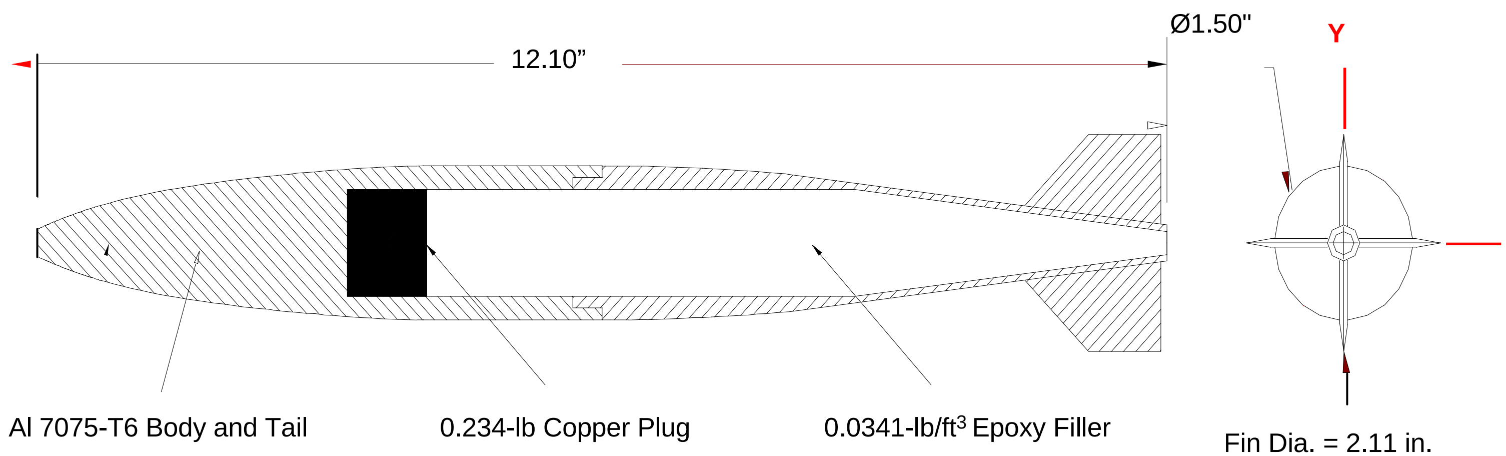


USN MXU-735 Nose

Conceptual Mk84 Nose Designs

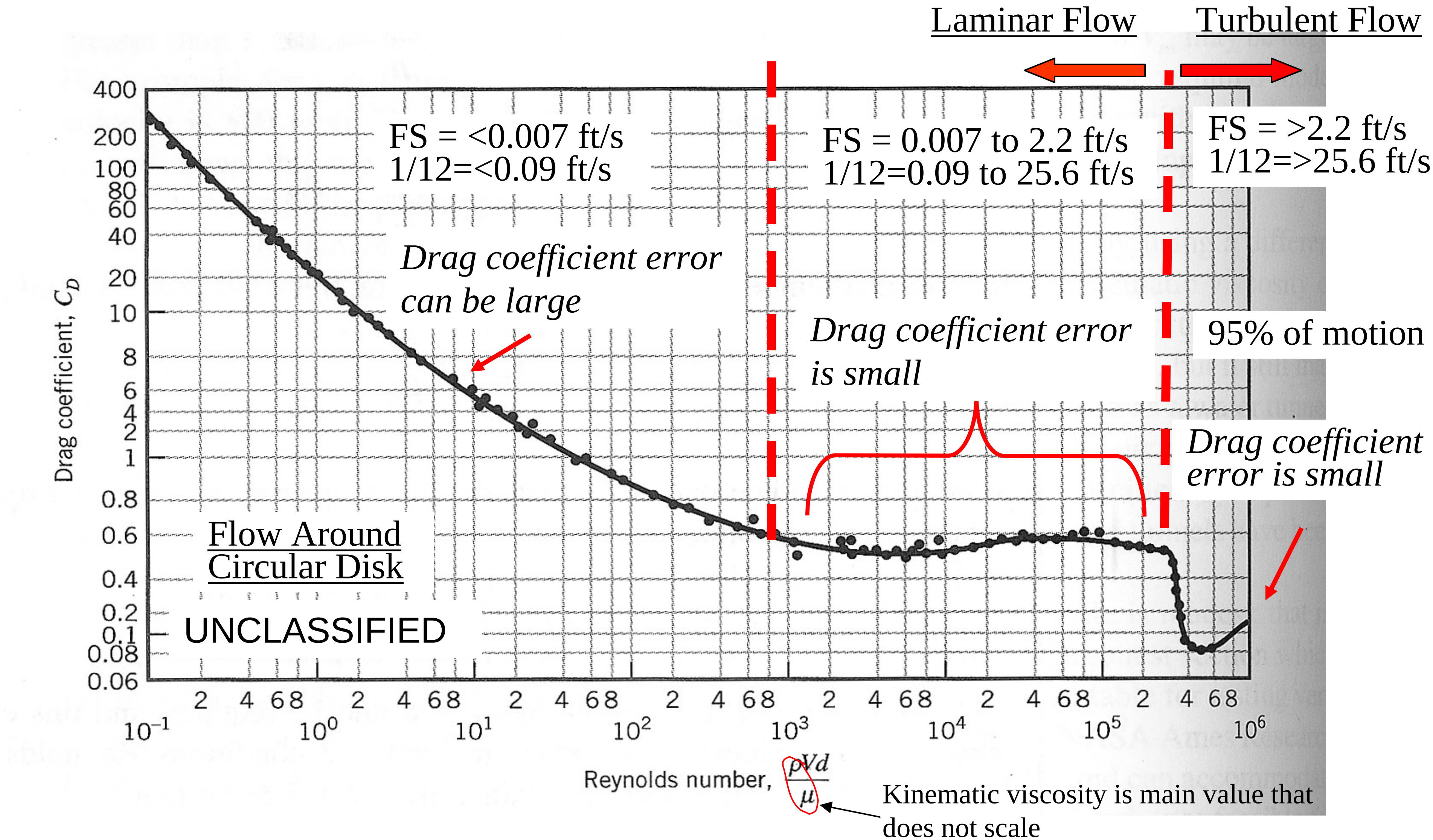


50% Blunt Nose



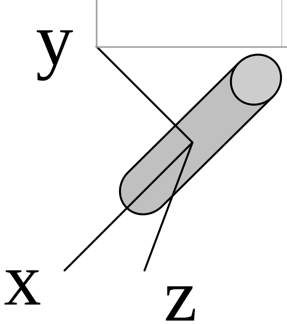
25% Blunt Nose

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

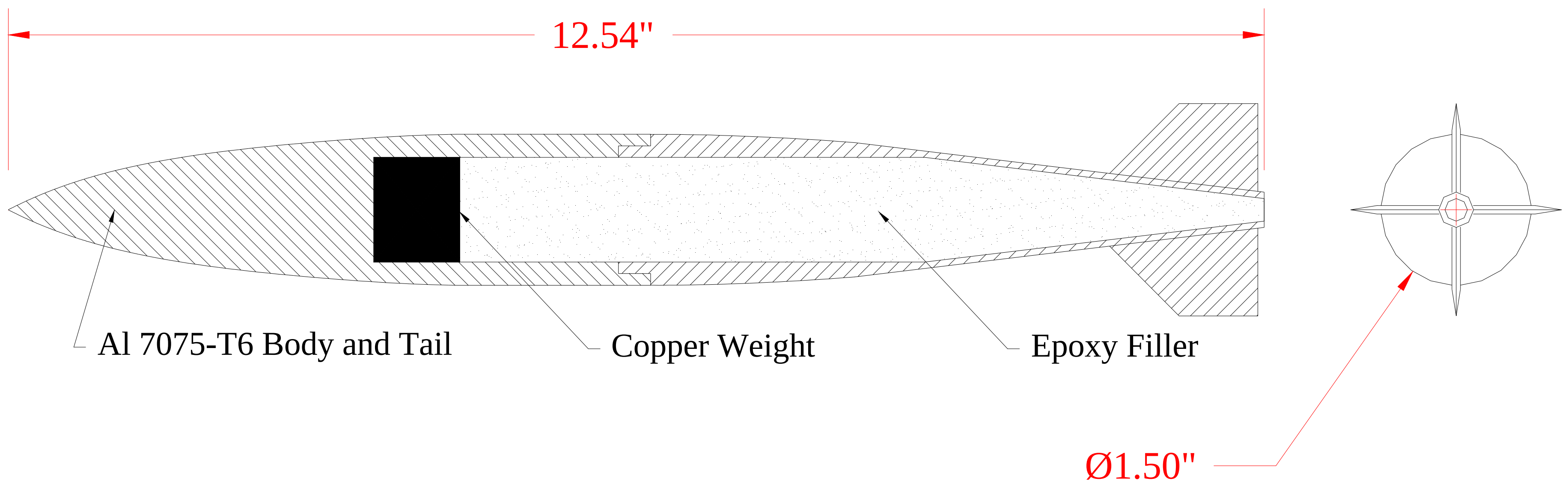


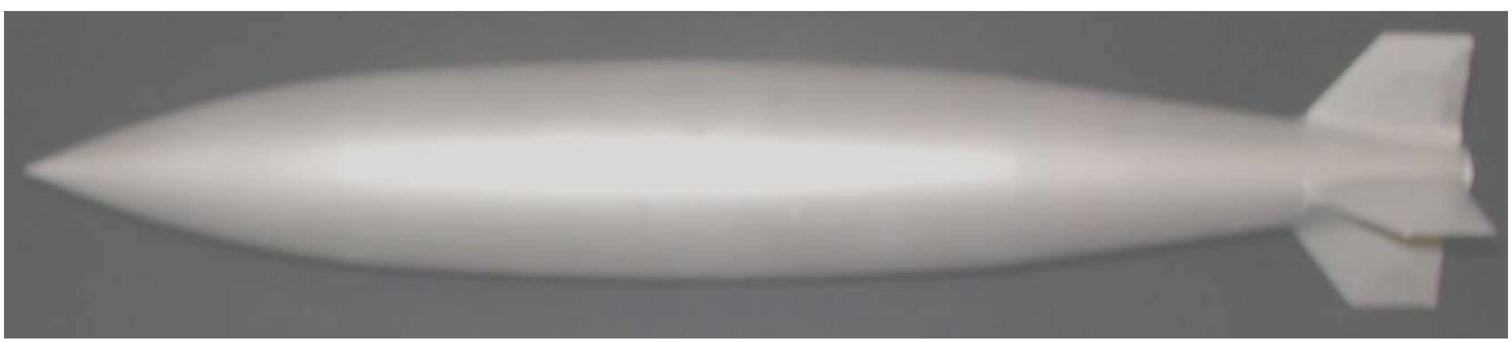
Due to neglecting casing lugs and strakes

Neglected because the bomb does not rotate about x-axis

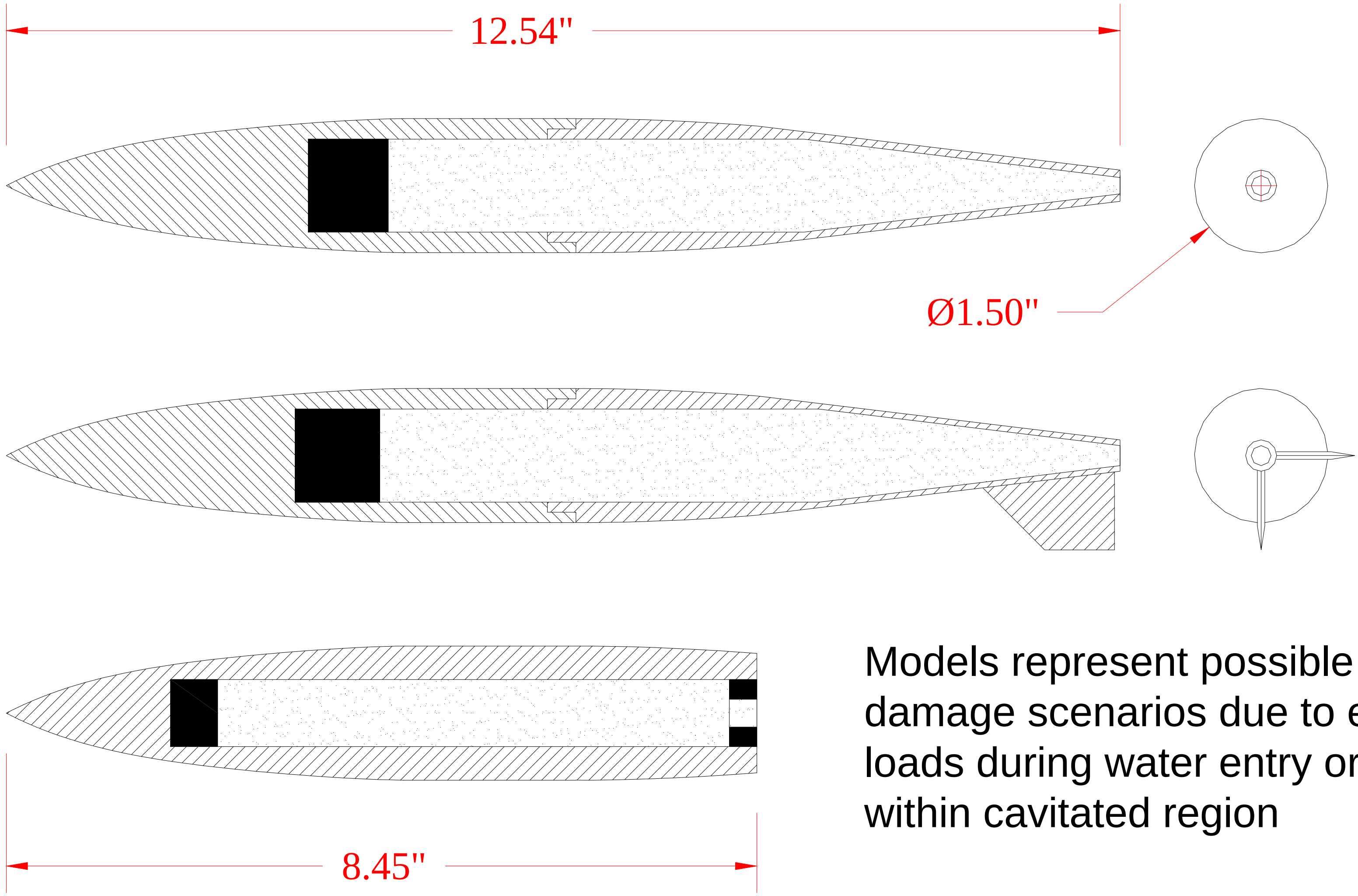
High-Fidelity 1/12-Scale Mk84 Scale Model - 4 Fins

UNCLASSIFIED





Tests With Simulated Fin or Tail Removal

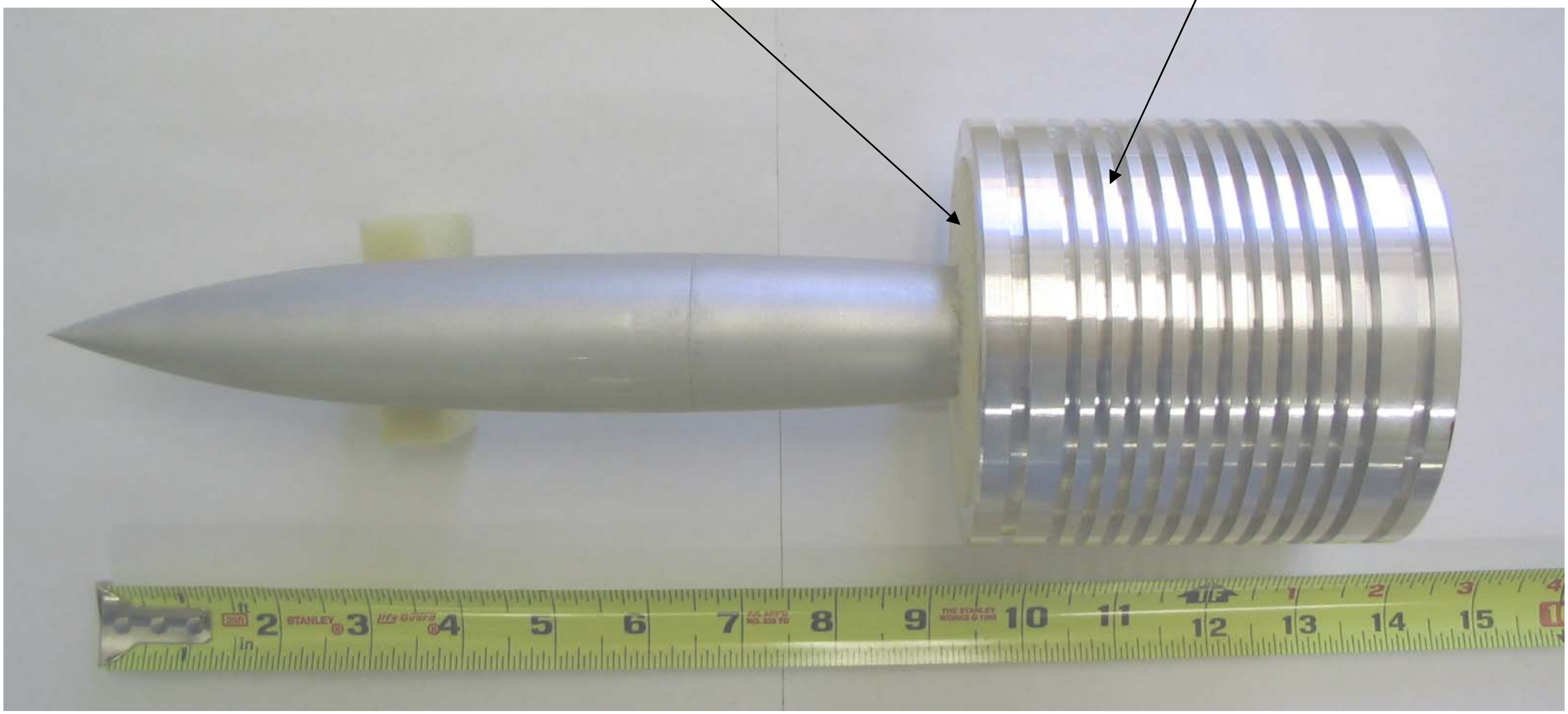


Models represent possible different damage scenarios due to excessive loads during water entry or tail slap within cavitated region

Sabot Design

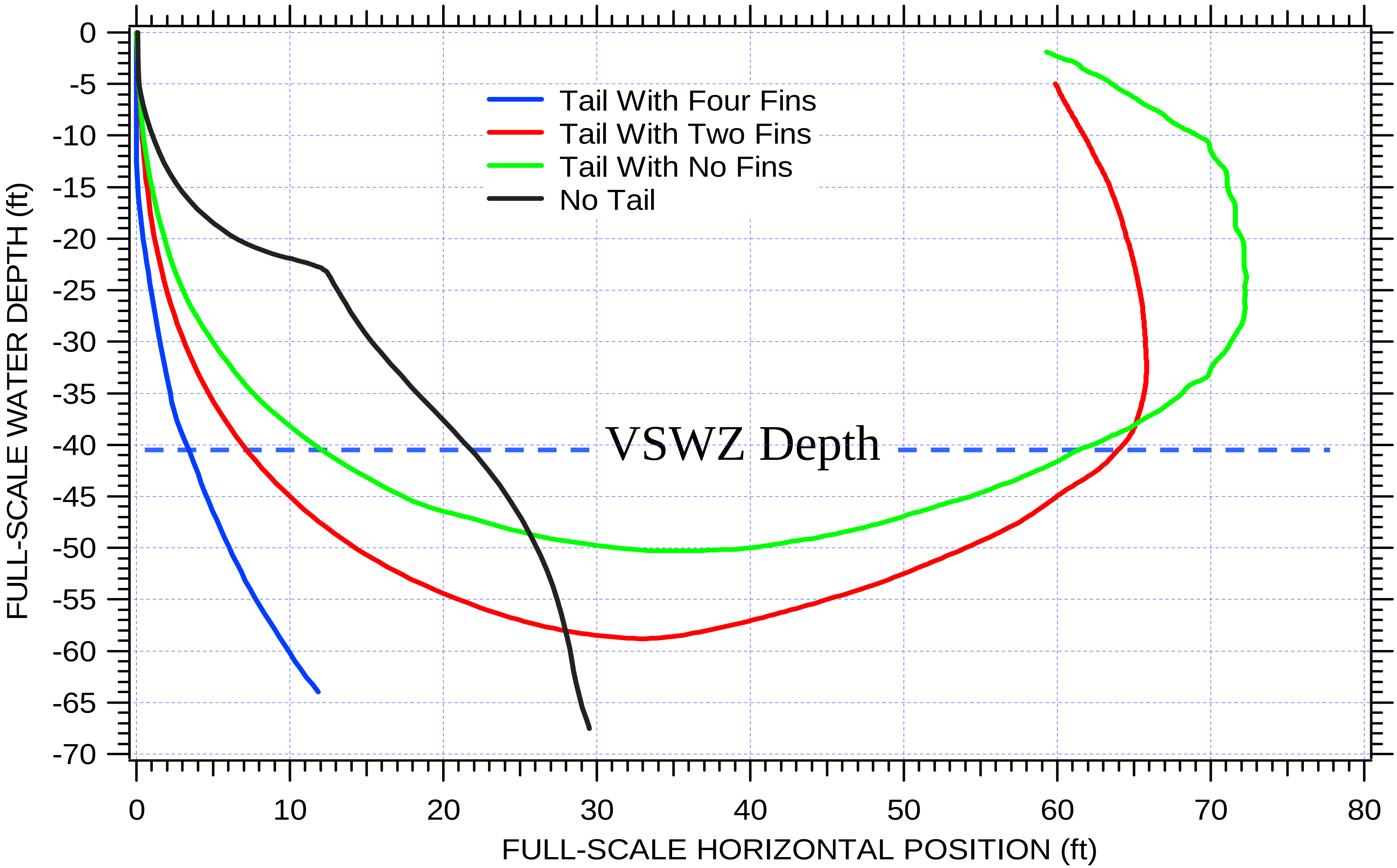
Low-Density Foam

Aluminum Crushable Sabot

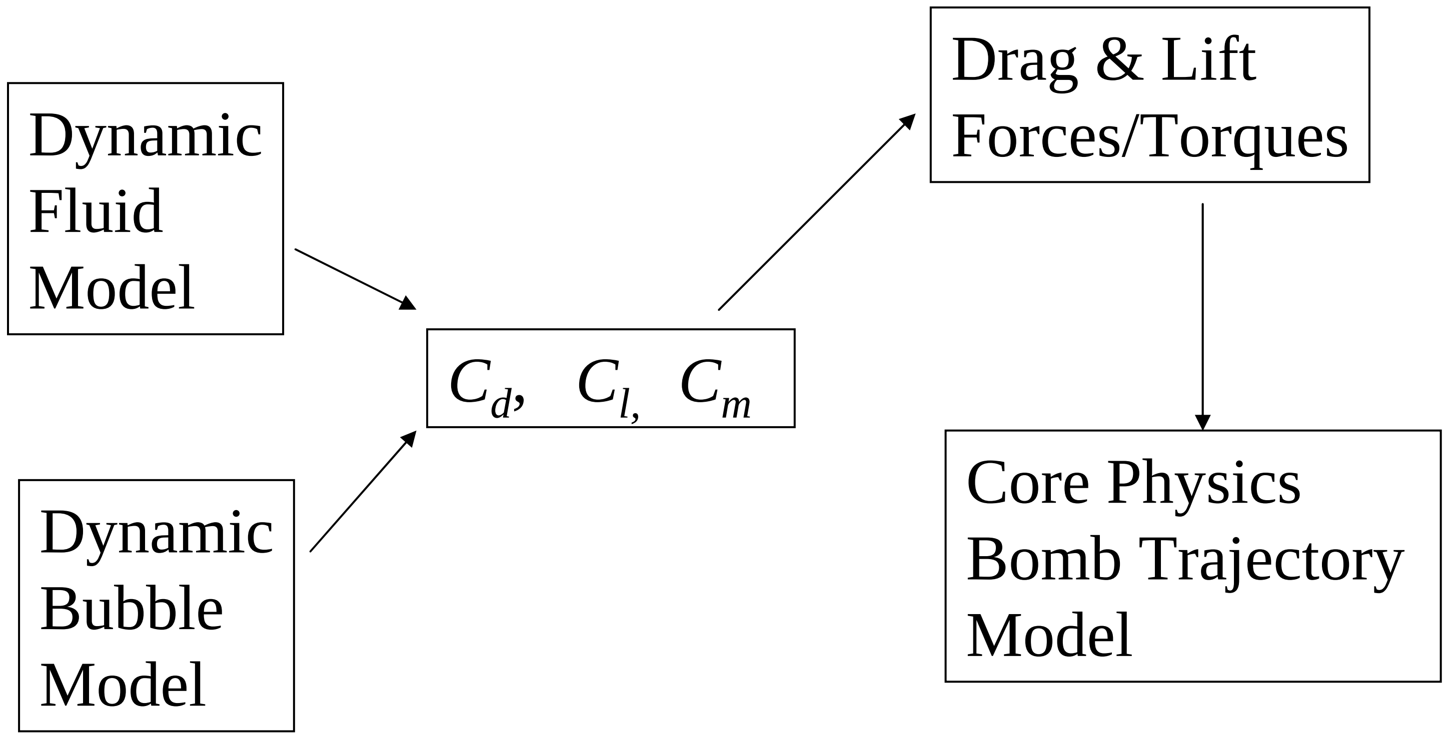


SRI Test Arrangement

1/12th Scaled Model Test Results

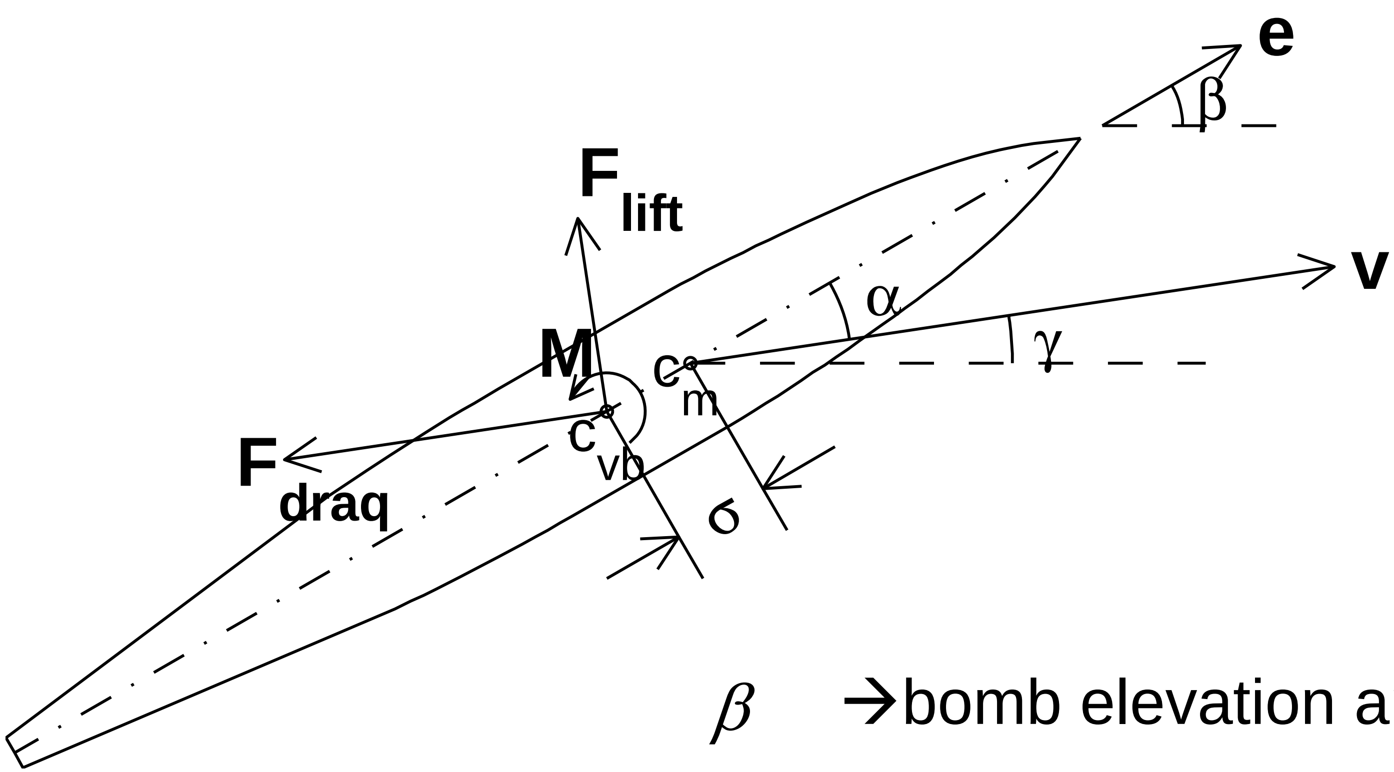


6-FOF Bomb Trajectory Model



There is no existing formulae for calculating C_d C_l C_m for MK-84 Bomb.

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.

Determination of C_d C_l C_m from Experimental Data

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

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

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

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

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)

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

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

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

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

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

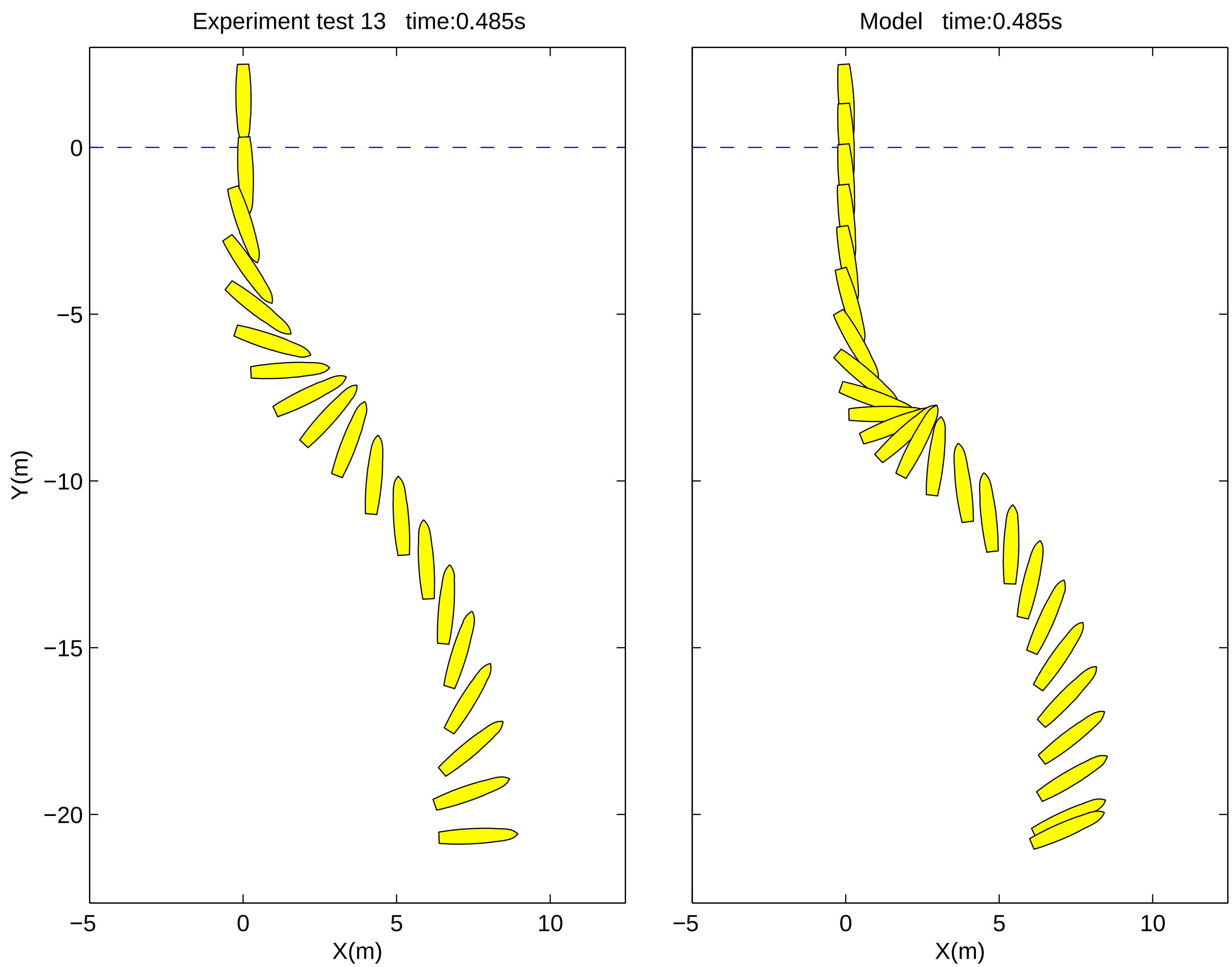
Semi-Empirical Formulas for C_m

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

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

UNCLASSIFIED

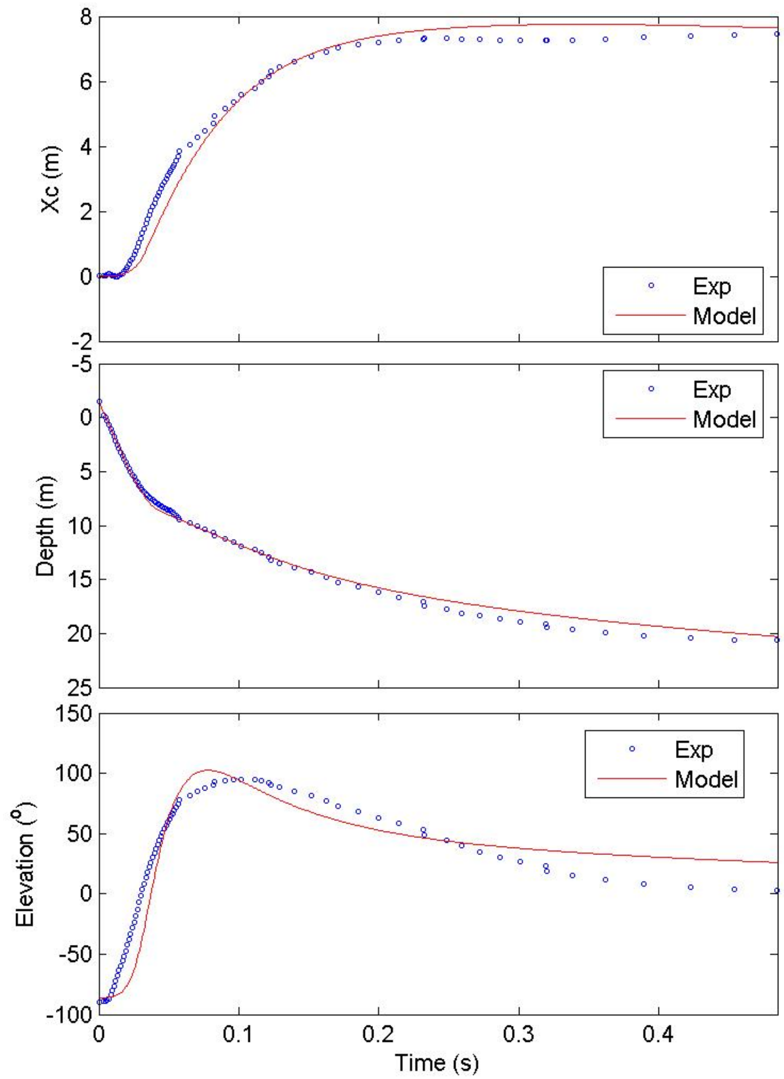
STRIKE35 and SRI Data Inter-Comparison Test-13



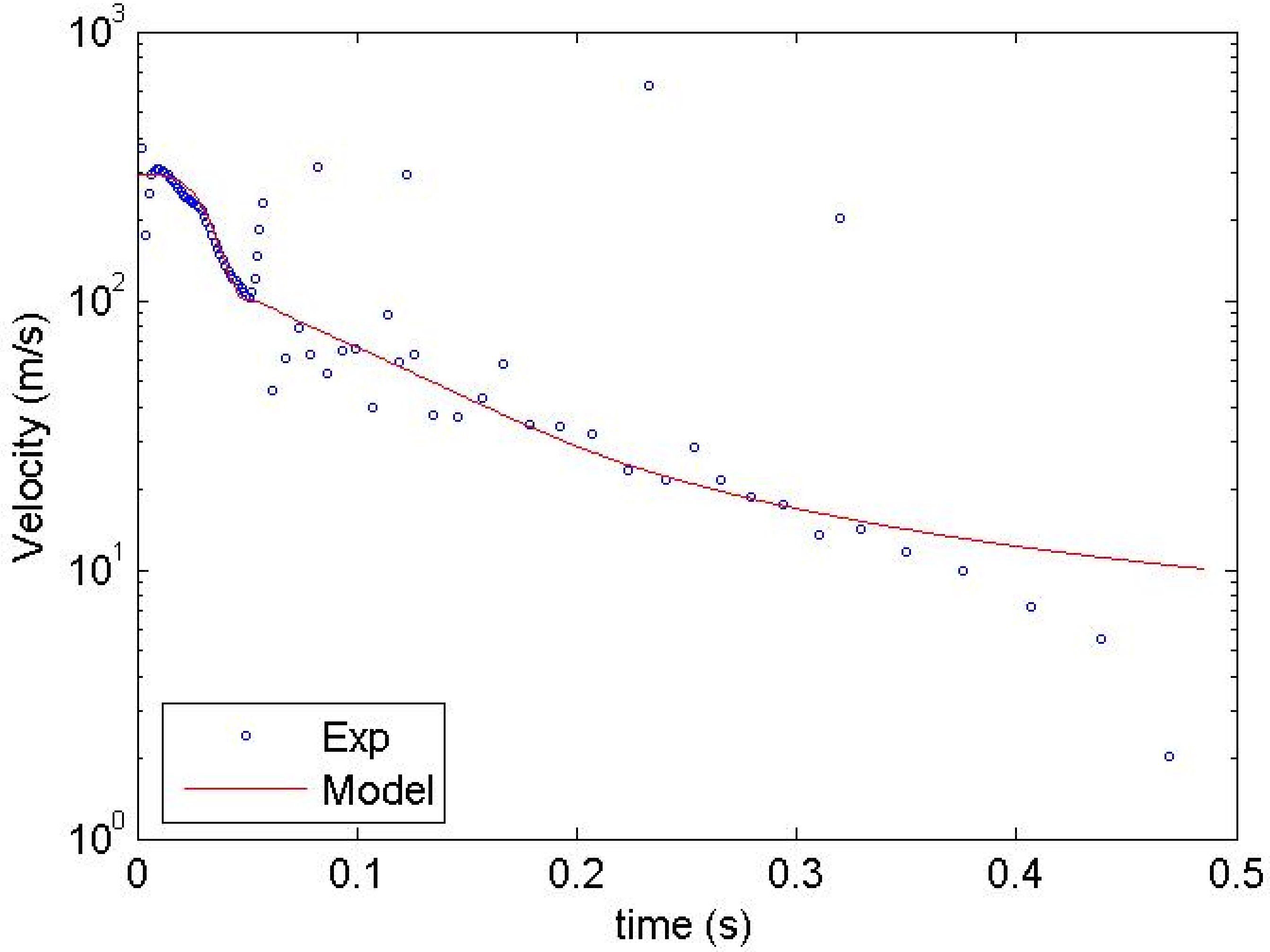
UNCLASSIFIED

STRIKE35 and SRI Data Inter-Comparison

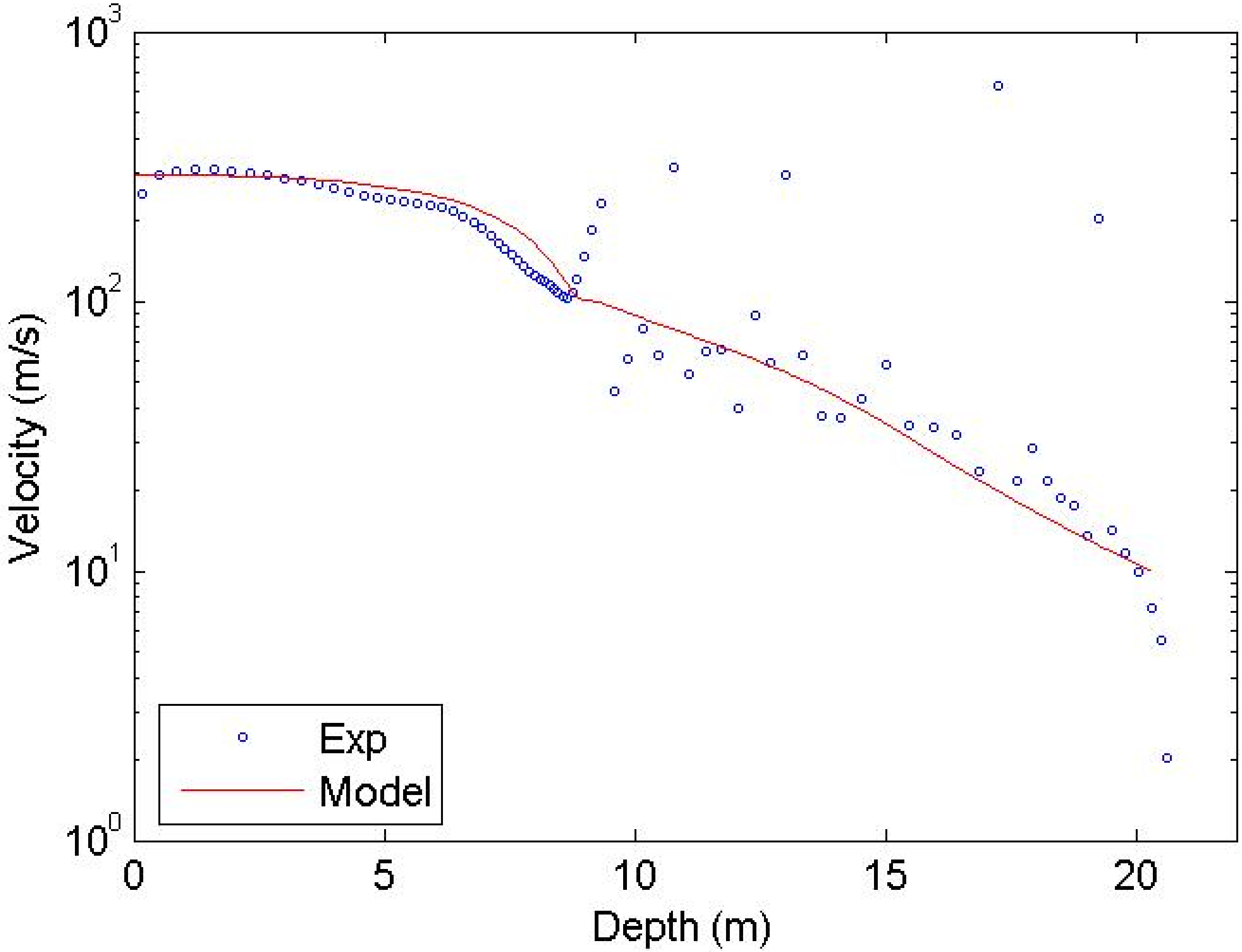
Test-13



STRIKE35 and SRI Data Inter-Comparison Speed vs Time (Test-13)

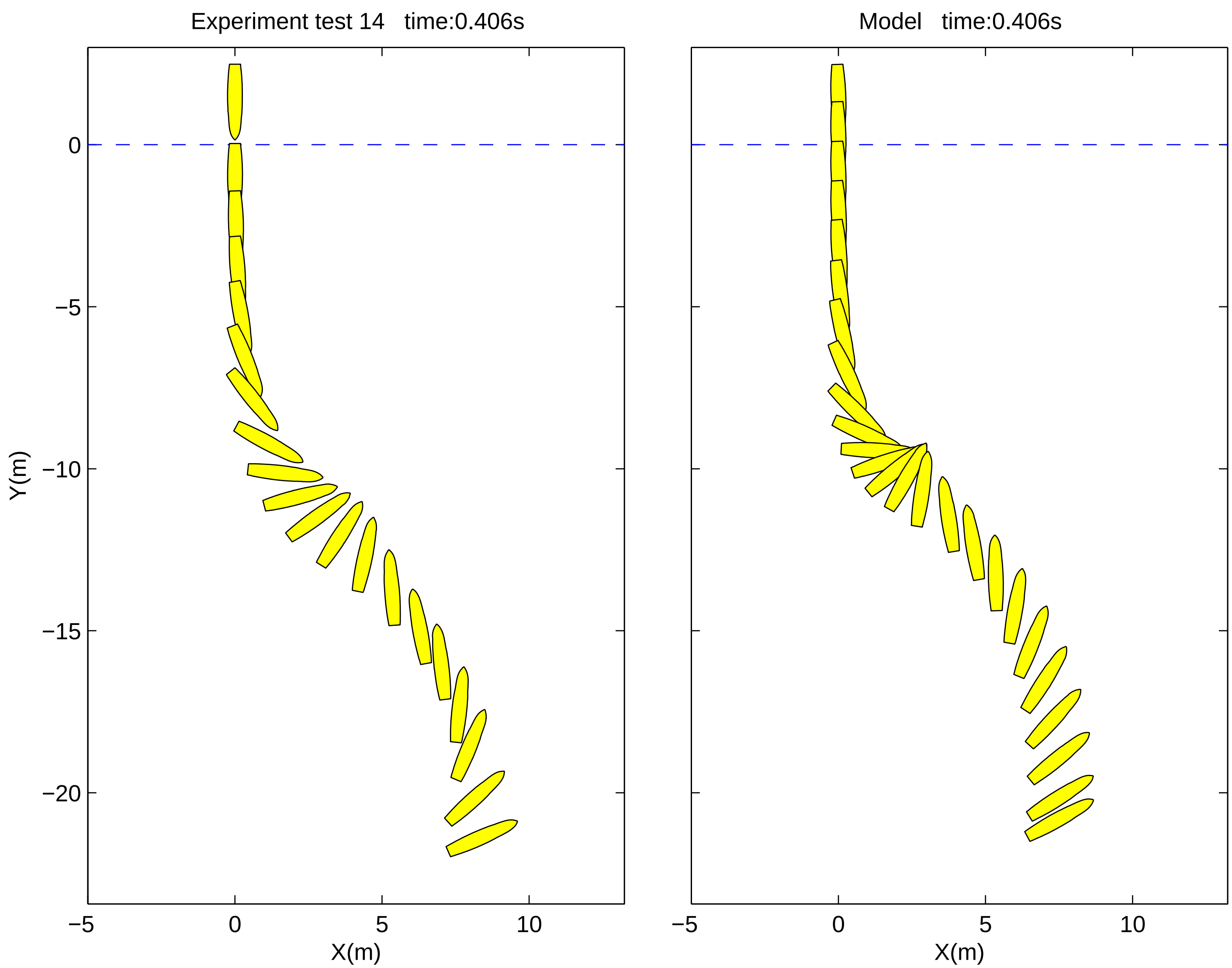


STRIKE35 and SRI Data Inter-Comparison Speed vs Depth (Test-13)



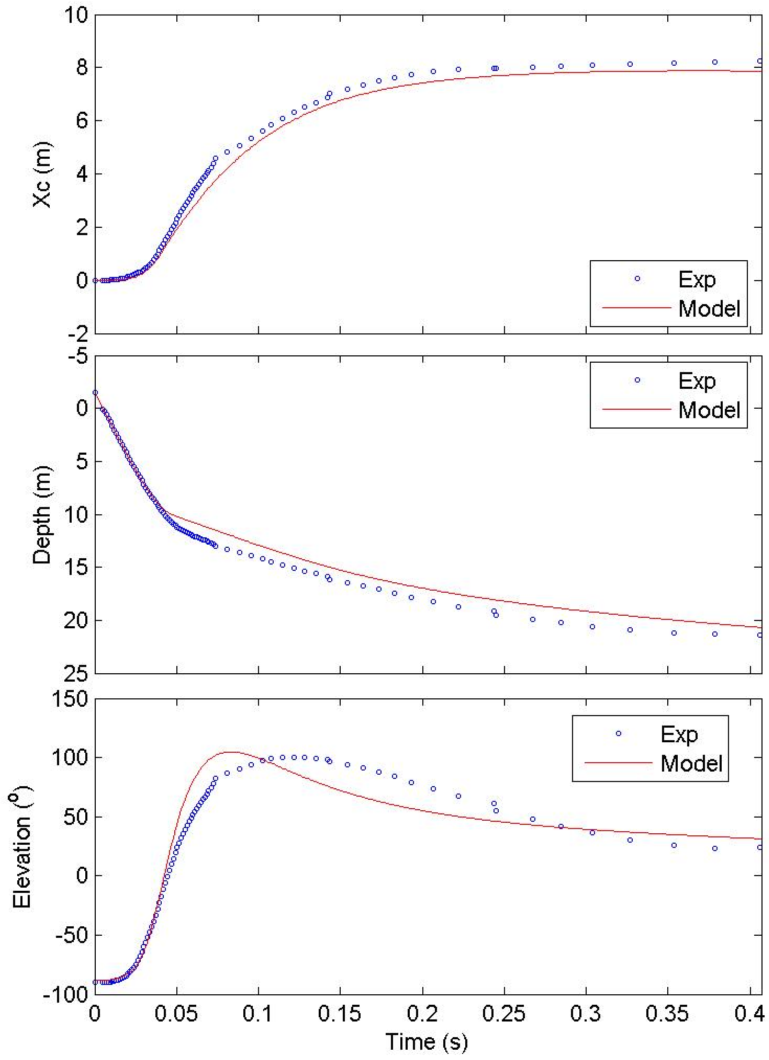
UNCLASSIFIED

STRIKE35 and SRI Data Inter-Comparison
Test-14

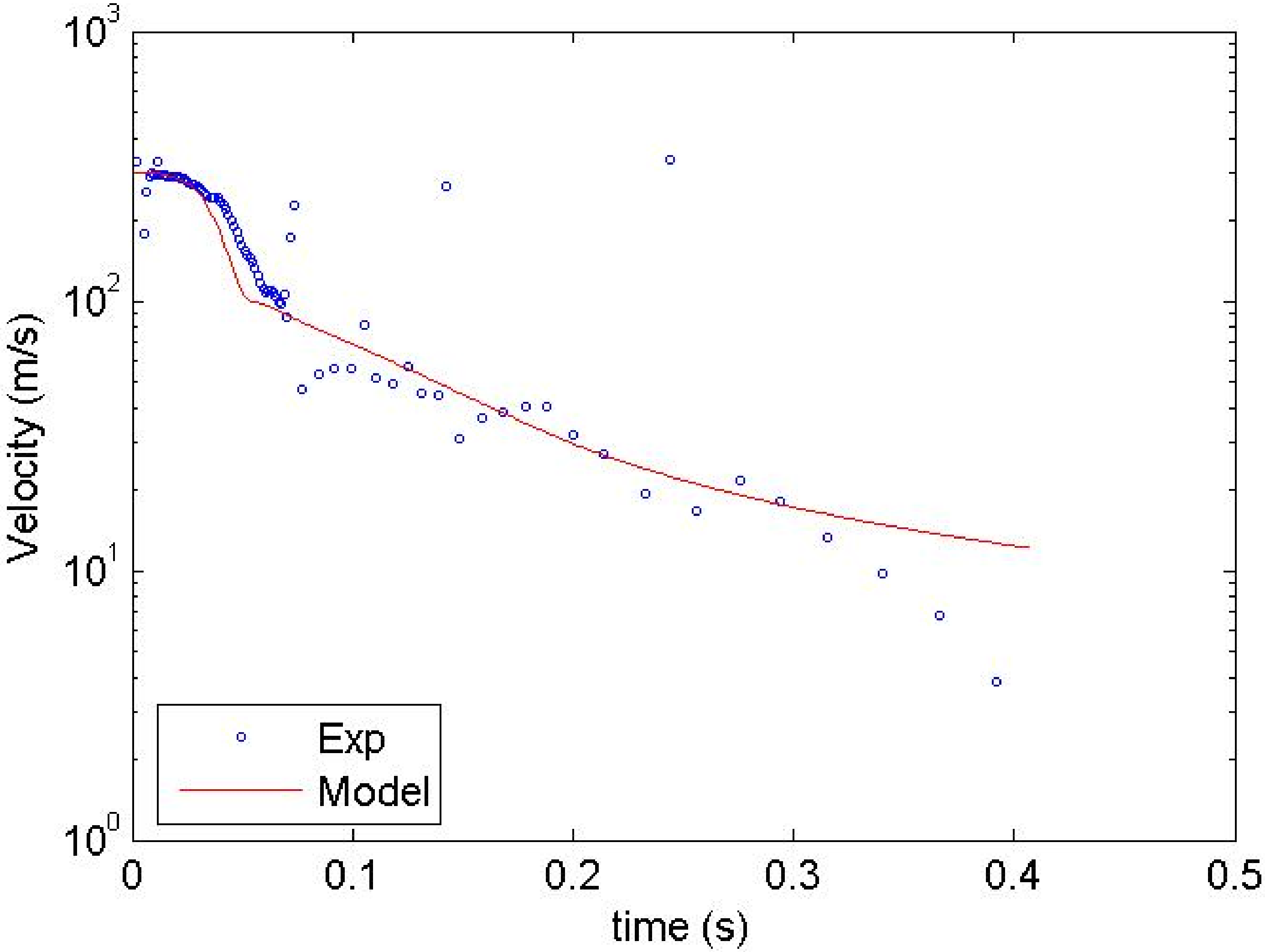


UNCLASSIFIED

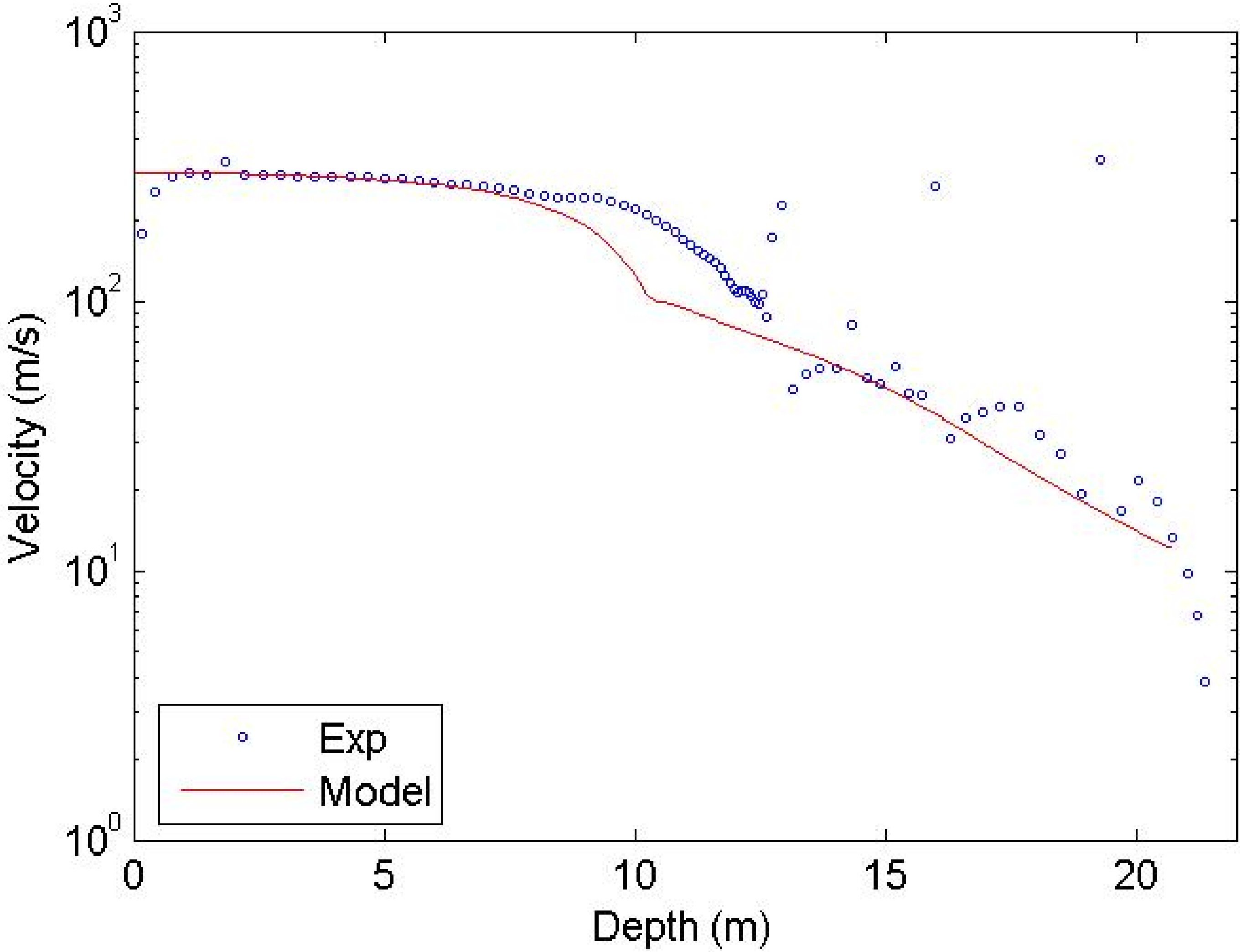
STRIKE35 and SRI Data Inter-Comparison Test-14



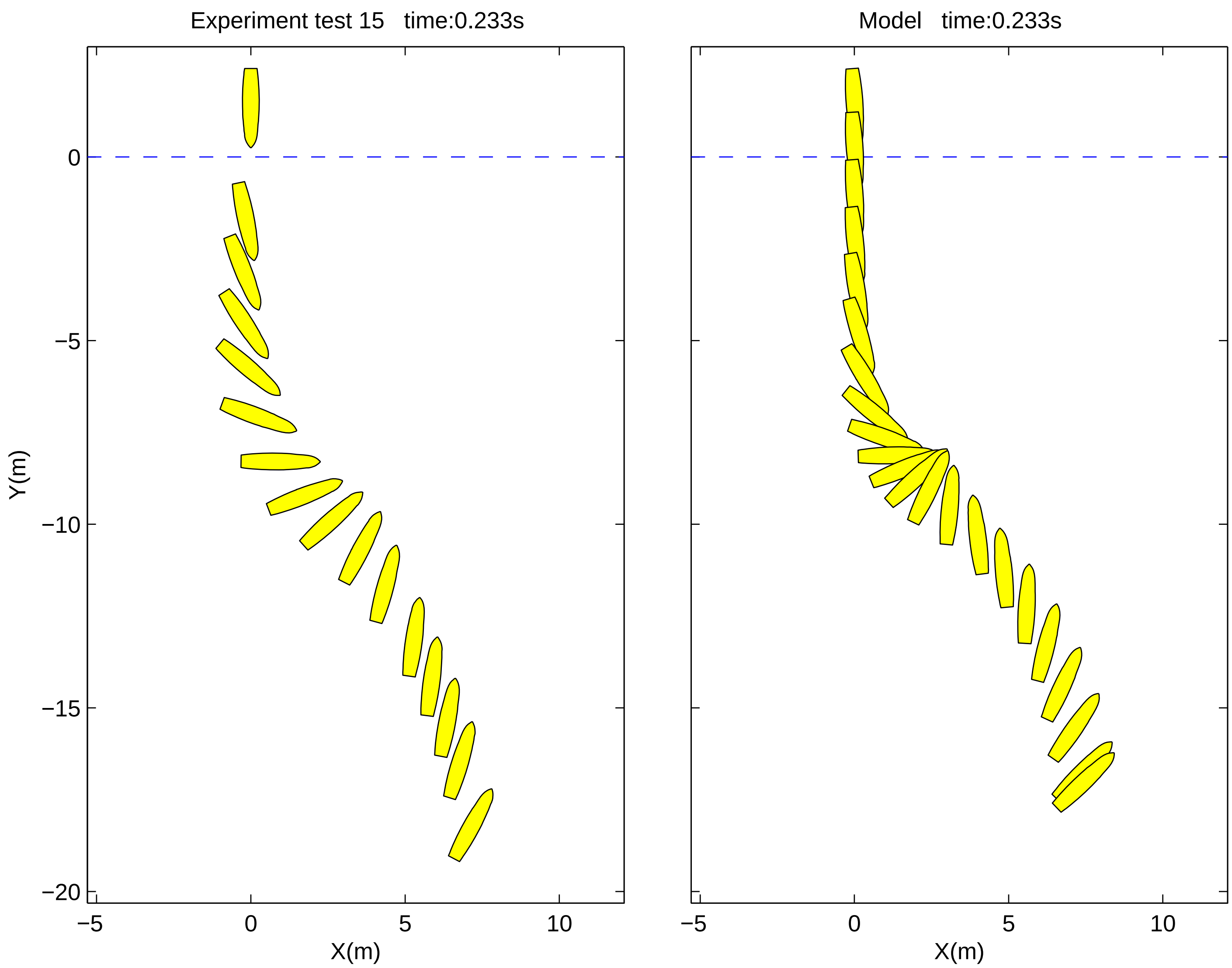
STRIKE35 and SRI Data Inter-Comparison Speed vs Time (Test-14)



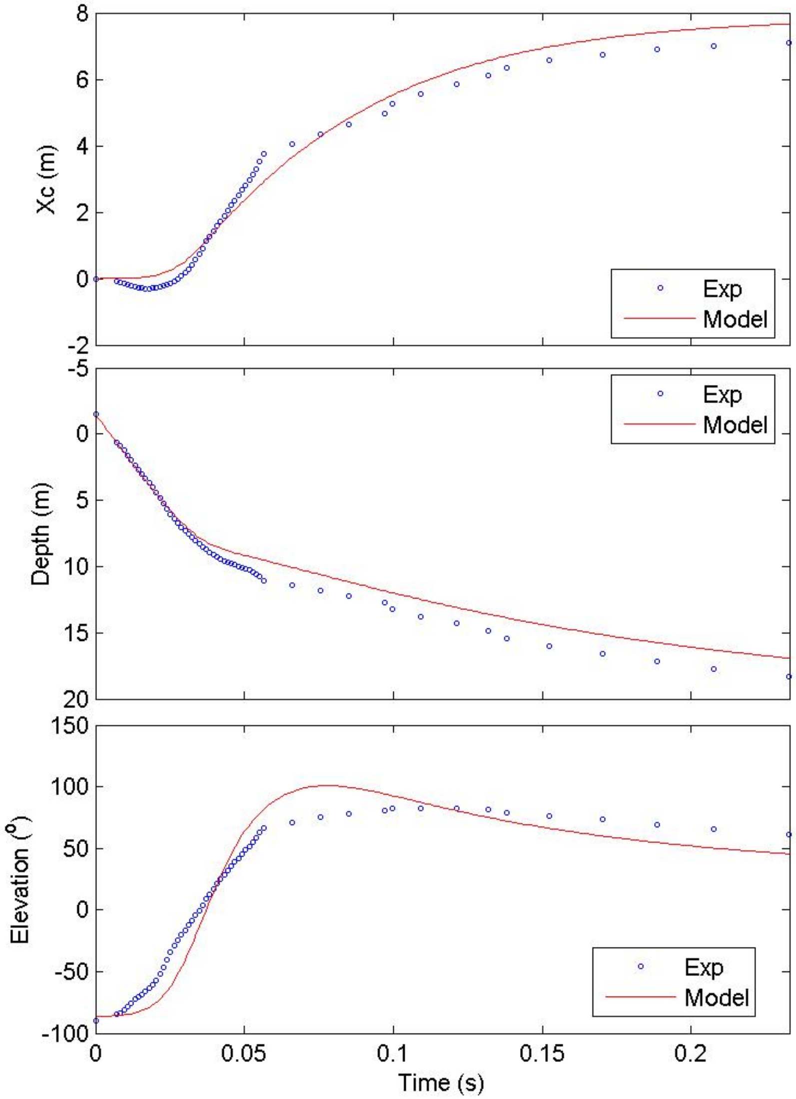
STRIKE35 and SRI Data Inter-Comparison Speed vs Depth (Test-14)



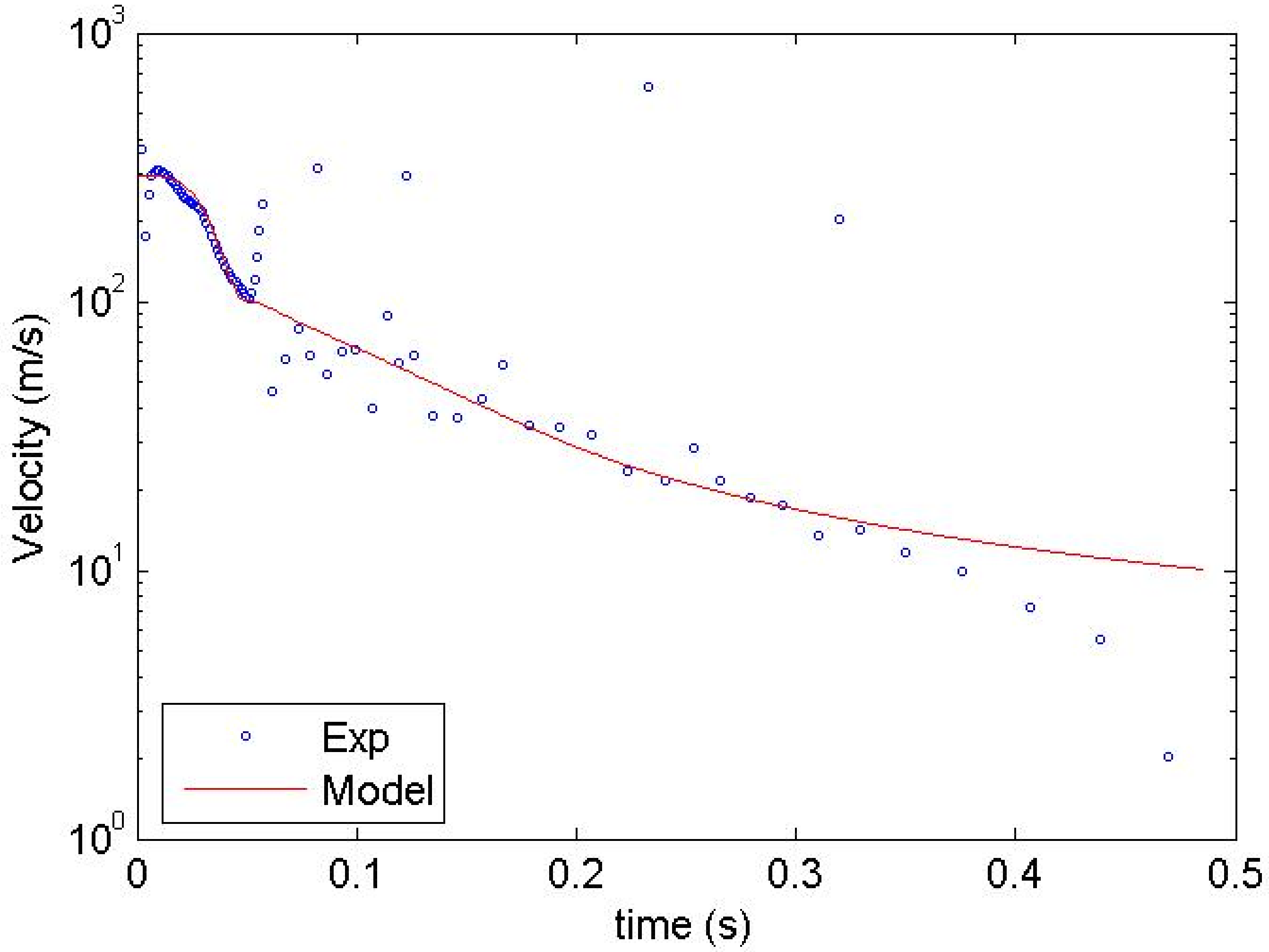
STRIKE35 and SRI Data Inter-Comparison
Test-15



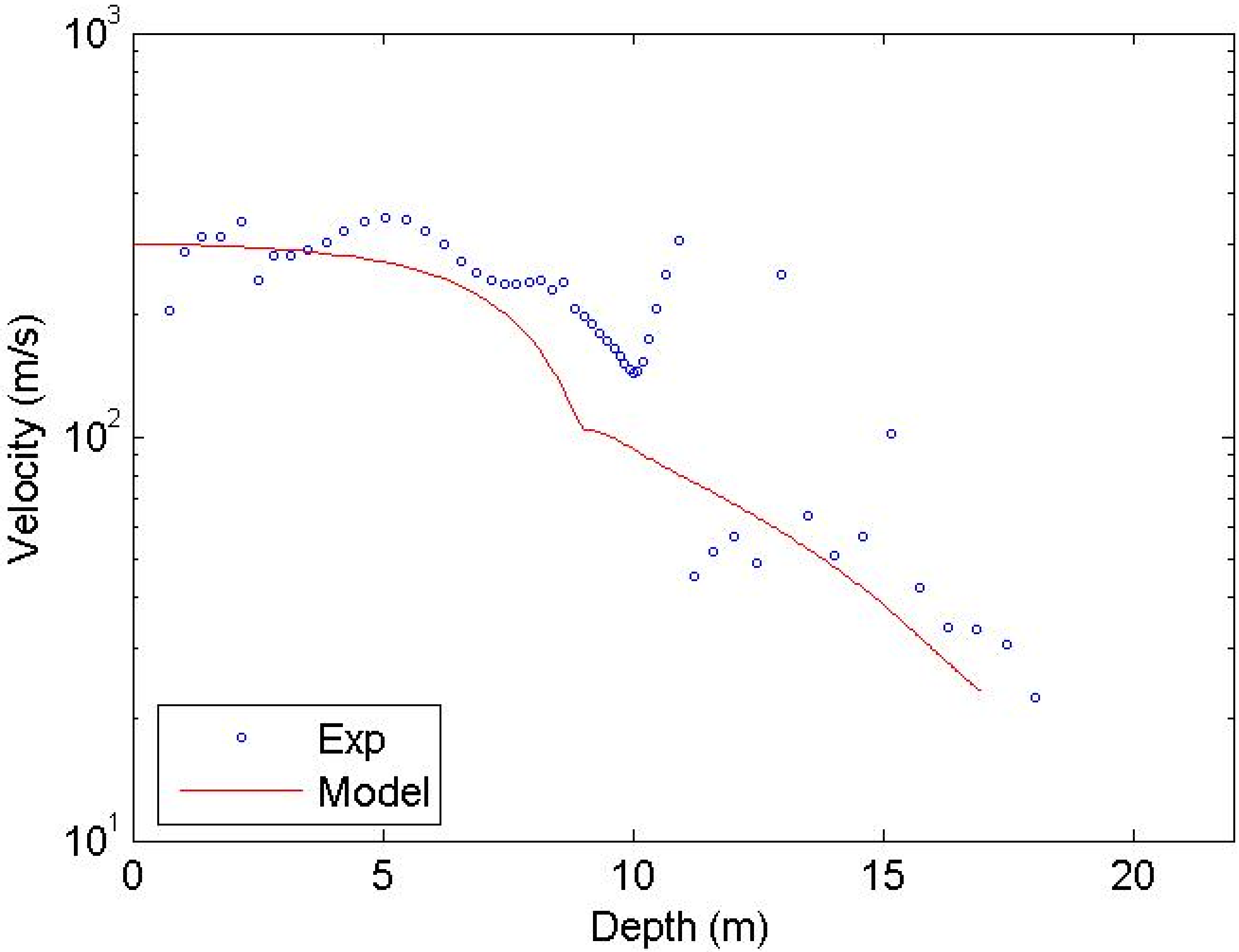
STRIKE35 and SRI Data Inter-Comparison Test-15



STRIKE35 and SRI Data Inter-Comparison
Speed vs Time (Test-15)

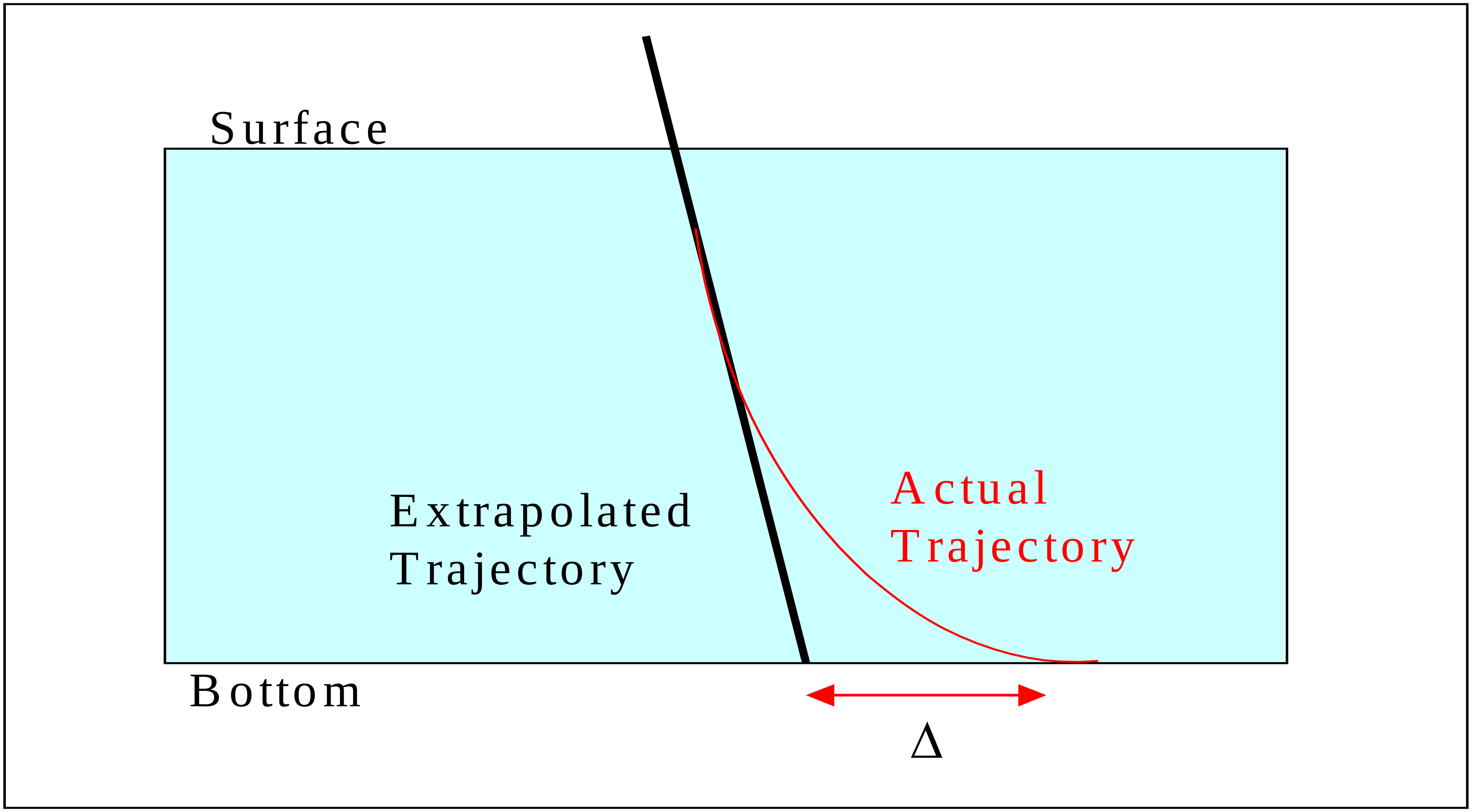


STRIKE35 and SRI Data Inter-Comparison Speed vs Depth (Test-15)



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

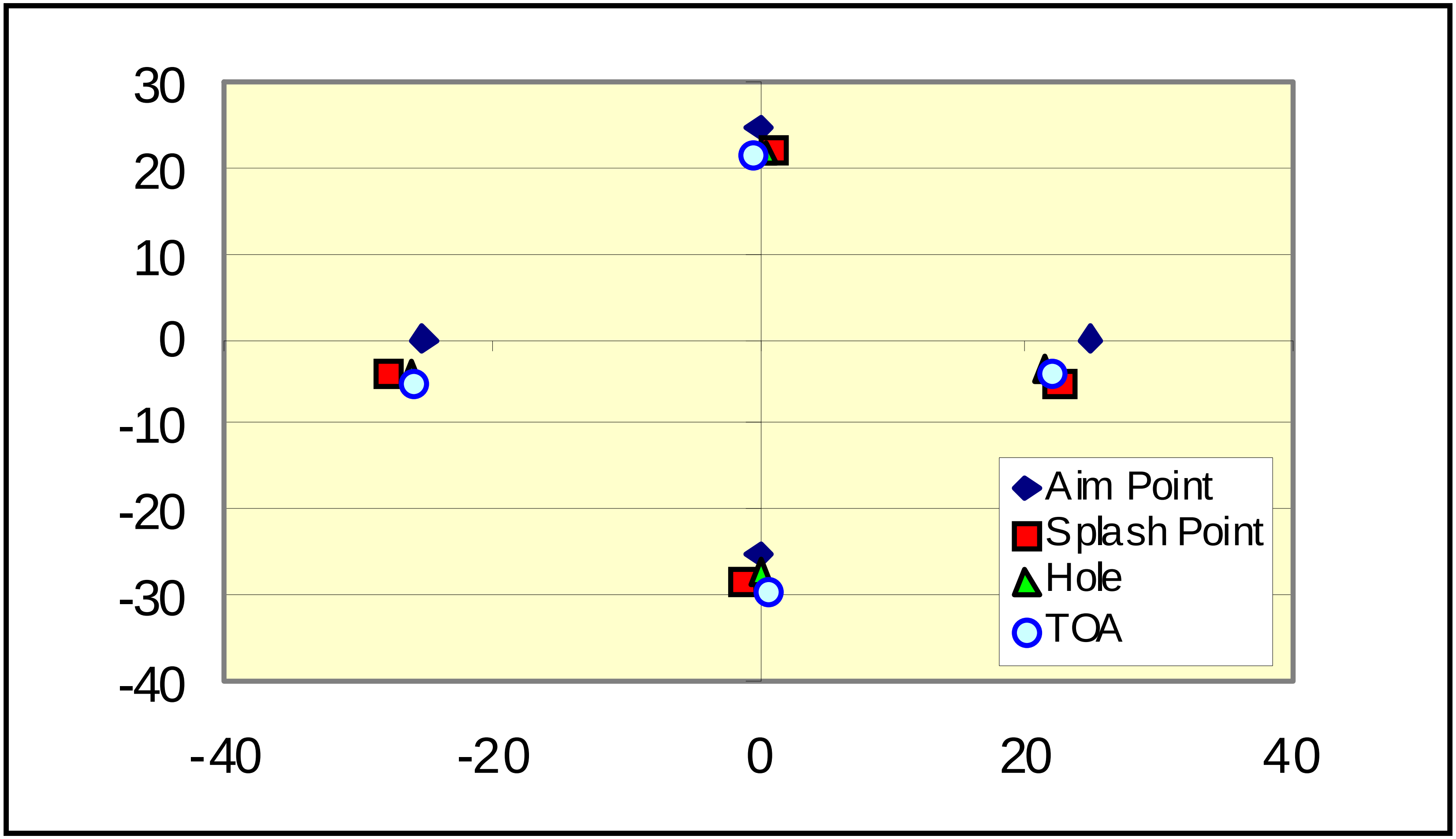
Provided by Boeing/ATR Corp


Surface
Extrapolated
Trajectory
Actual
Trajectory
Bottom
Δ

UNCLASSIFIED

CLASSIFIED

Avg surface impact error = 4.4 ft (4 shots)
Avg bottom impact error = 3.6 ft



Summary

- Small Distance Between Water Entry and Bottom Impact Points →

  Achieving Objective Requirement to Deliver MK-84 JDAM to a Depth of 40 ft

- 6-DOF Underwater Trajectory Model has been developed, and verified with Test Data, which could be used to facilitate transition to operational capability

Future Work

- **Extending SOABWFI to deep water**