Comparison of Experiments and OVERFLOW Modeling of Store Release from a Cavity at Mach 3

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*currently F-18E/F training systems IPT co-lead, NAVAIR

Impetus

The AFIT of Today is the Air Force of Tomorrow.

- Defense Trends

Supersonic

Reduced Signature

Precision Guided/Low Yield

Store Certification Process

- Computational Fluid Dynamics (CFD)
  - Parametric flexibility
  - Computational resources
  - Verification/Validation
- Experimental Fluid Dynamics (EFD)
  - Freedrop:
  - Captive trajectory system: Steady state flowfield
  - Scale-up is challenging
- Flight testing
  - Provides the “true solution”
  - Unsteady flow
  - Untenable during R and D

Project Research Objectives

- **Develop robust freedrop test capability at AFIT**
- **Utilize advanced CFD software (OVERFLOW) to model the wind tunnel experiments**
  - **Simple sphere model released from a cavity into Mach 3 flow**
  - **Multiple stagnation pressures**
- Freedrop test realistic geometry (Mk-82)
- Characterize how a flow control device (spoiler) affects cavity flow and store separation at Mach 3

Cavity Flow

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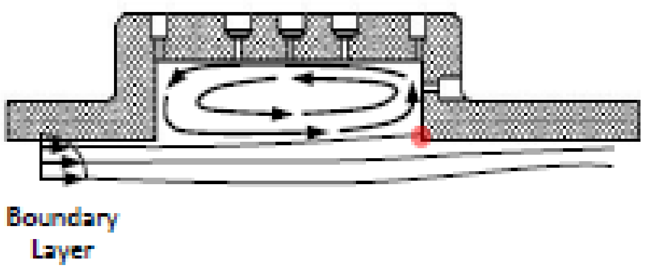
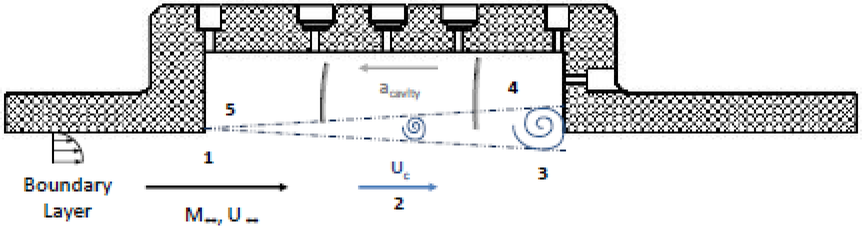
- Supersonic cavity flow[1]
- Open cavity pressure resonance[2,3]
  - Frequency prediction
- Cavities pose challenges for store release[4]



$$Str = \frac{fL}{U_\infty} = \frac{n-\beta}{\frac{M_\infty}{\sqrt{1+\frac{1}{2}(\gamma-1)M_\infty^2}} + \frac{1}{k_c}}, n = 1, 2, 3...$$



[1]Stallings and Wilcox (1987)
[2]Rossiter (1964)
[3]Heller, Holmes, and Colvert (1970)
[4] e.g. Bjorge et al. (2003)

Store Release Scaling

- Often difficult to scale wind tunnel tests to flight tests (Marshall, 1977)
  - Forces due to pressure and shear scale with area ratio
  - Weight scales with volume ratio
  - Froude scaling works for incompressible (but not compressible) flows
- Heavy Mach scaling
  - Often increase wind tunnel model density (e.g., weighted with lead)
  - Trajectory information attained
  - Conservative for scale-up
  - Generally preferable to light Mach scaling
- Light Mach scaling
  - Ejector force common, sometimes used for moments/store dynamics
- Large-scale tunnel tests are generally preferred.

Store Release Method

- One may minimize stagnation pressure for supersonic freedrop tests (Marshall, 1977)
  - Instead of raising material density for tunnel models
  - Vacuum chamber at tunnel exit
    - Can pose an added challenge for drop testing
- Our approach utilized ice models released at Mach 3
- Stagnation pressures from 4 psia up to 20 psia
  - Effectively changes “scale” without changing model
- Small tunnel (2.5” by 2.5” cross-section)
  - WICS bay (scaled down by 0.375) to L=6.75” and D =W=1.5”
- CFD used to compare to (and extend) experimental results using sphere-shaped stores
- Using a sphere greatly simplifies scaling

OVERFLOW 2.1

- Overset solver with 6-DOF relative motion capability
- Background grids from Dr. Robert Nichols
  - Assistance from Maj. Andrew Lofthouse and CDR Neal Kraft (US Naval Academy)
- Capabilities
  1) Overset structured grids
  2) Used extensively for unsteady/turbulent flow
  3) Robust solver with current numerical methods and turbulence modeling
- Other keys to success
  - Proper non-dimensionalization
  - Management of overset grids, blanked-out regions/X-rays, fringe/donors/orphans

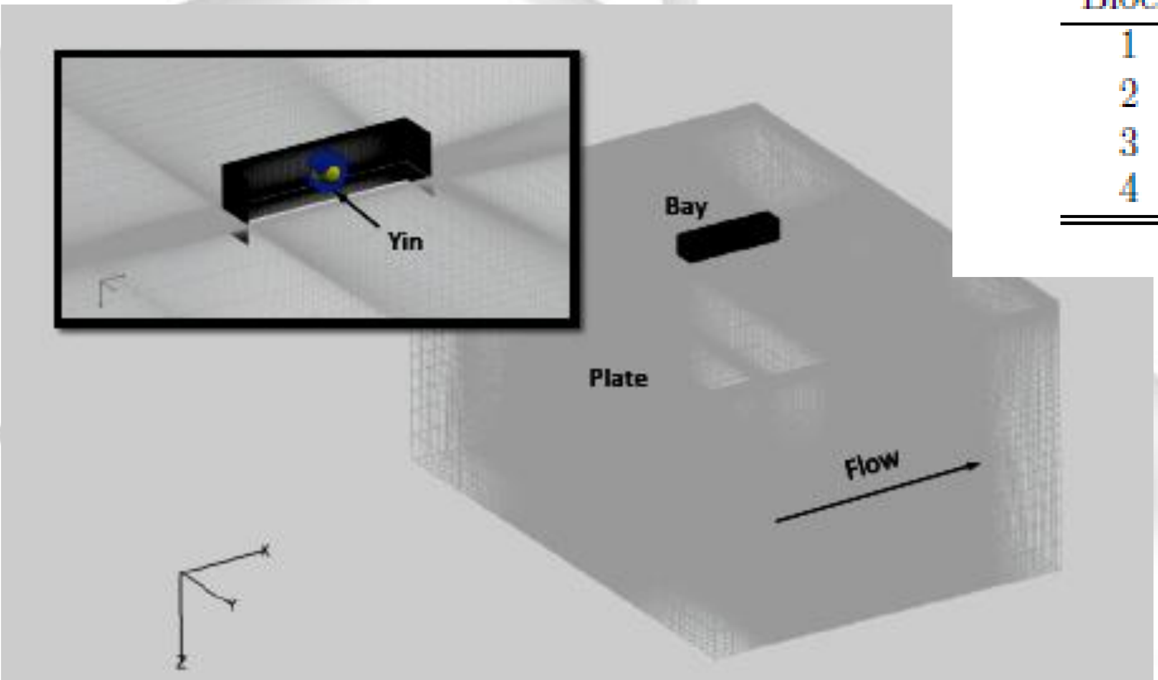
OVERFLOW 2.1 Settings

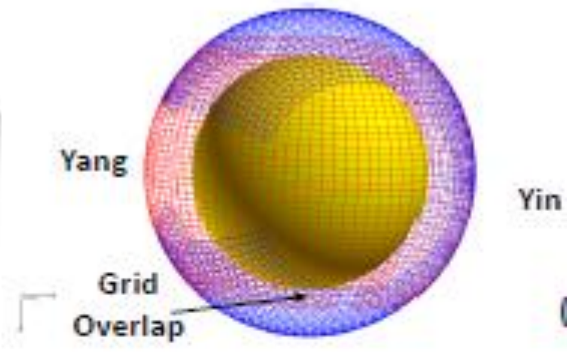
- Numerical Method
  - Hartax Lax van Leer Contact (HLLC) upwind scheme with van Albada flux limiters
  - 5th-order spatial flux algorithm
  - Symmetric Successive Over-Relaxation (SSOR) scheme
  - 2nd-order time with Newton sub-iterations used on temporal terms
- Turbulence Model
  - Delayed Detached Eddy Simulation/ Shear Stress Transport Hybrid RANS/LES model
    - RANS in boundary layer
- Time step of 5 $*10^{-6}$ seconds

CFD Methodology

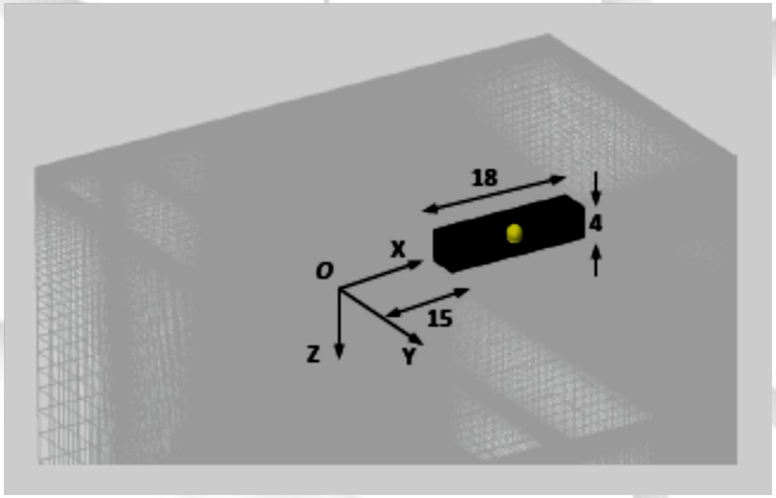
- Weapons Internal Carriage and Separation (WICS) bay (Nichols, 2008)
- Two overlapping C-type grids (Yin and Yang) set up about the sphere [after Kageyama and Sato (2004)].

Block	Name	Cells	Dimensions
1	Plate	5600000	351x201x81
2	Bay	1920000	201x81x121
3	Yin	140000	41x71x51
4	Yang	140000	41x71x51

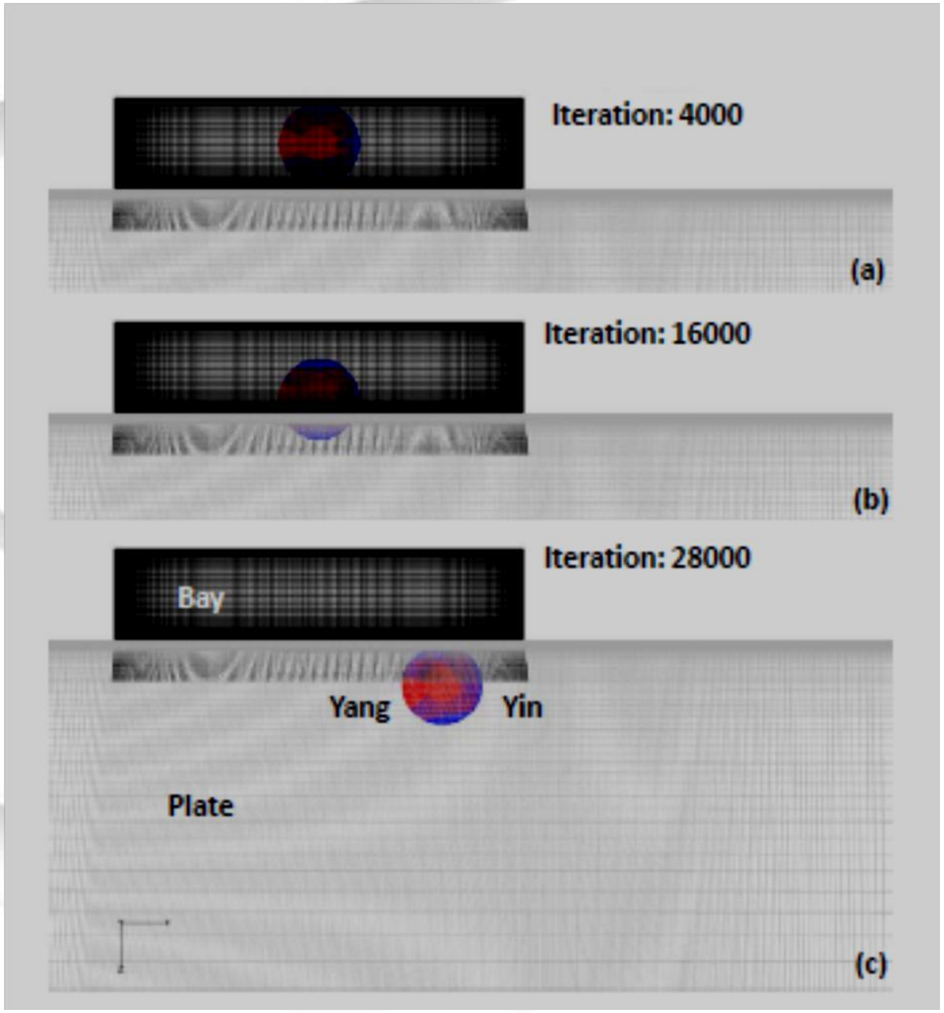




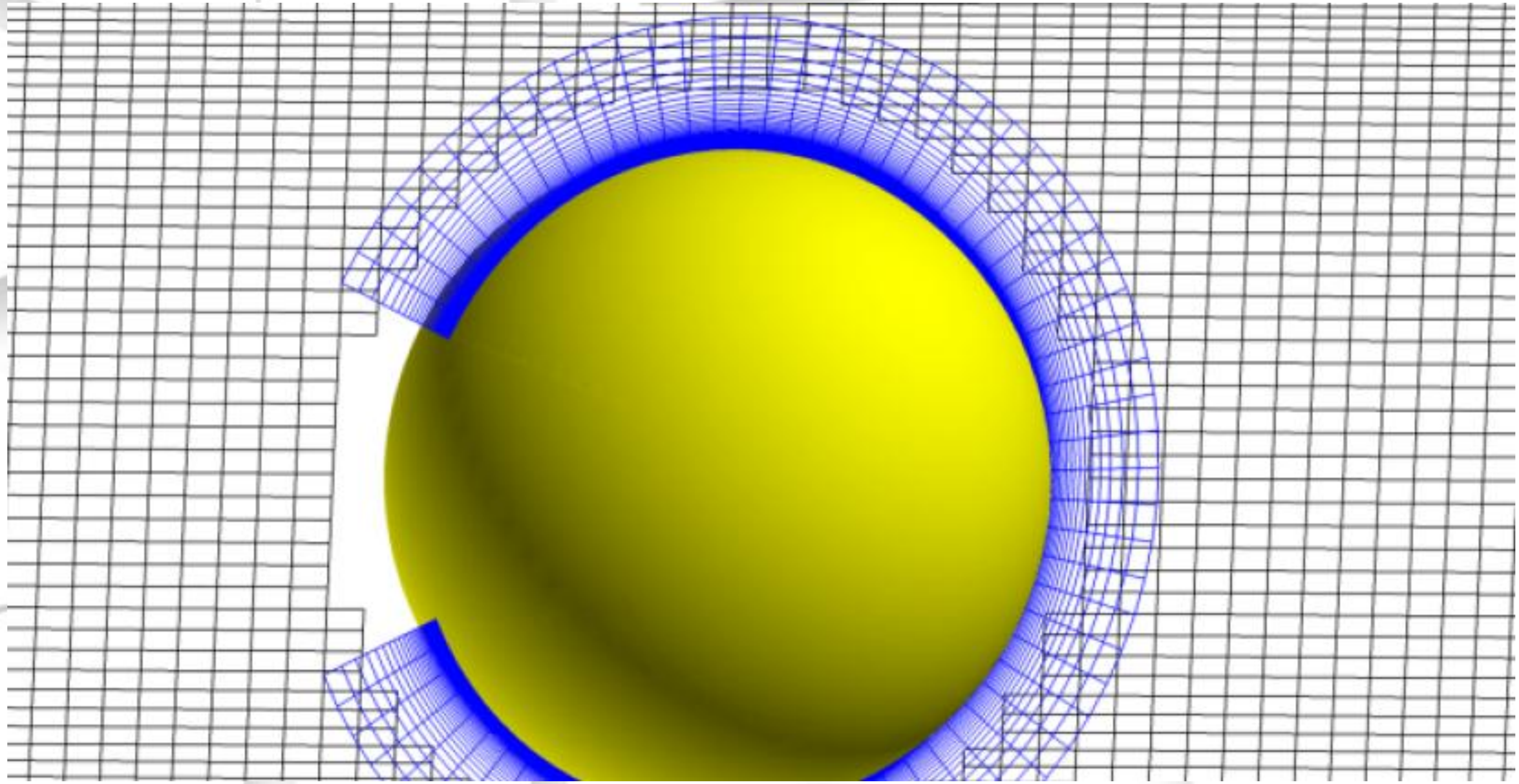
- Grid sizing



- Grid relative movement



Bay/“Yin” Grid Overlap



CFD Parameters

Run	CT1B	CT4B	CT2B	CT3B
P_T (Psia)	4	12	2	1
Re_{ft} (million)	0.64	1.93	0.32	0.16
Δt (sec)	$5.0x10^{-6}$	$5.0x10^{-6}$	$5.0x10^{-6}$	$5.0x10^{-6}$
M	3.0	3.0	3.0	3.0
$Re_{gridunit}$	20000	60300	10000	5030

Tunnel and Test Section

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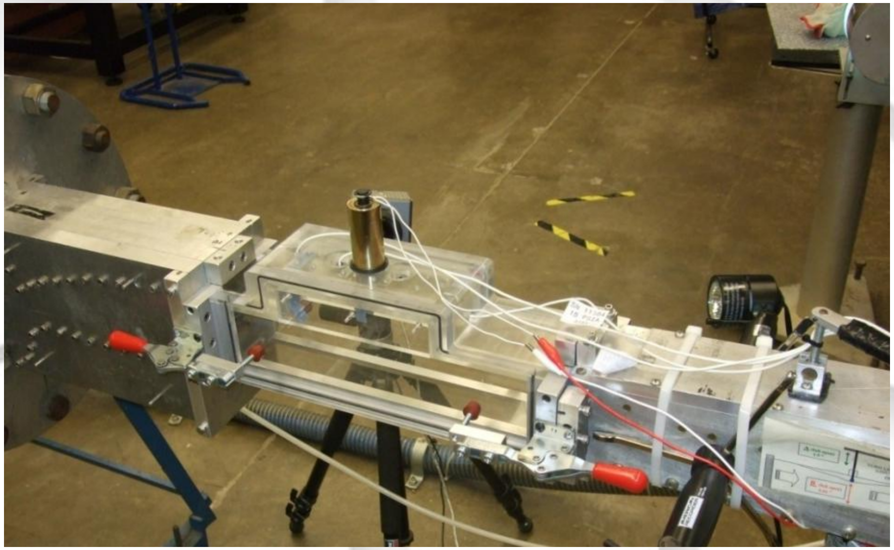
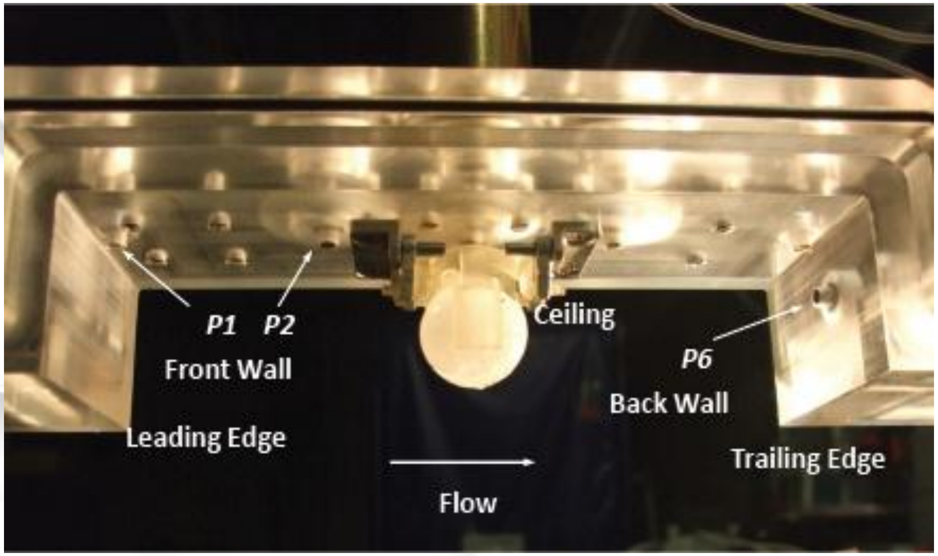
- Supersonic (M= 2.94) variable density blowdown tunnel
- Two high-speed cameras
  - One conventional and one with Schlieren visualization setup
- Piezo-resistive pressure transducers





Model Fabrication

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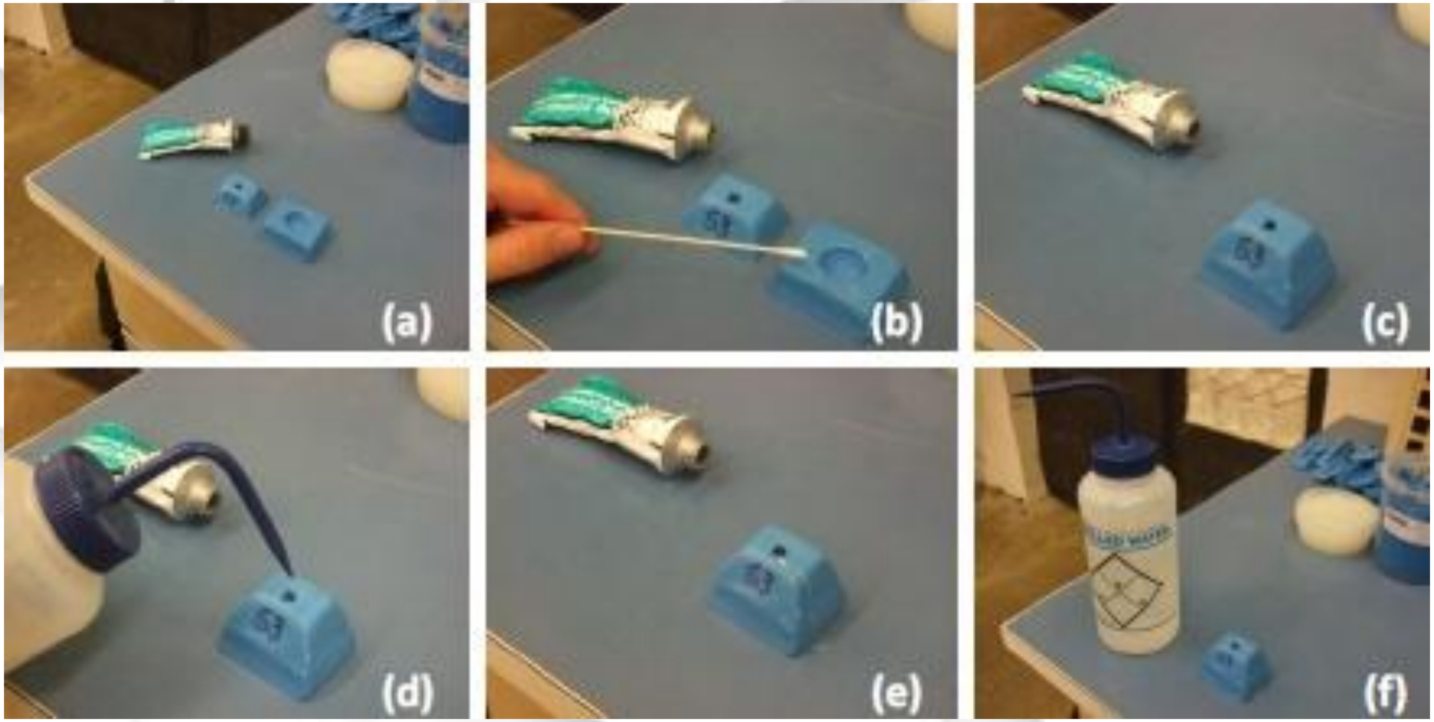

Test Conditions

$P_{T,sc}$ (Psia)	4	12	20
$T_{T,sc}$ (°R)	536	540	544
P_∞ (lb/ft^2)	17	52	86
V_∞ (ft/s)	2021	2027	2034
ρ_∞ (slug/ft^3)	5.11×10^{-5}	15.2×10^{-5}	25.1×10^{-5}
Re_{ft} (million)	0.65	1.93	3.18

Results and Analysis

Frequency Spectra

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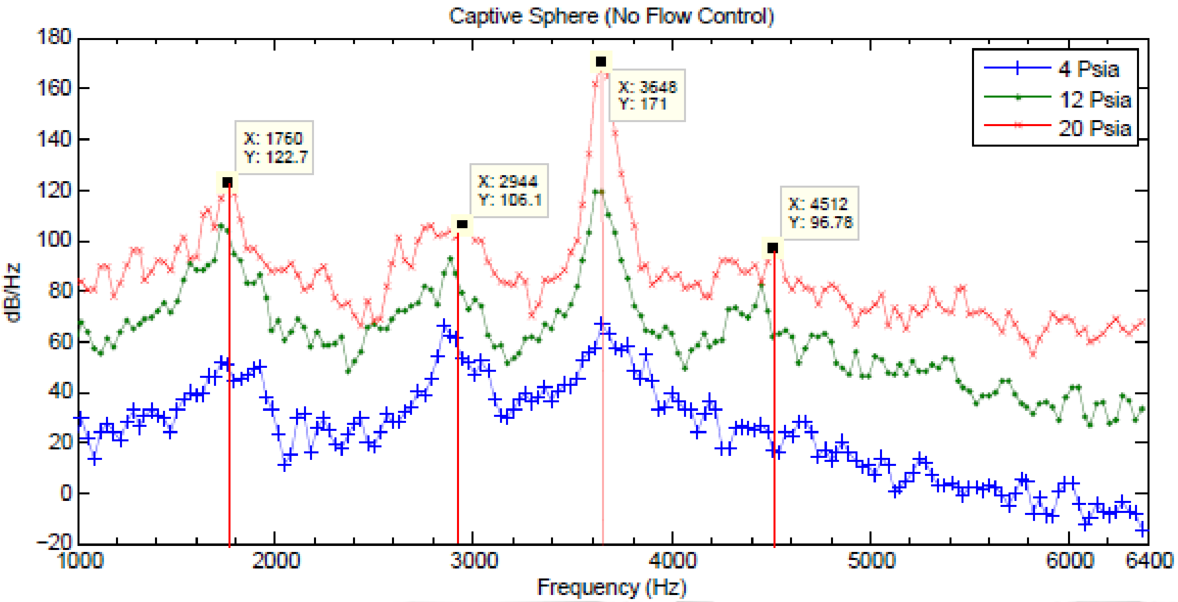

- Experimental data shows that resonant frequency is essentially independent of pressure.
  - Consistent with literature
- Low signal-to-noise ratio for low pressure data.

4 Psia

	Heller et al		Experimental
mode	*Str*	*f* (Hz)	*f* (Hz)
1	0.21	760	No distinct peak
2	0.50	1774	1760
3	0.78	2787	2848
4	1.06	3801	3648
5	1.34	4814	No distinct peak
6	1.63	5828	No distinct peak

12 Psia

	Heller et al		Experimental
mode	*Str*	*f* (Hz)	*f* (Hz)
1	0.21	764	No distinct peak
2	0.50	1783	1728
3	0.78	2801	2880
4	1.06	3820	3616
5	1.34	4839	4448
6	1.63	5857	No distinct peak

20 Psia

	Heller et al		Experimental
mode	*Str*	*f* (Hz)	*f* (Hz)
1	0.21	767	No distinct peak
2	0.50	1791	1760
3	0.78	2815	2976
4	1.06	3839	3648
5	1.34	4862	No distinct peak
6	1.63	5886	No distinct peak

CFD/EFD Spectra

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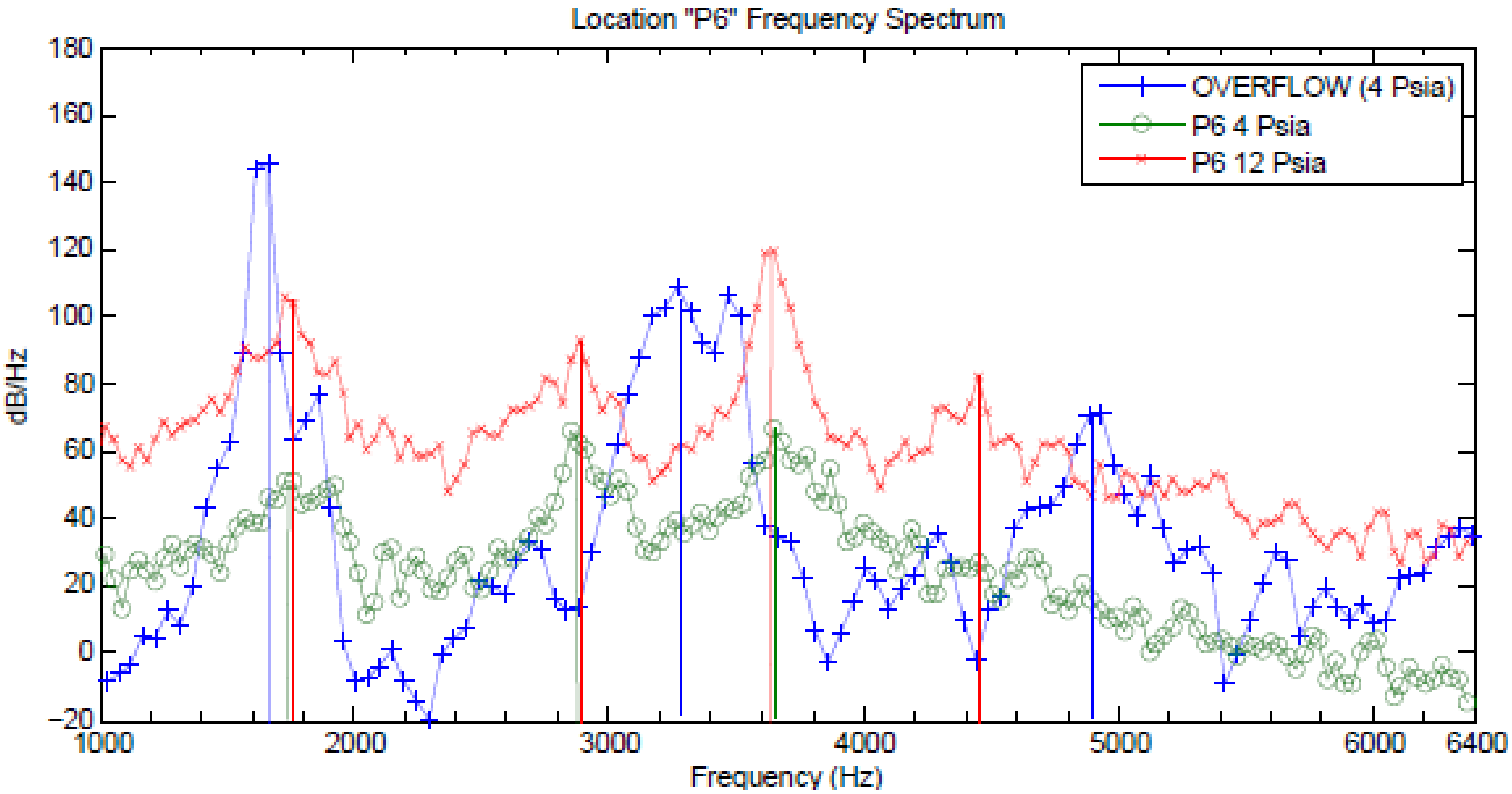

- Computational spectral data is comparable but not a precise match to experimental spectra for a clean cavity.
  - Based on 17,000 iterations (Welch's method)

CFD/EFD Visualization

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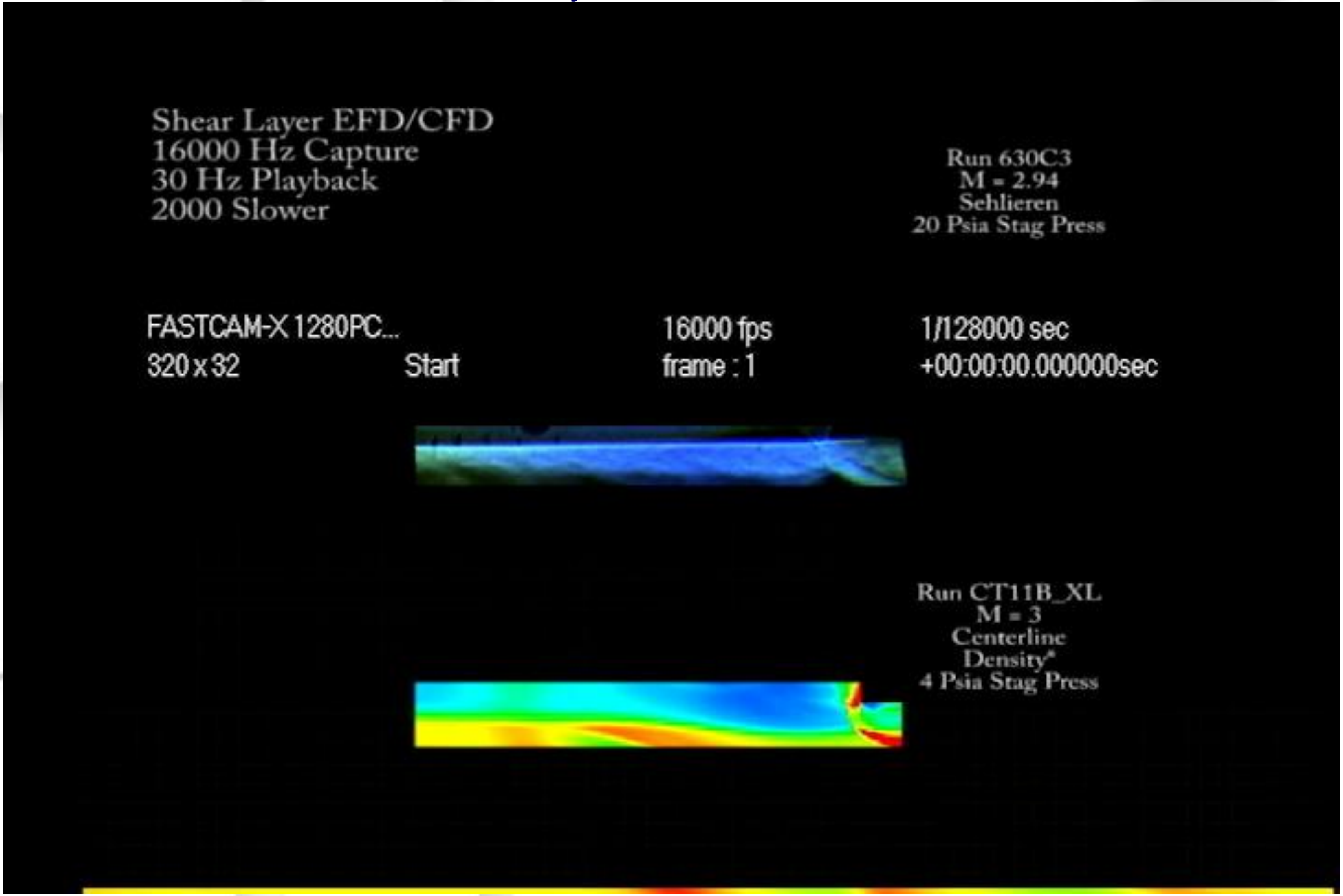
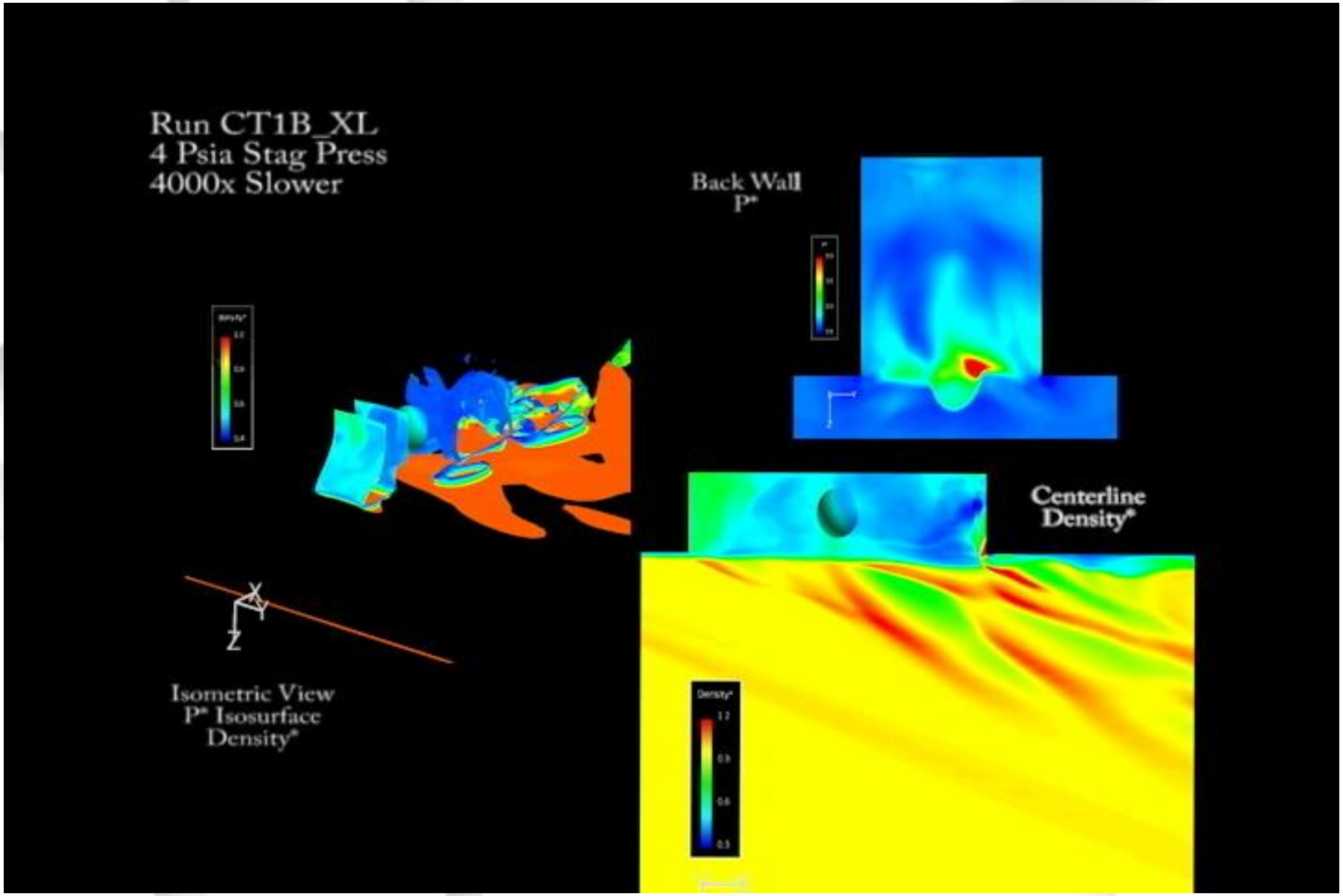
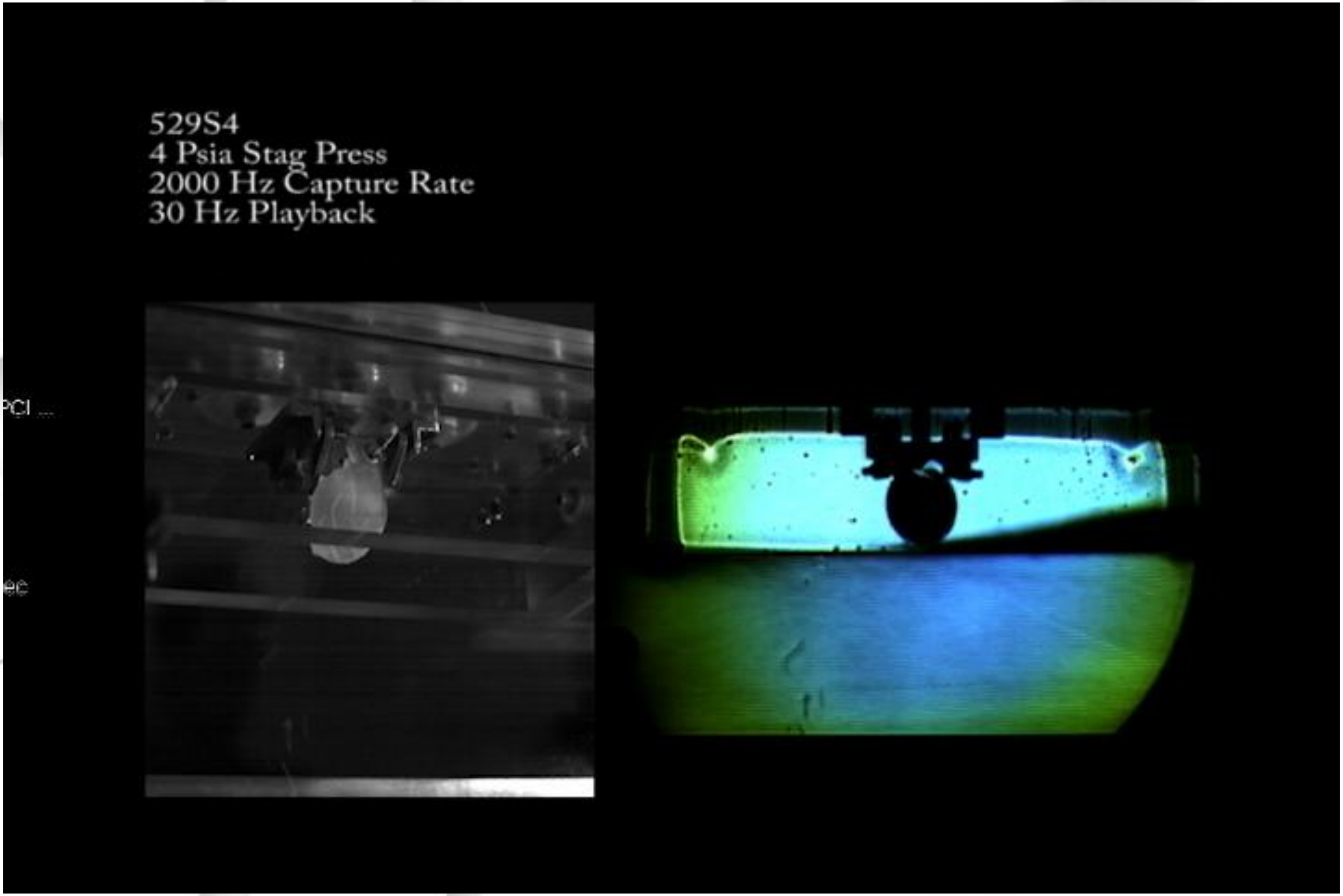


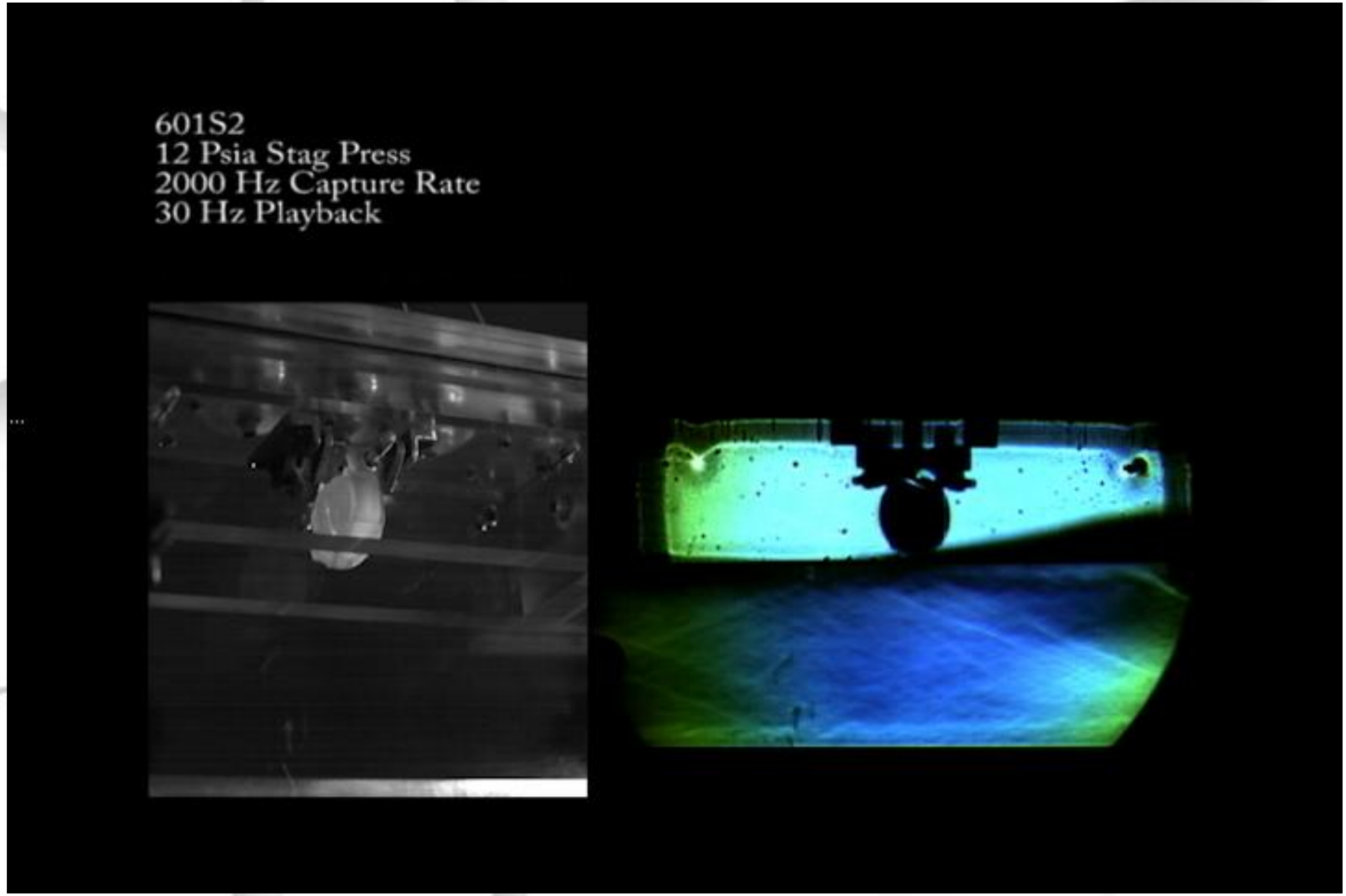
Cavity Flow: Stationary Sphere



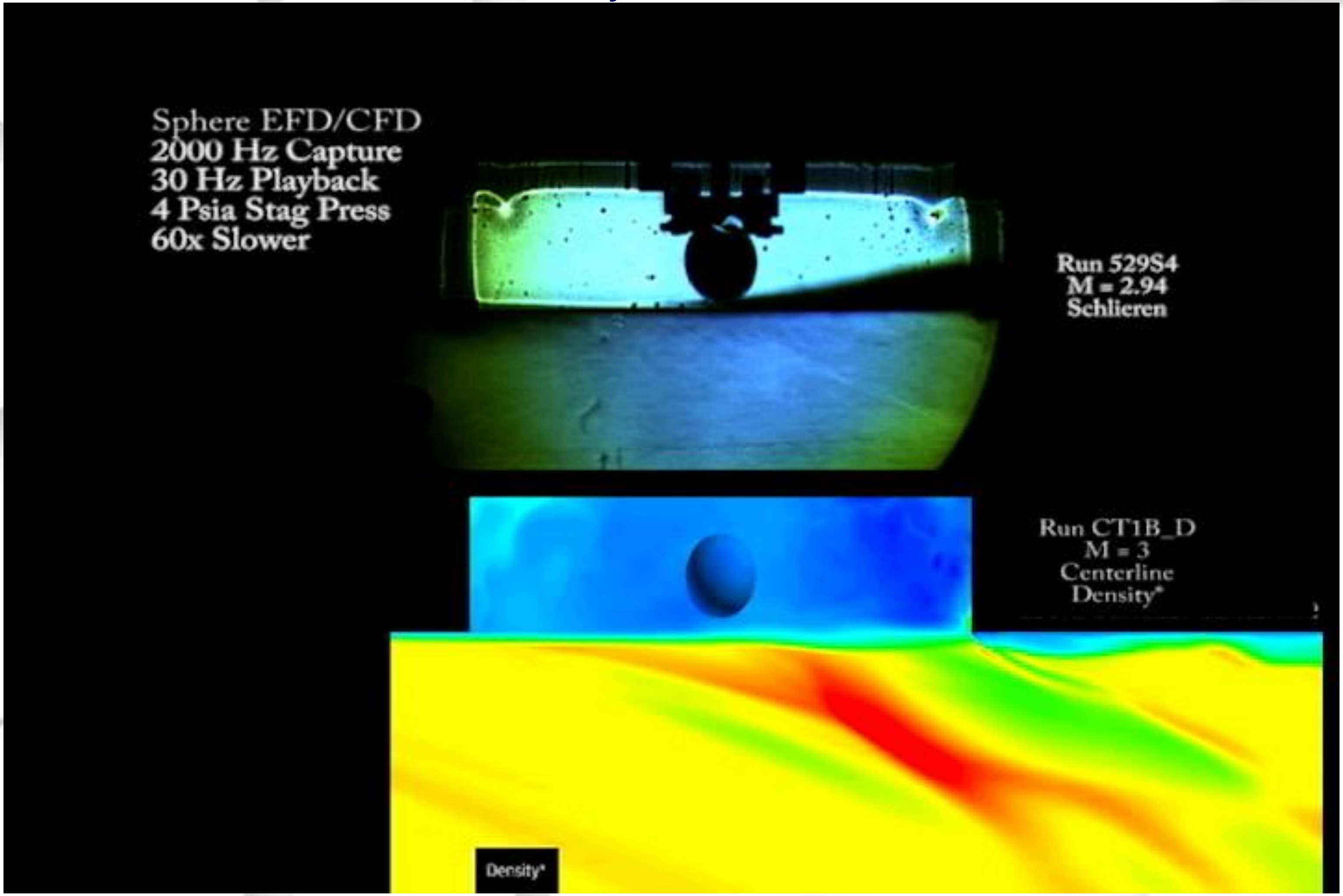
Sphere Drop (4 psia)



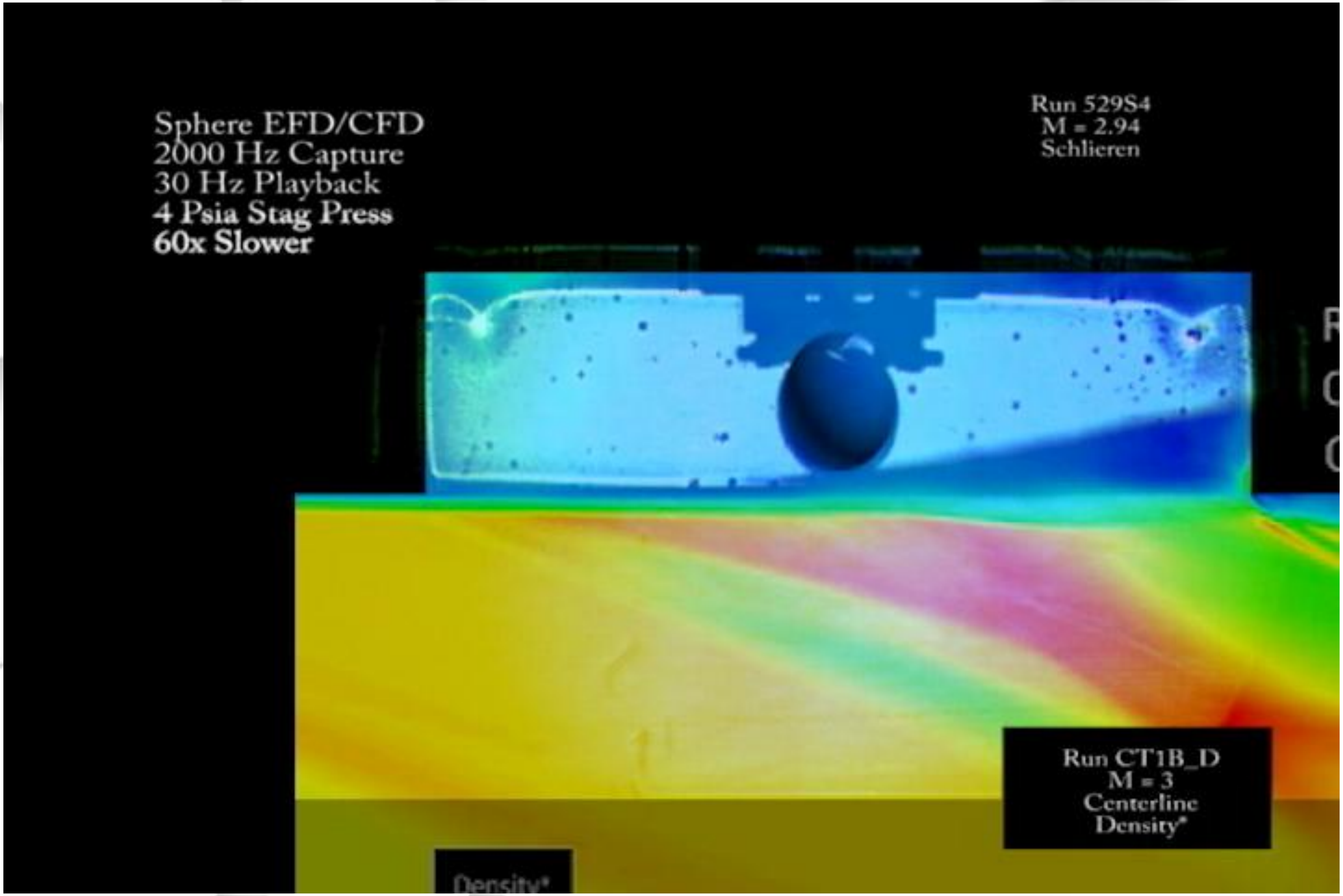
Sphere Drop (12 psia)



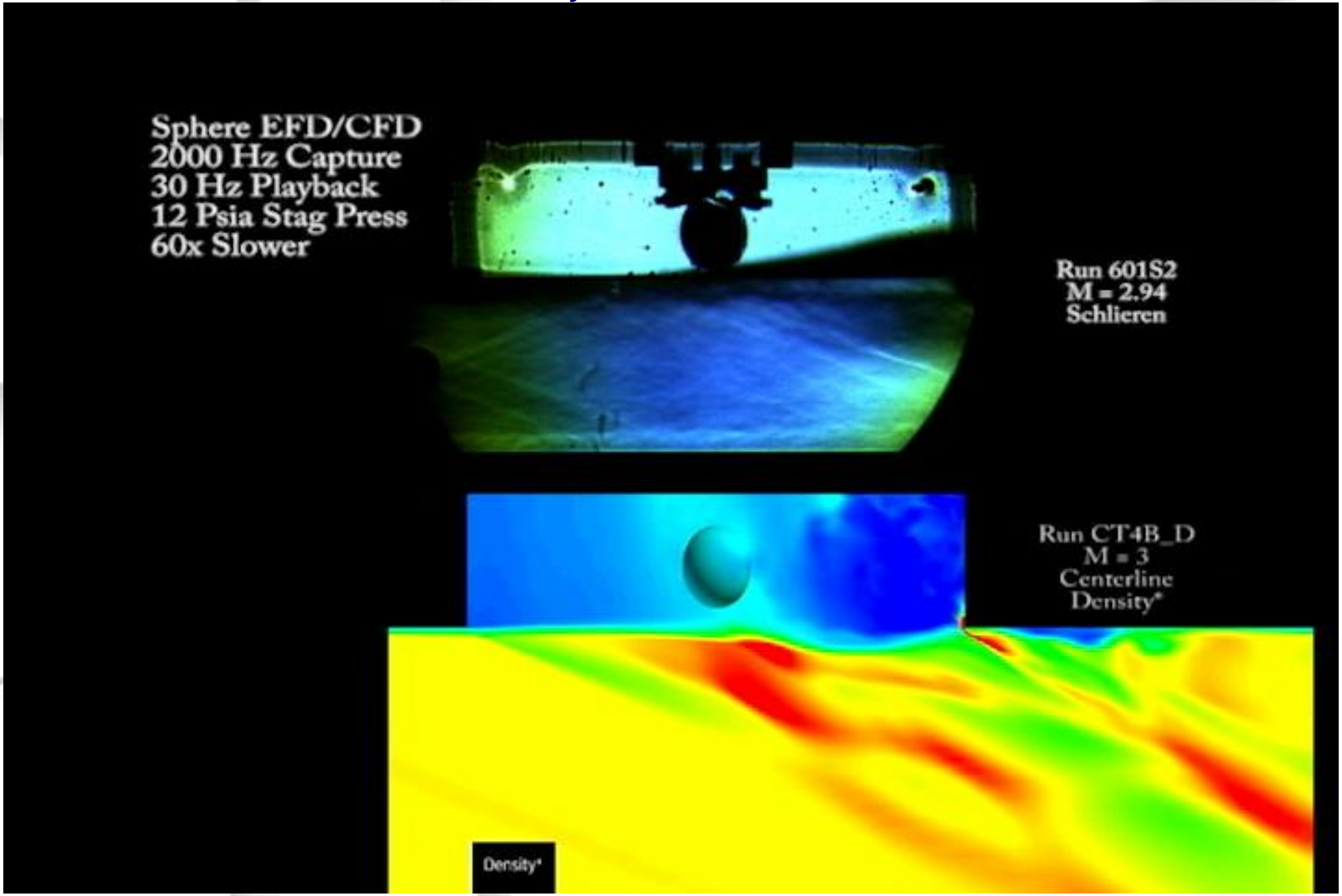
Sphere Drop CFD



Sphere Drop Overlay



EFD/CFD Sphere Drop



CFD Sphere Drop

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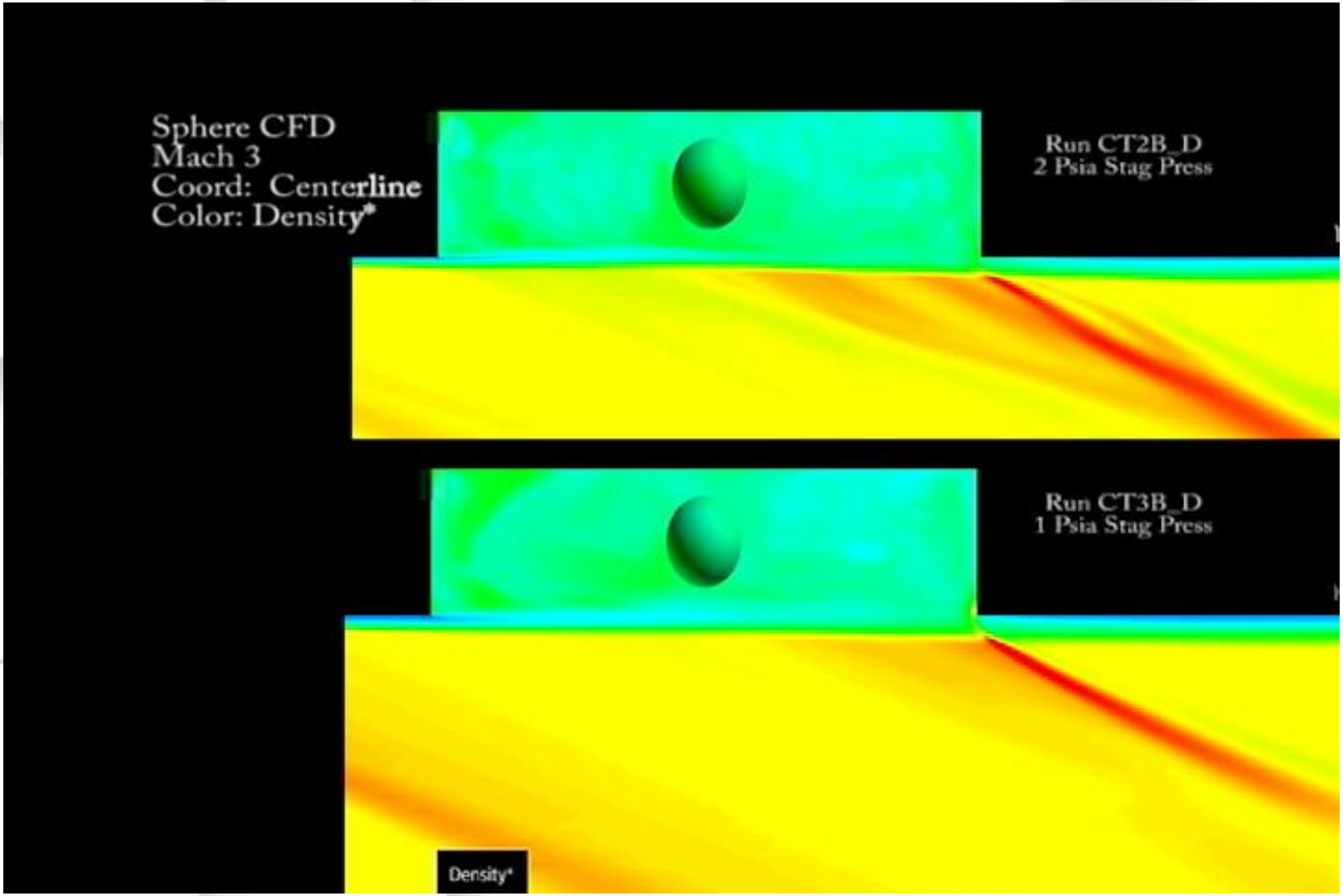

View of Recirculation

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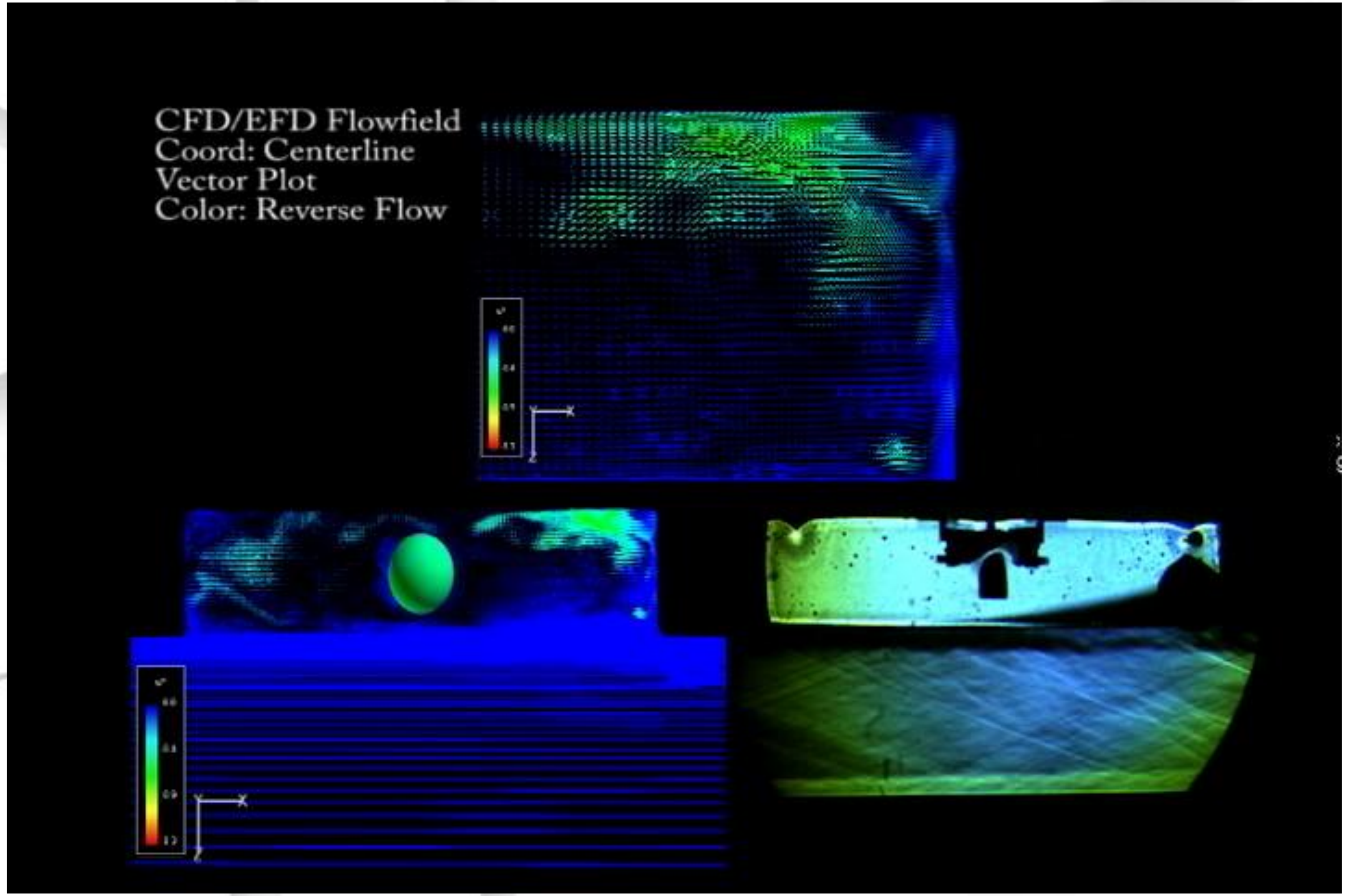

Mk-82 Shaped Store

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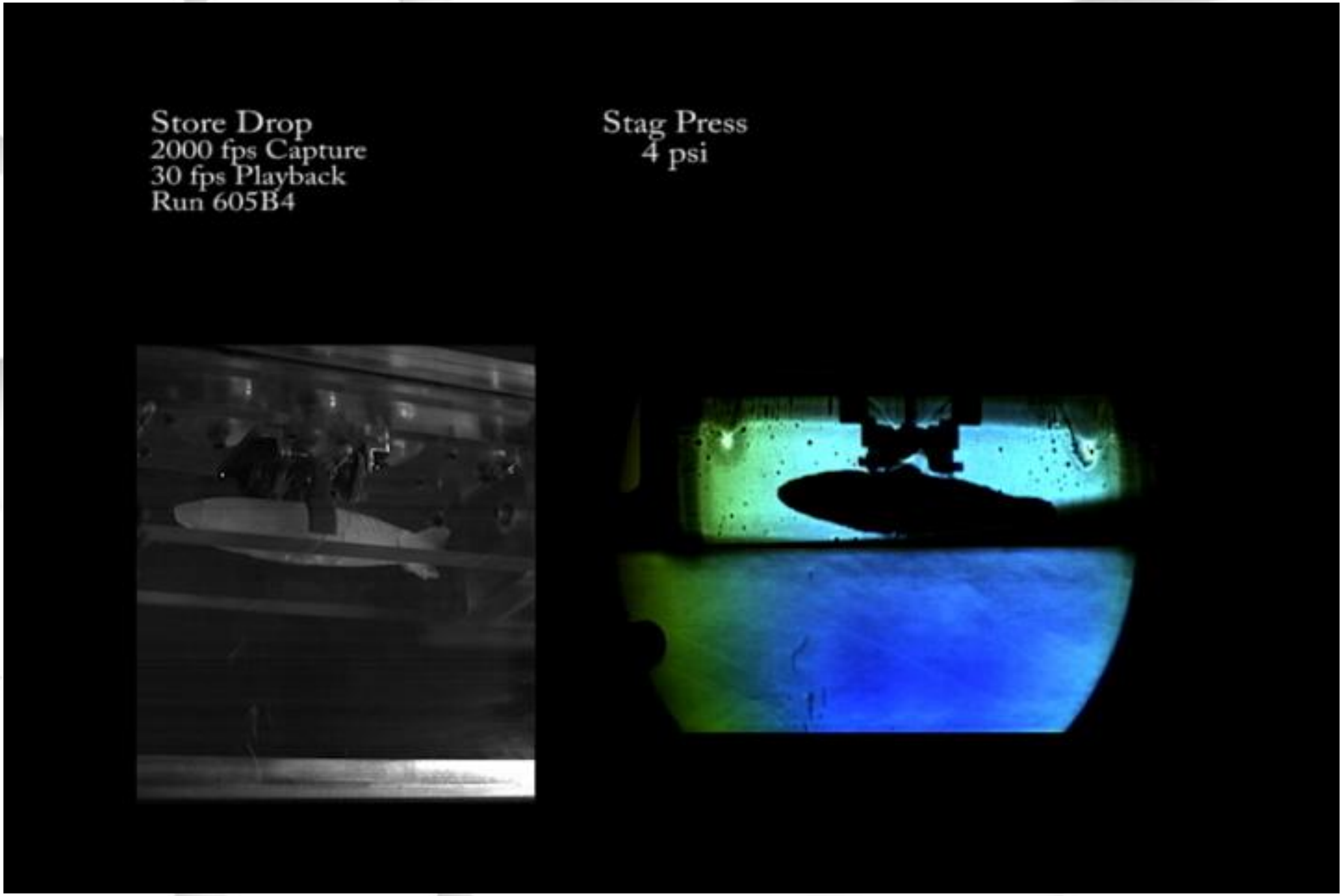

Sphere Separation

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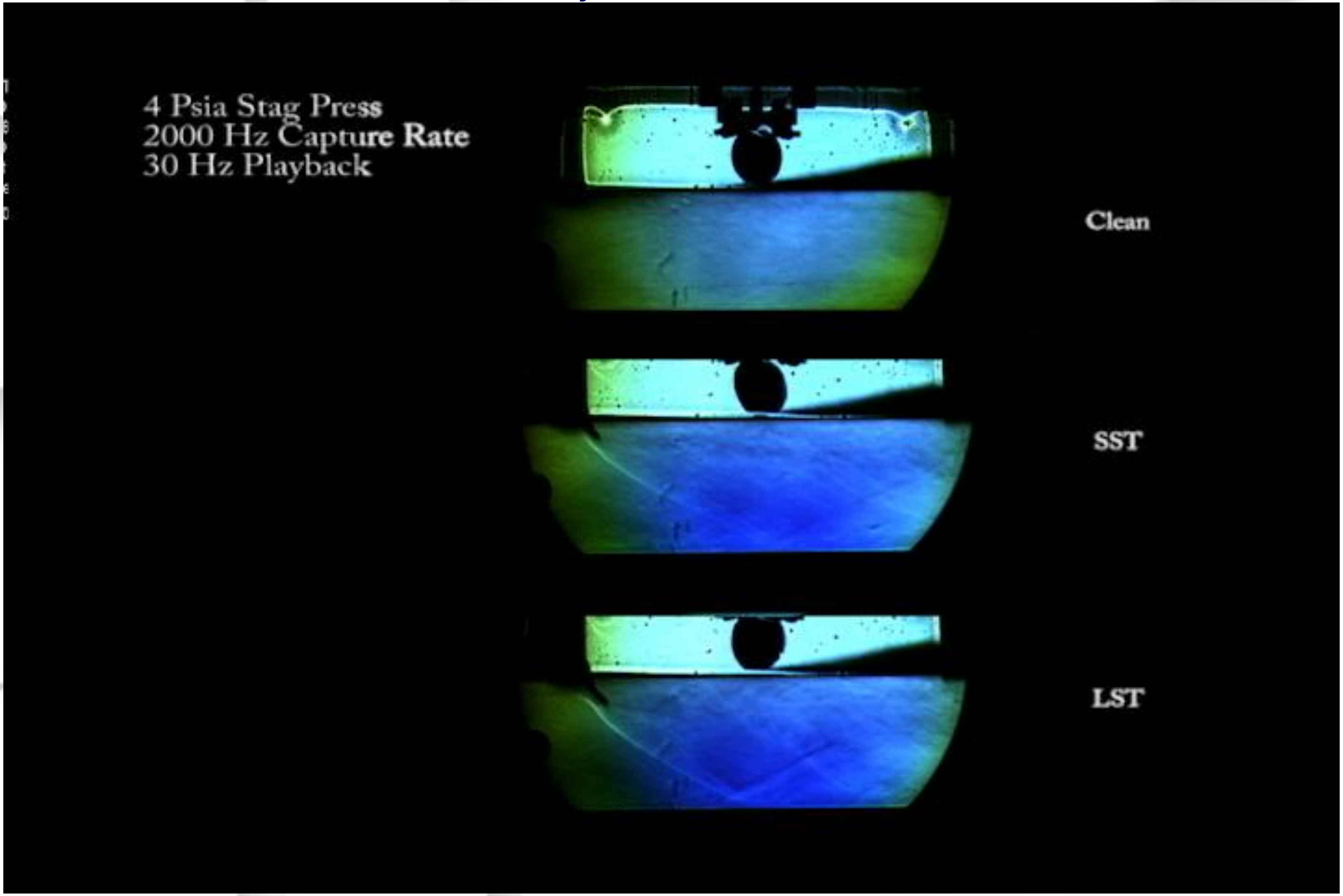
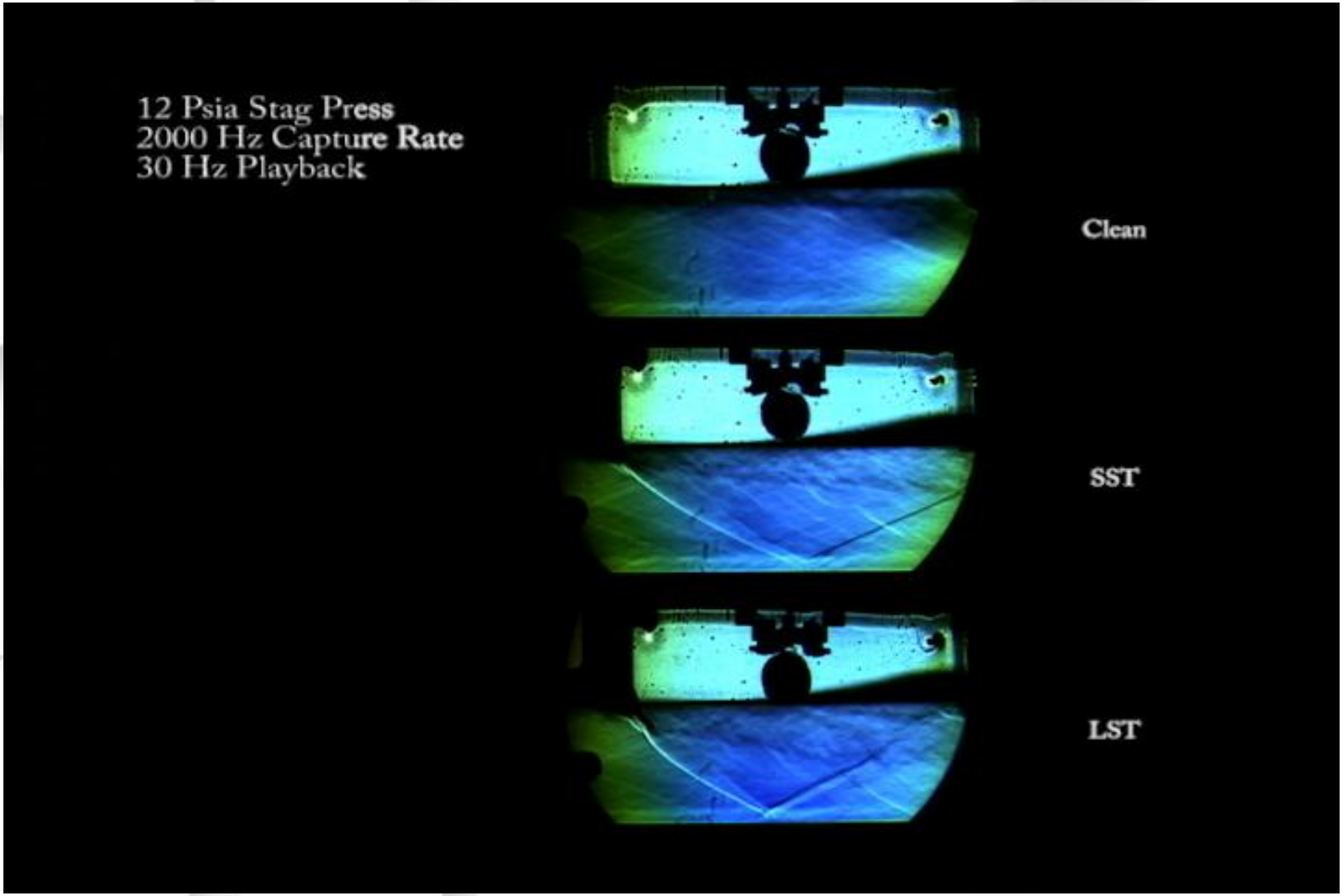


Sphere Separation



Mk-82/Spoiler Combination

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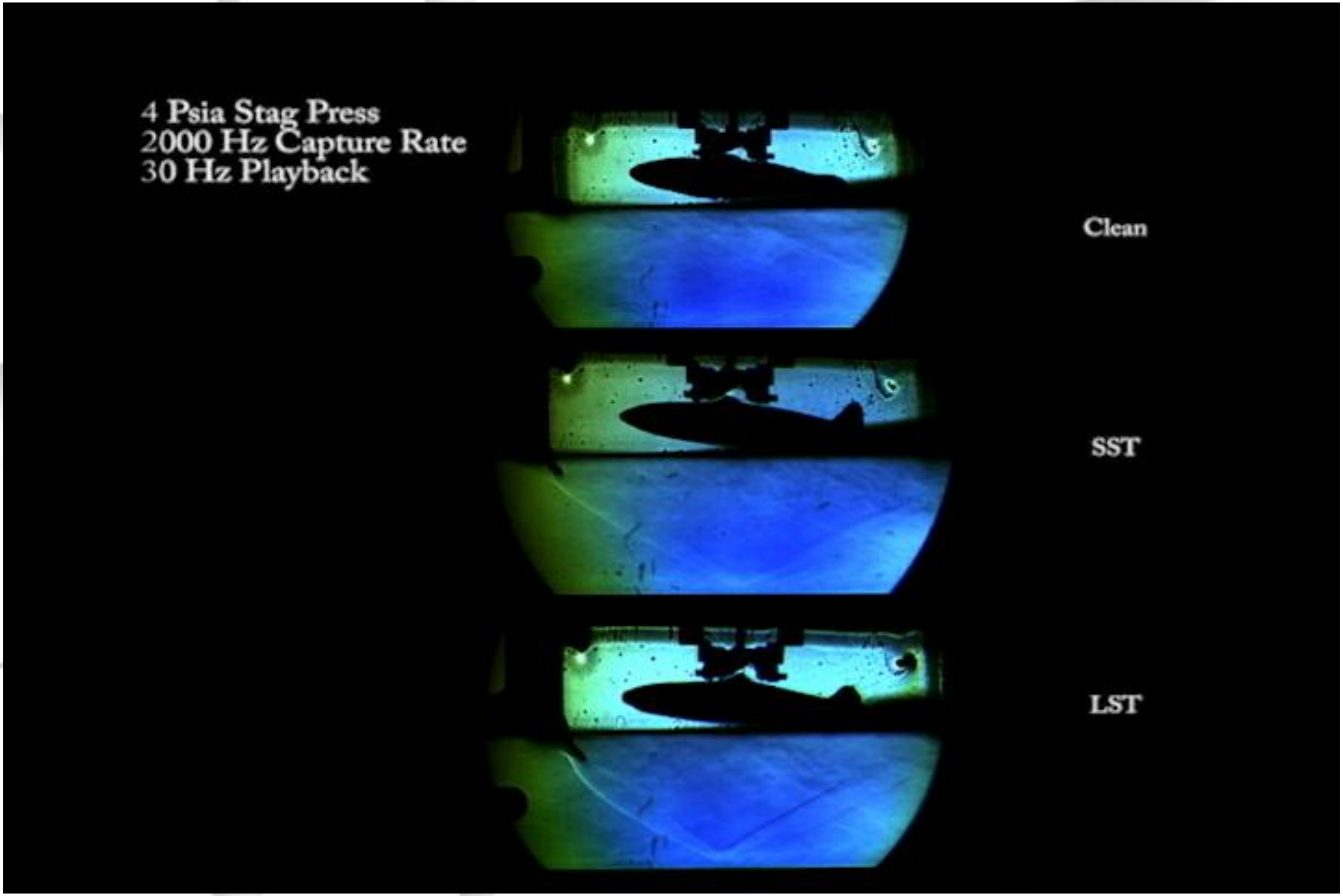


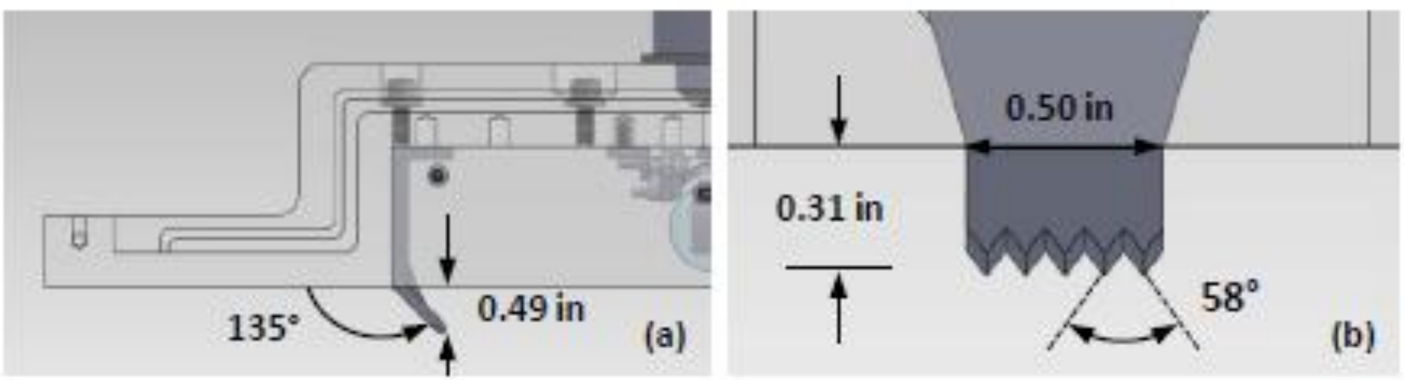
Summary

- OVERFLOW 2.1 used to compare to Mach 3 store separation events for spheres
- “Reasonable” correlation between predicted and measured Rossiter tones
- Successfully demonstrated the capability to conduct freedrop testing at Mach 3 in the AFIT supersonic tunnel
- Very good matching of the sphere dynamics between experiment and CFD results.

Flow Control

Passive Flow Control

- Tab Design
- Short Sawtooth (SST): 1δ
- Long Sawtooth (LST): 2δ



Spoiler Spectra

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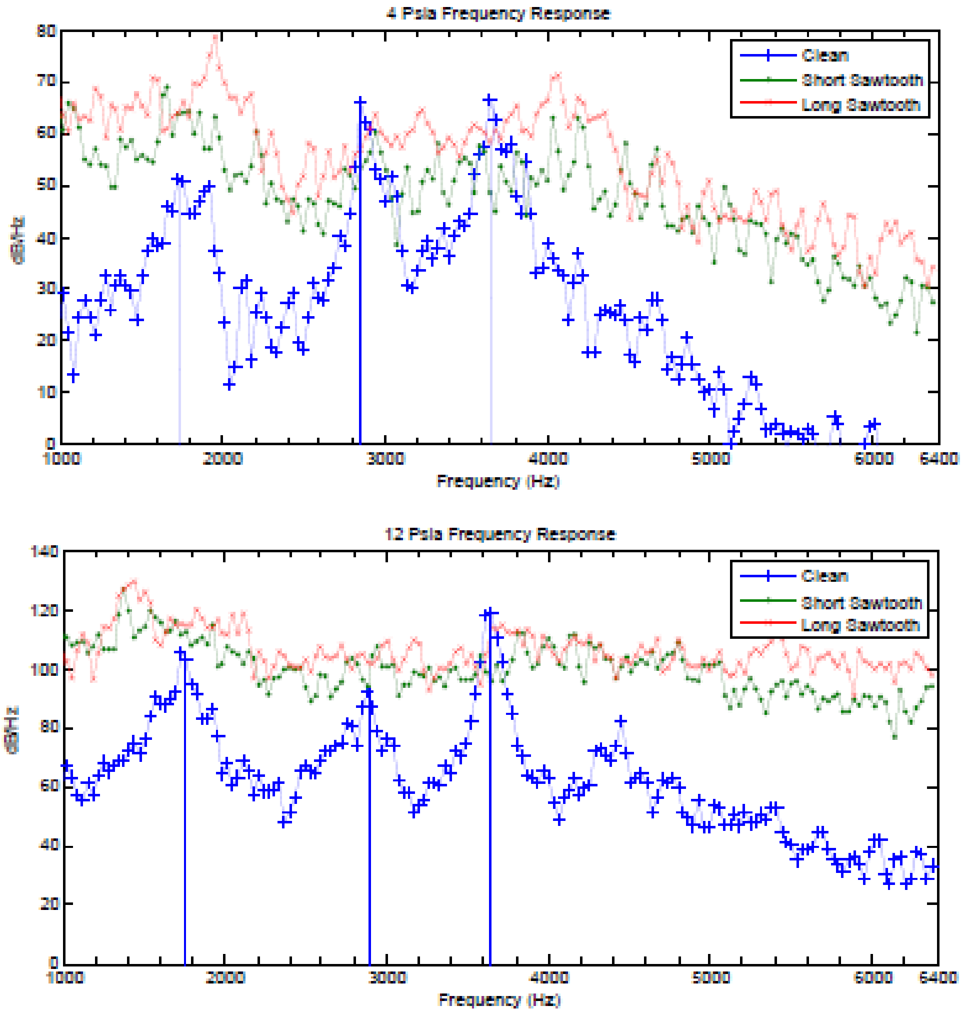

Sphere Heavy Mach Scaling

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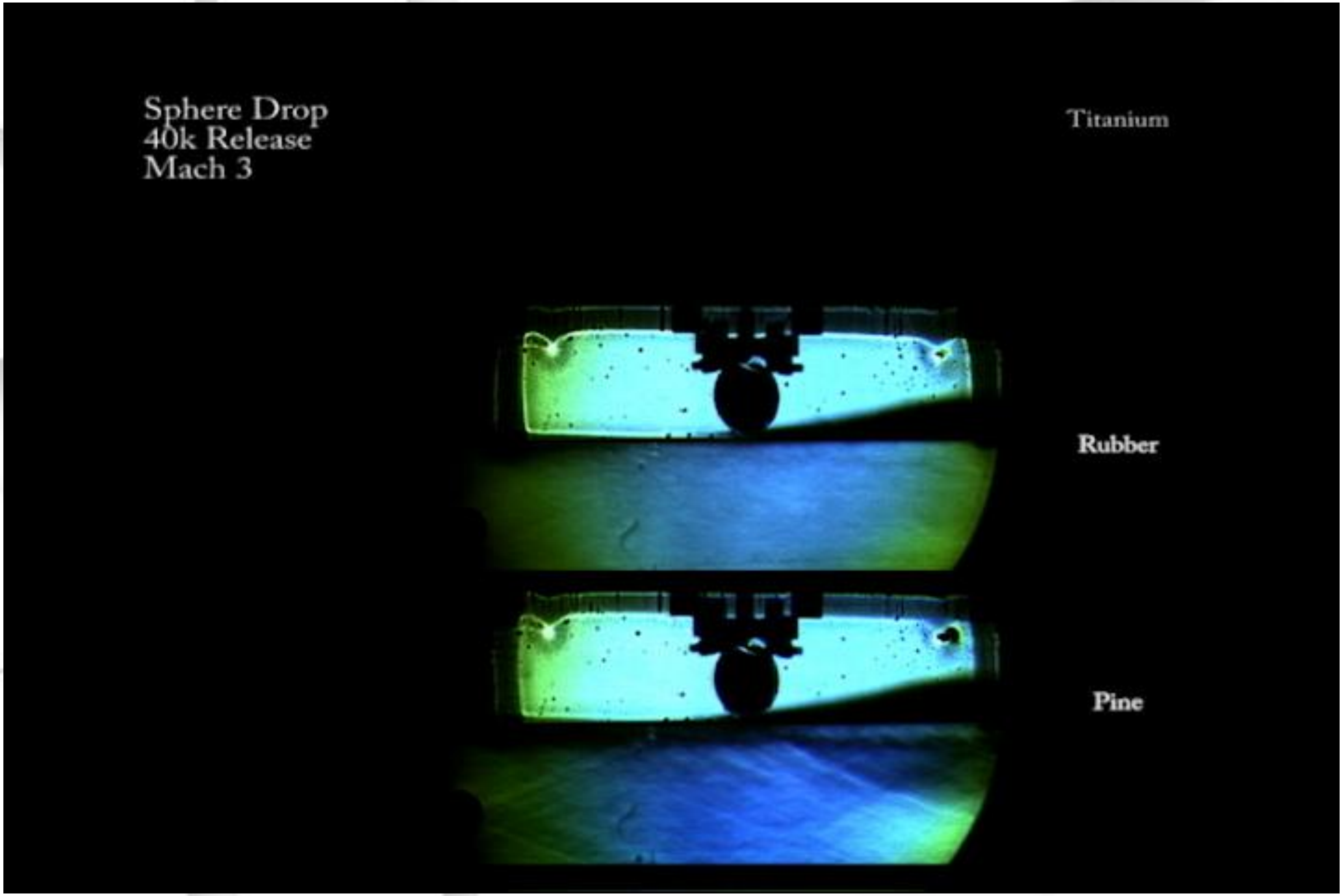
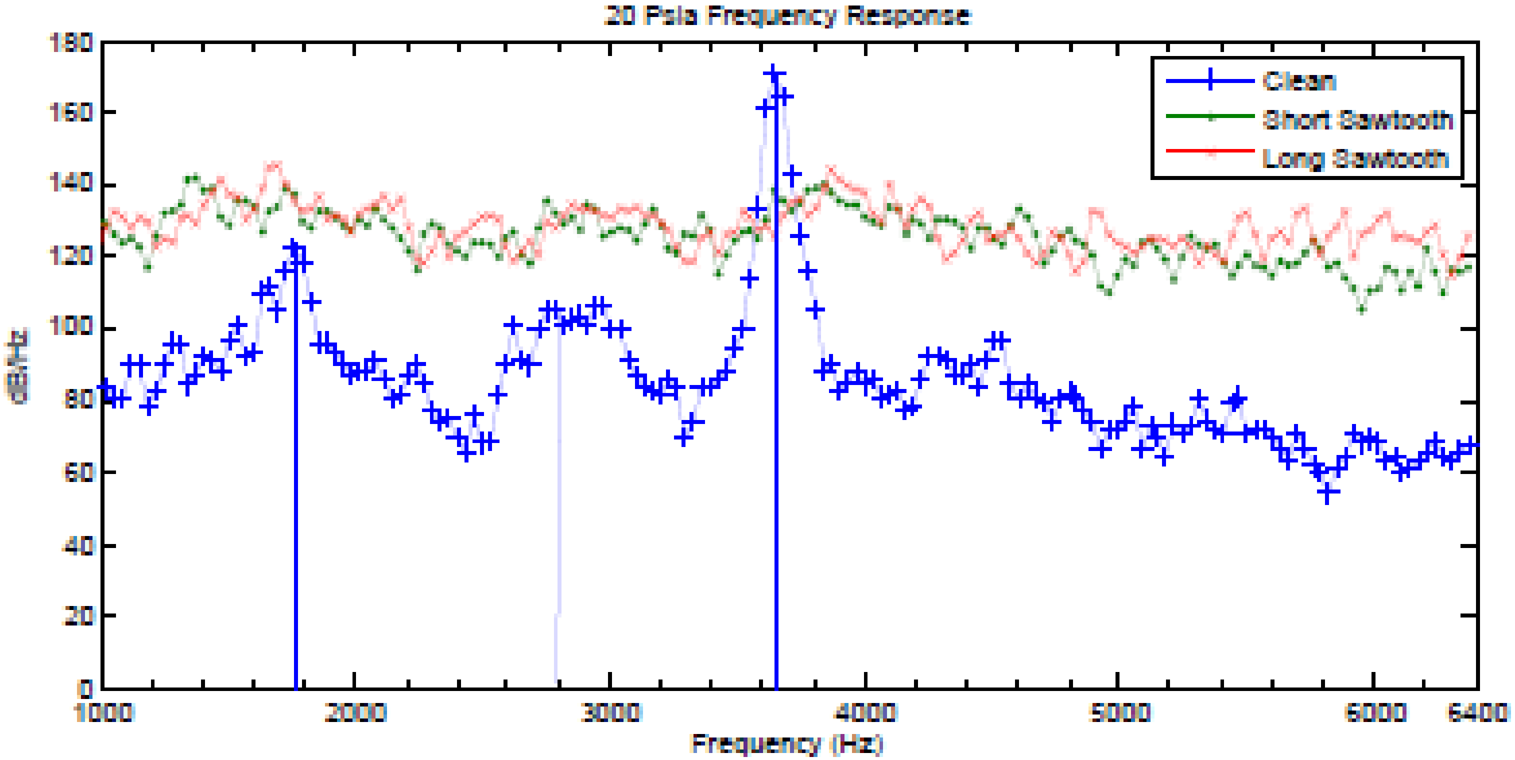


Spoiler Spectra

The AFIT of Today is the Air Force of Tomorrow.



Mk-82 Model

Mk-82 Model

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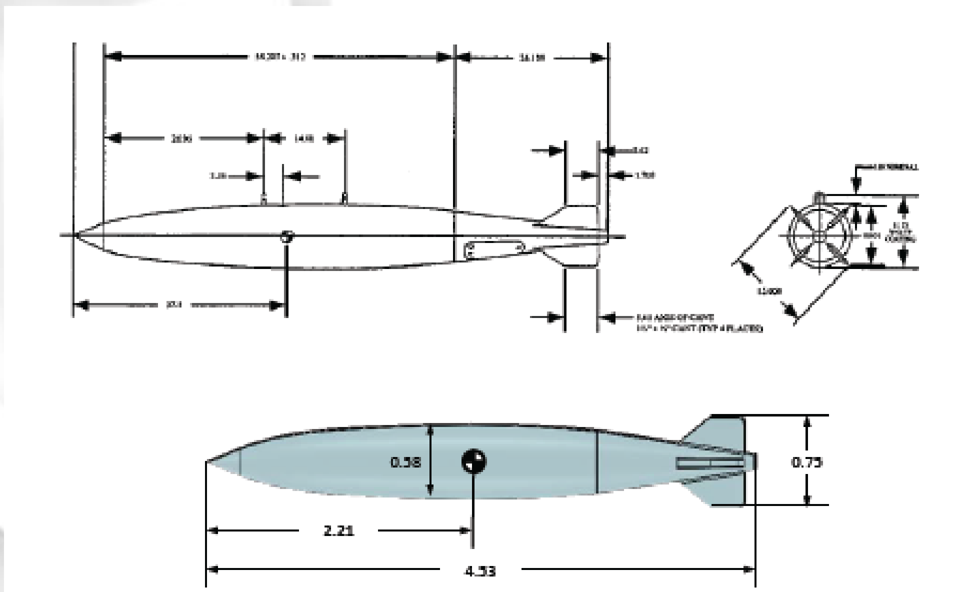
- $1/20^{th}$
- Ogive nose/conical fin



Mk-82 Shaped Store

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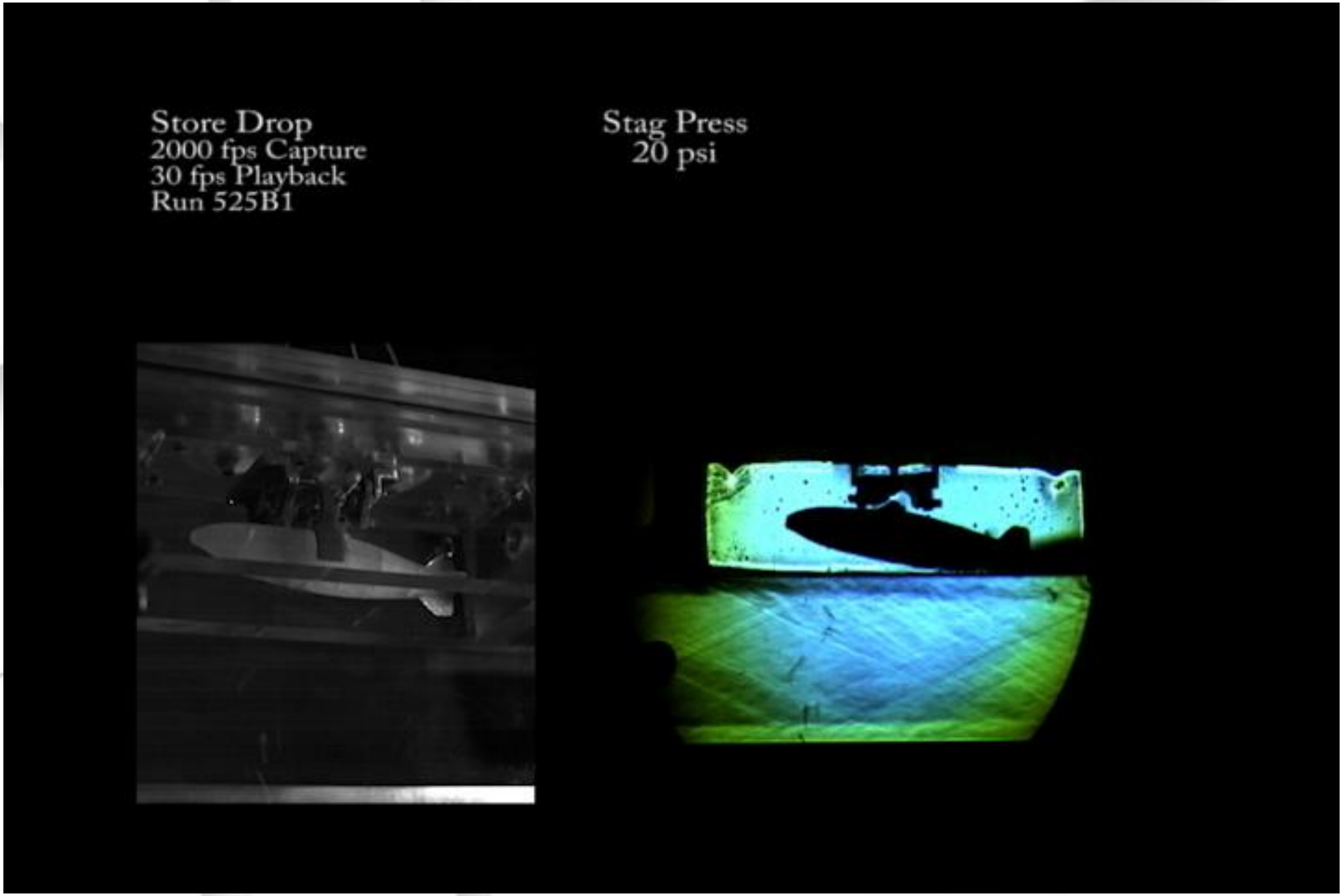
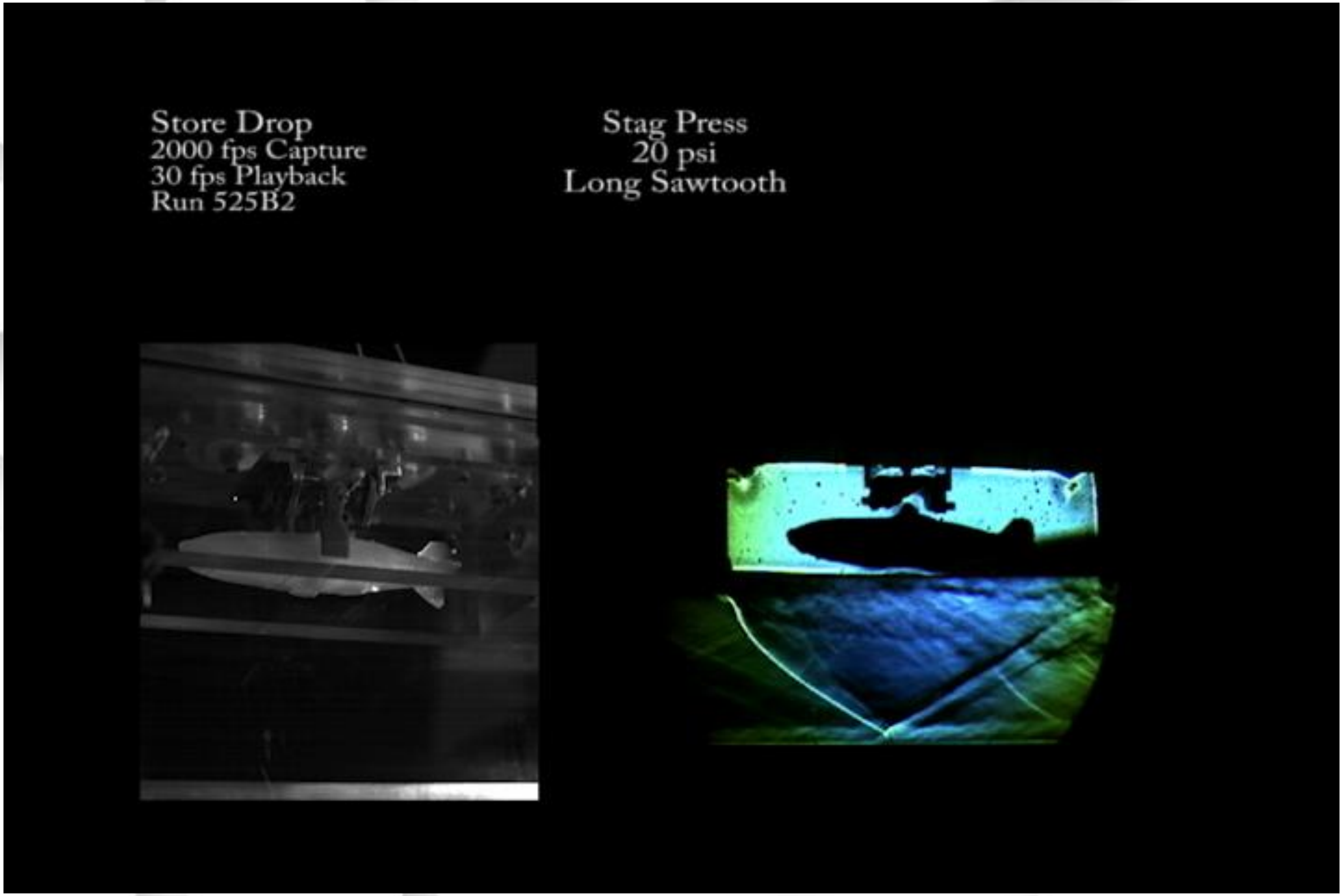


Mk-82 Shaped Store



Scaling Laws Applied

Heavy Mach Scaling

- Test gravity = 32.2 ft/s^2 $\left(g^{'} / g = 1\right)$
- $V_{\infty}^{'}$
- Translation – Representative
- Rotation – Too large
- $$m^{'} = m\left(q_{\infty}^{'} / q_{\infty}\right)\lambda^{2}$$
  $$I^{'} = I\left(q_{\infty}^{'} / q_{\infty}\right)\lambda^{4}$$

Sphere Heavy Mach Scaling

The AFIT of Today is the Air Force of Tomorrow.

- 40k release, Mach 3

$P_{T,sc}$ (Psia)	1	4	12	20
q'_∞ / q_∞	0.011	0.044	0.13	0.22
Weight (lb)	550	138	46	28
Density (lb/ft^3)	225	69	23	14
Material	Titanium	Rubber	Pine	Balsa

Heavy Mach Scaling

- 1 Psia stagnation pressure

Simulated Altitude (ft)	20k	40k	57625	60k
q'_∞ / q_∞	0.0044	0.011	**0.0248**	0.028
Weight (lb)	2813	1136	**500.0**	436
I_{yy} (lb·ft^2)	218	88	**38.7**	34

- 4 Psia stagnation pressure

Simulated Altitude (ft)	20k	27905	40k	60k
q'_∞ / q_∞	0.018	**0.0248**	0.044	0.11
Weight (lb)	703	**500.0**	284	109
I_{yy} (lb·ft^2)	54	**38.7**	22	8

Conclusions

Conclusions

- Good correlation between predicted and measured Rossiter tones
- Pretty reasonable comparison of pressure spectra between experimental runs and CFD model
- Successfully demonstrated the capability to conduct quick, inexpensive freedrop testing at Mach 3 in the AFIT lab
- Good matching of the sphere dynamics between experiment and CFD results.
  - Demonstrated ability to validate the CFD run with in-house experiments.

Conclusions (cont.)

- Determined that the spoiler design used detuned the Rossiter modes in the cavity yet significantly raised the broadband tones
- Demonstrated the positive influence of the spoiler on the separation from a spherical store from a cavity
- Demonstrated the capability to conduct ice freedrop testing of shapes representative of actual stores
- Developed the case that if the stagnation pressure could be sufficiently reduced, heavy Mach scaling laws can be attained with this freedrop test method.

Acknowledgements

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  - Chris Harkless
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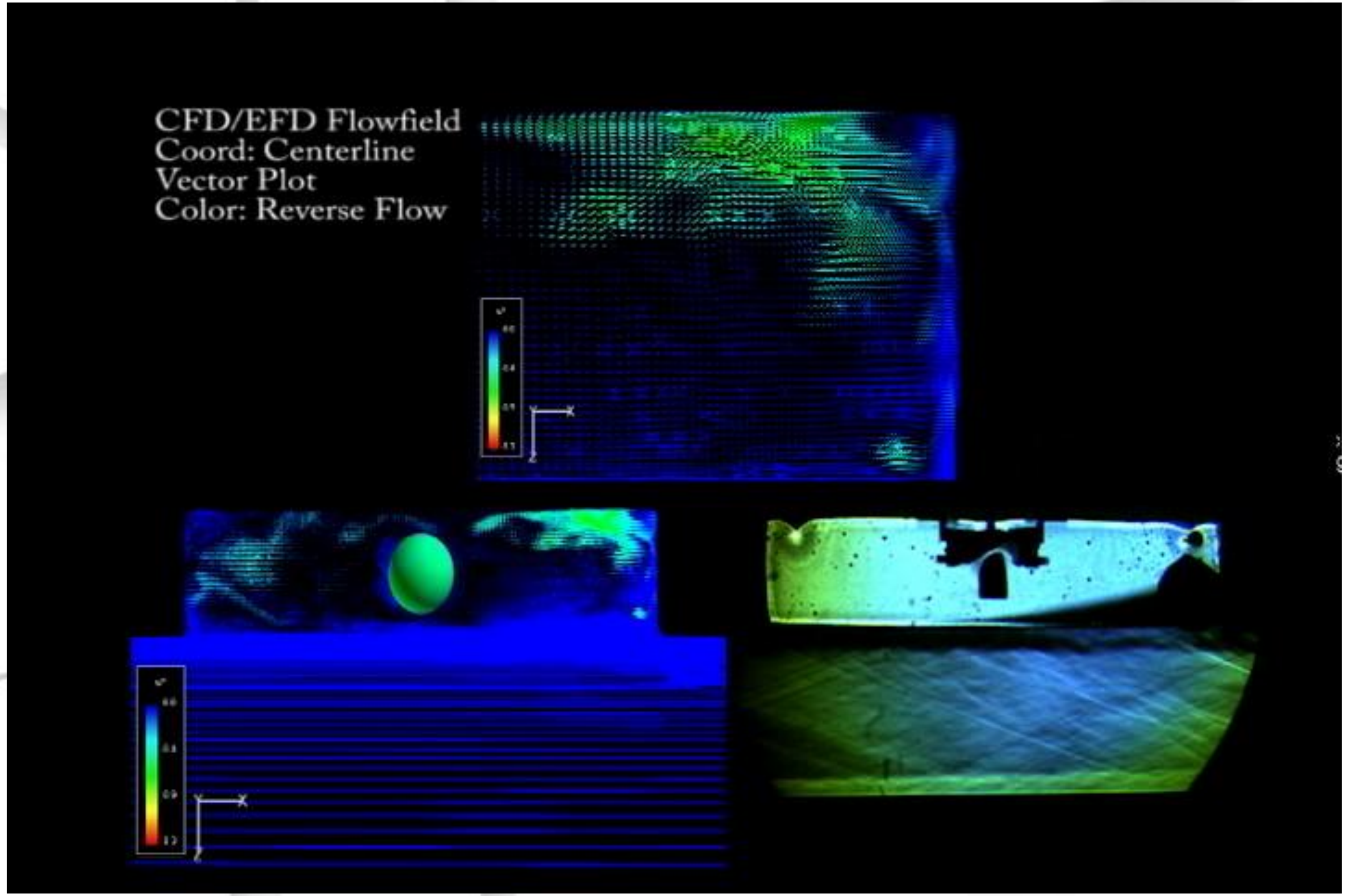
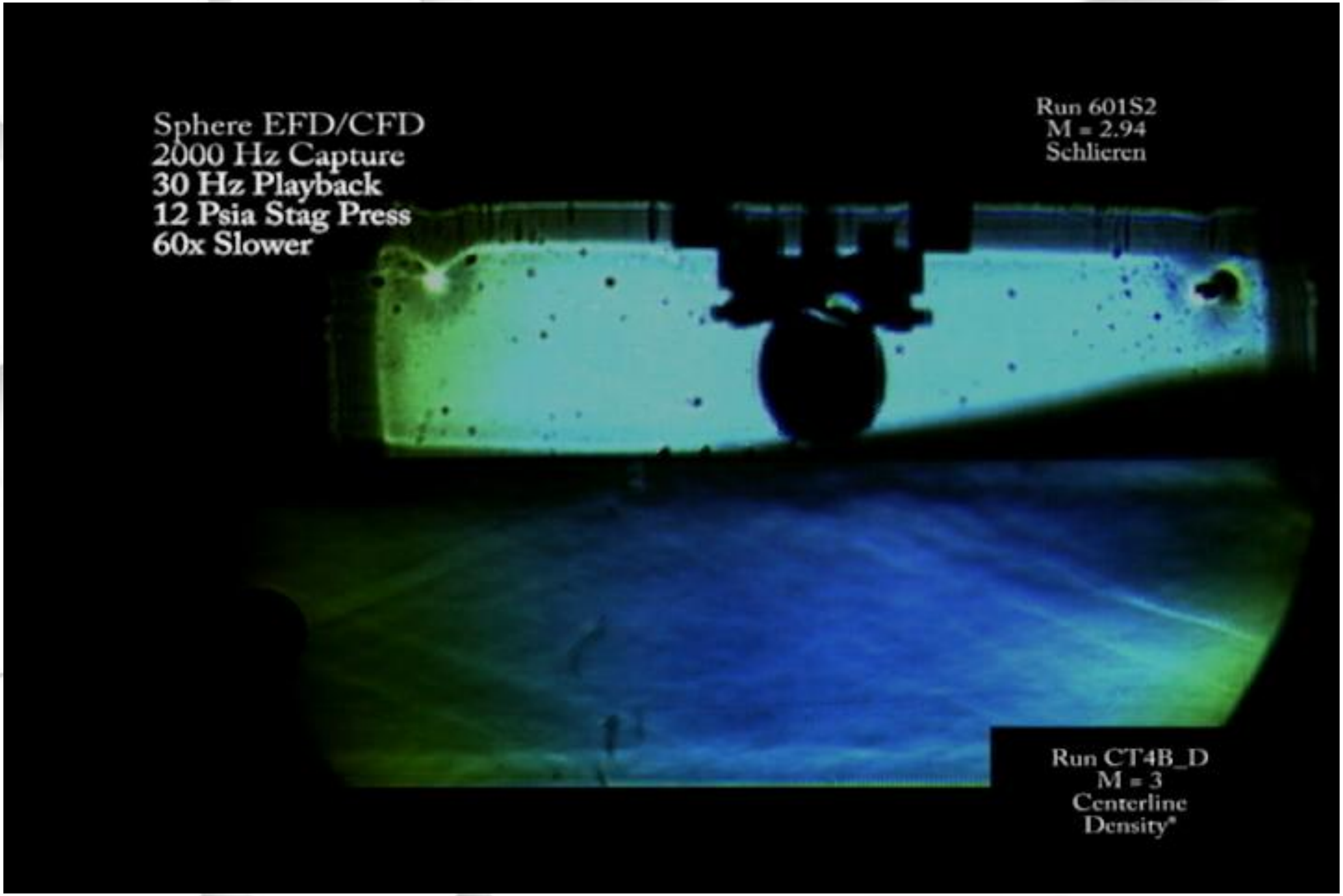
  - Dr. Robert Nichols
  - CDR Neal Kraft
  - Dave Doak
  - Maj Andrew Lofthouse

Questions?

Cavity Flow


CFD/EFD Flowfield
Coord: Centerline
Vector Plot
Color: Reverse Flow

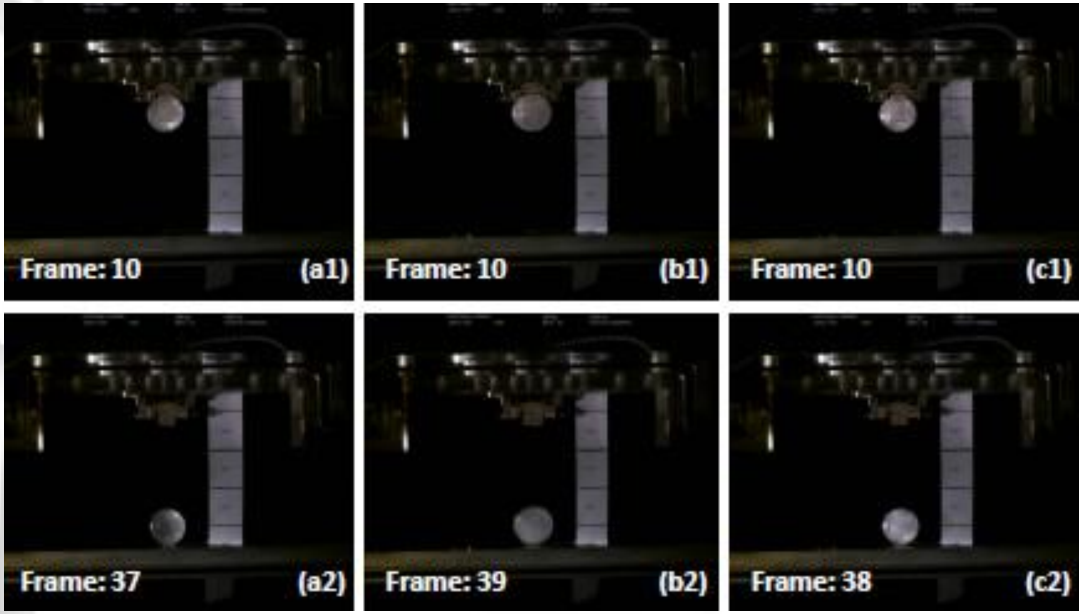
EFD/CFD Sphere Drop



HIFEX

- Long Range Strike Aircraft
- High speed separation
- Active flow control devices
- Acoustic testing
- Separation testing
- Full-scale sled tests

Release Mechanism



- Governing equations

$$\frac{\ddot{Z}}{g} = 1 - \left[C_{N_\alpha}\left(\theta + \frac{\dot{Z}}{V_\infty} + \Delta\alpha\right)\cos\theta - C_A \sin\theta \right]\left(\frac{qS}{mg}\right) + \left(\frac{F_{ej}}{mg}\right)\cos\theta$$

$$\ddot{\theta} = \left[C_{m_\alpha}\left(\theta + \frac{\dot{Z}}{V_\infty} + \Delta\alpha\right) + C_{m_q}\left(\frac{d\dot{\theta}}{2V_\infty}\right)\right]\left(\frac{qSd}{I}\right) + \left(\frac{F_{ej}X_{ej}}{I}\right)$$

- Freedrop scaling laws*
  - Aerodynamic scaling → $M'_\infty = M_\infty$
  - Dynamic scaling → $M'_\infty = M_\infty \sqrt{\lambda \frac{g'}{g} \frac{T_\infty}{T'_\infty}}$

*Marshall (1977)

Dynamic Scaling

- $M_{aero} \neq M_{dynamic}$
- Subsonic
  - Froude scaling
- Transonic/Supersonic
  - Heavy Mach scaling
  - Light Mach scaling

$$Z' = Z\lambda$$

$$\theta' = \theta$$

$$m' = m\left(\rho'_\infty / \rho_\infty\right)\left(V'_\infty / V_\infty\right)^2 \lambda^2 \left(g / g'\right)$$

$$I' = I\left(\rho'_\infty / \rho_\infty\right)\left(V'_\infty / V_\infty\right)^2 \lambda^4 \left(g / g'\right)$$

$$F'_{ej} = m\left(\rho'_\infty / \rho_\infty\right)\left(V'_\infty / V_\infty\right)^2 \lambda^2$$

$$X'_{ej} = X\lambda$$

$$V'_\infty = V_\infty \sqrt{\lambda\left(g' / g\right)}$$

$$t' = t\lambda\left(V'_\infty / V_\infty\right)$$

Heavy Mach Scaling

- Test gravity = 32.2 ft/s² $\left(g^{'}/g=1\right)$
- $V_{\infty}^{'}$
- Translation – Representative
- Rotation – Too large
- $$m^{'}=m\left(q_{\infty}^{'}/q_{\infty}\right)\lambda^{2}$$
  $$I^{'}=I\left(q_{\infty}^{'}/q_{\infty}\right)\lambda^{4}$$

Light Mach Scaling

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- Augmented gravity $\left(g^{'} \neq g\right)$
- Translation – Vertical displacement under predicted
- Rotation – Representative
- $$m^{'} = m\left(\rho_{\infty}^{'} / \rho_{\infty}\right)\lambda^{3}$$
  $$I^{'} = I\left(\rho_{\infty}^{'} / \rho_{\infty}\right)\lambda^{5}$$

Sphere Freedrop

- Simple shape
- Consistent mass properties
- No pitch considerations
- Tractable grid generation