SAND2018-0195PE

Engineering Sciences and National Security Applications at Sandia National Laboratories

Turbulent Jet-in-Crossflow Insights from Approximate Analytical Solution Methods

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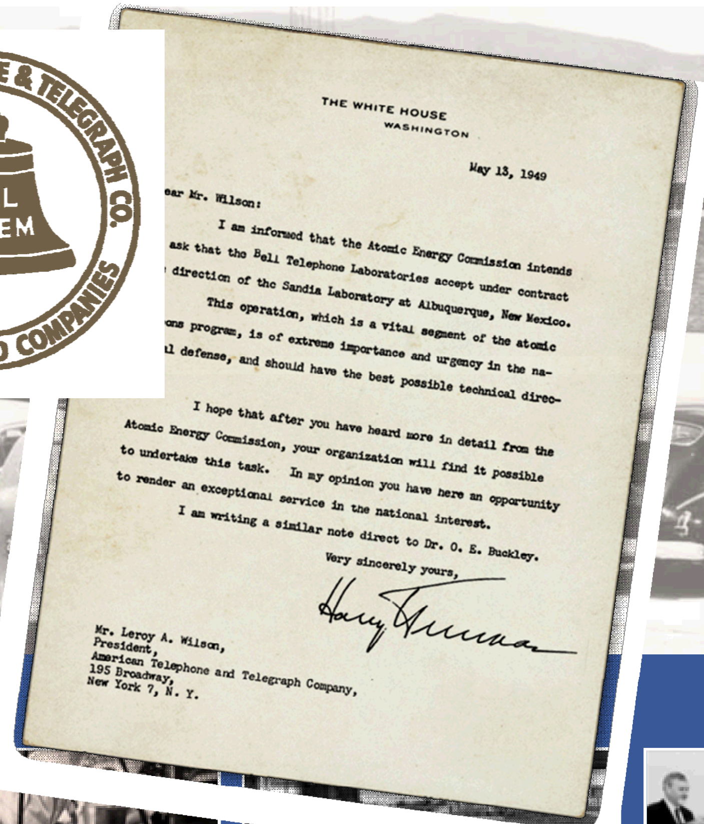
Aero Sciences Group; Engineering Sciences Center

10/24/2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia's History

Exceptional service in the national interest



THE WHITE HOUSE
WASHINGTON

May 13, 1949

ear Mr. Wilson:

I am informed that the Atomic Energy Commission intends
ask that the Bell Telephone Laboratories accept under contract
direction of the Sandia Laboratory at Albuquerque, New Mexico.
This operation, which is a vital segment of the atomic
ons program, is of extreme importance and urgency in the na-
l defense, and should have the best possible technical direc-

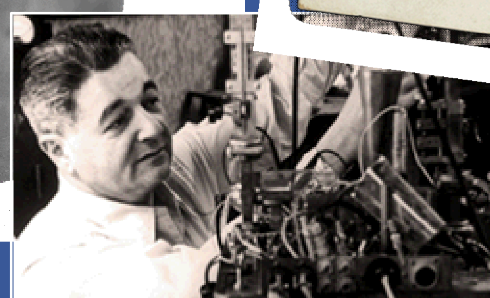
I hope that after you have heard more in detail from the
Atomic Energy Commission, your organization will find it possible
to undertake this task. In my opinion you have here an opportunity
to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.



Sandia's Governance Structure

Sandia Corporation

- AT&T / Bell Labs: 1949 – 1993
- Martin Marietta: 1993 – 1995
- Lockheed Martin: 1995 – April 30, 2017
- NTESS: May 1, 2017 -

Government-owned contr

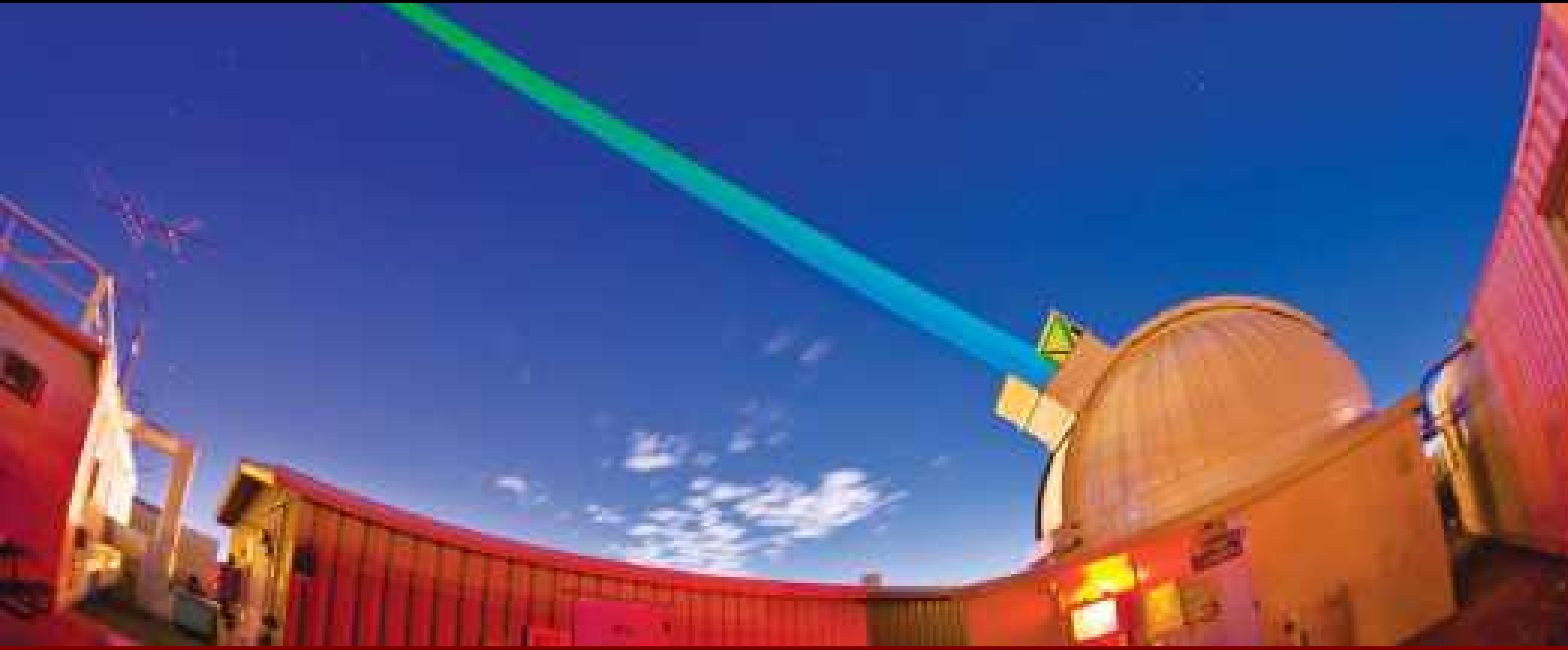
Federally funded research and development center

Sandia Addresses National Security Challenges

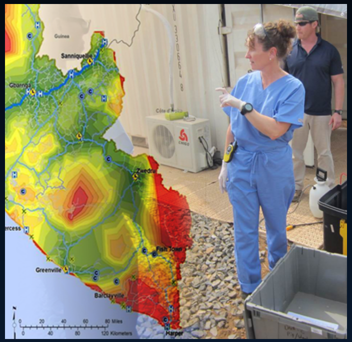
1950s	1960s	1970s	1980s	1990s	2000s	2010s
Nuclear weapons	Development engineering	Multiprogram laboratory	Missile defense work	Post–Cold War transition	START Post 9/11	LEPs Cyber, biosecurity proliferation
Production and manufacturing engineering	Vietnam conflict	Energy crisis	Cold War	Stockpile stewardship	National security	Evolving national security challenges

Sandia - *Today*

As a multi-faceted national security laboratory, Sandia has delivered essential science and technology for more than 60 years and plays a critical role in ensuring U.S. technical superiority.



Sandia's Impact



Ebola Outbreak

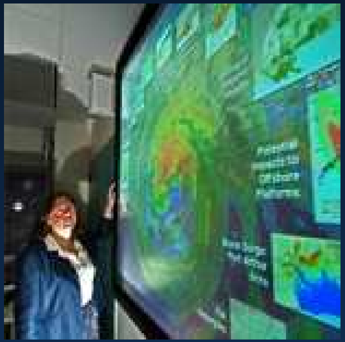
Sandia contributes to global response of Ebola outbreak by developing a sample delivery system cutting the wait time and potentially fatal exposure.

Detecting IEDs

Combat personnel now have a new tool for uncovering improvised explosive devices: Sandia's highly modified miniature synthetic aperture radar system, which is being transferred to the U.S. Army.

Cleanroom invented 1963

$50 billion worth of cleanrooms built worldwide It's used in hospitals, laboratories and manufacturing plants today.

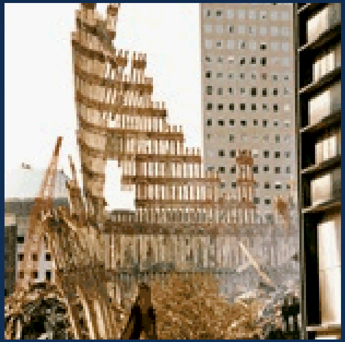


Hurricane Katrina

Sandia is called to assess flooding and infrastructure failures.

Fukushima Quake

Sandia helps clean up radioactive wastewater.



9/11

Sandia sets contingency plans for release of materials and aircraft attacks on critical facilities immediately after 9/11. Search dogs are equipped with cameras for search and rescue K-9 handlers. The capability allowed search efforts to be carried out in spaces inaccessible to humans.

Sandia has two main locations

Science labs

Nuclear energy lab

Fossil energy lab

Energy efficiency and renewable energy lab

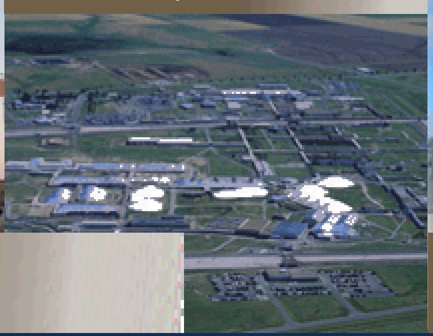
Sandia Sites

Albuquerque, New Mexico

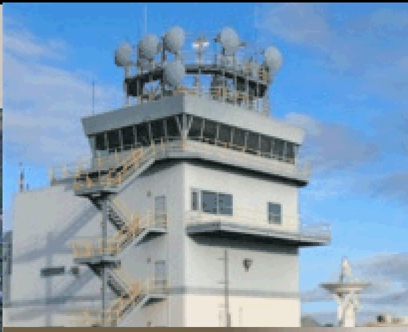
Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

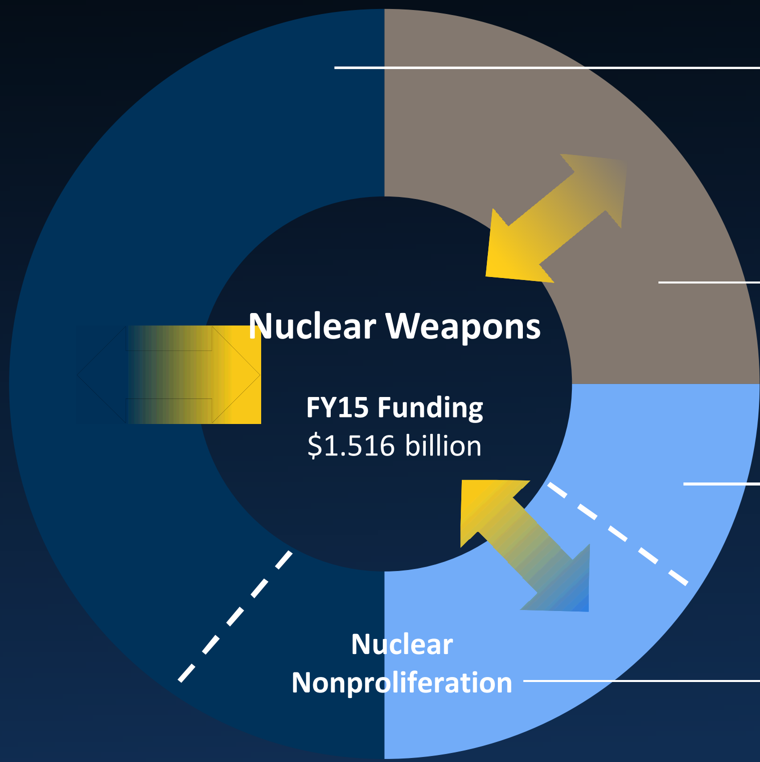


Pantex Plant, Amarillo, Texas



Tonopah, Nevada

Sandia’s Funding - ~$2.8 Billion



Department of Defense
$614M + $92M (Nuclear Nonproliferation)
= $706M

Department of Energy (DOE)
Energy Programs
$167M

Department of Homeland Security &
Department of Defense Infrastructure Security
$81M

NNSA Nuclear Nonproliferation
$144M

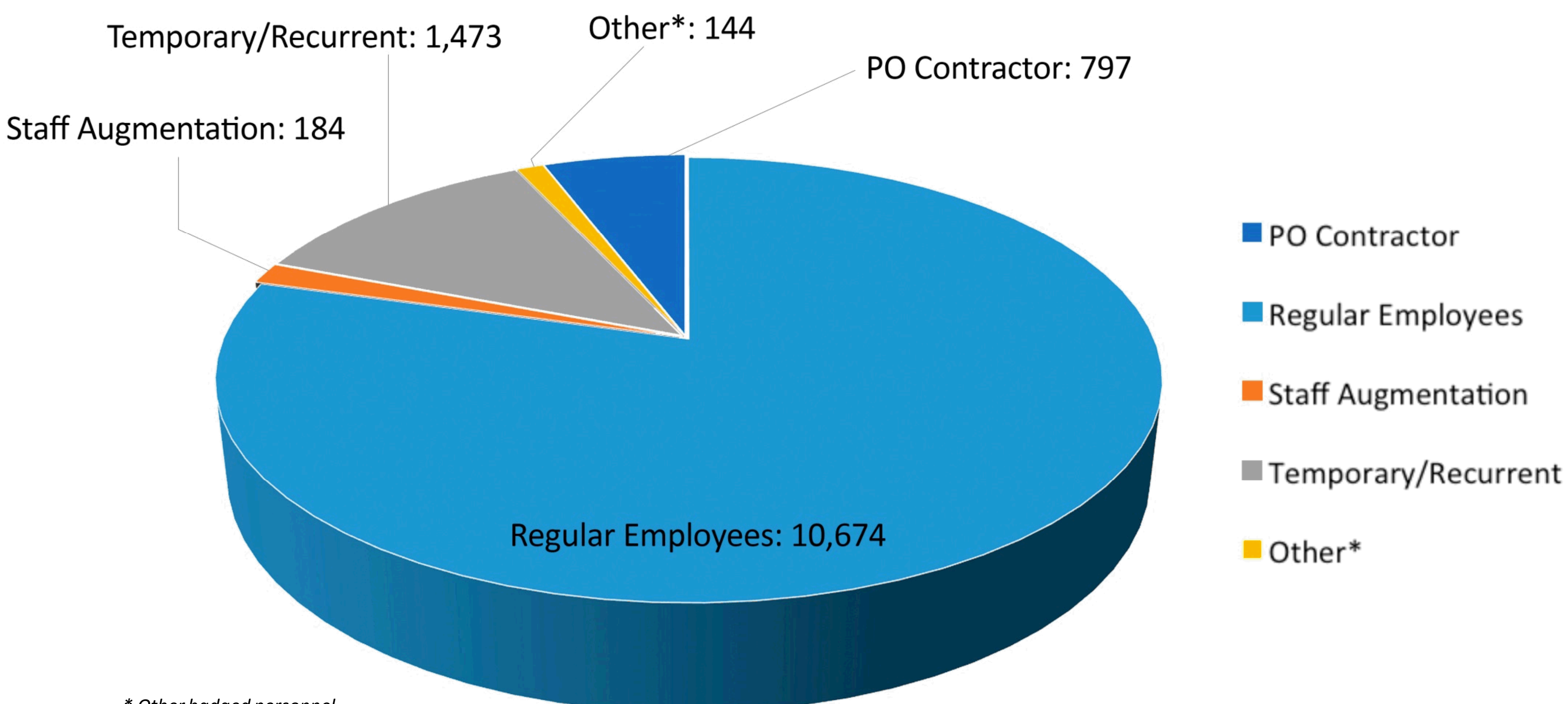
***Note:* Other DOE and non-DOE Funding**
$195M

High reliability, high consequence of failure, challenging environments, and technology solutions

Our Workforce

- Total Sandia workforce: 13,332
- Regular employees: 10,574
- Advanced degrees: 6,085 (57%)

Data as of January 31, 2017



** Other badged personnel*

Fulfilling Our National Security Mission

Nuclear Weapons

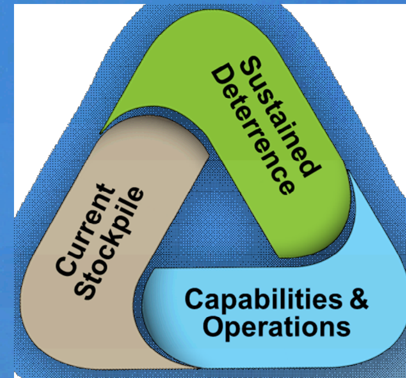
Global Security

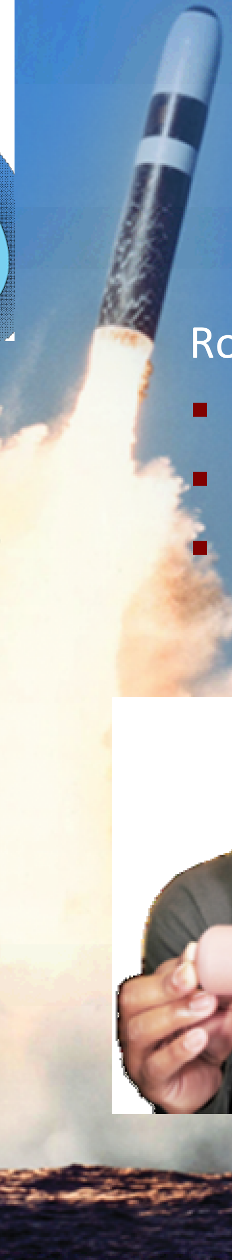
Energy & Climate

Defense Systems & Assessments

Nuclear Weapons

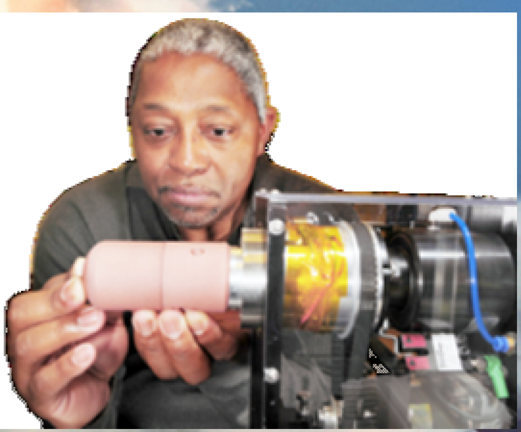
Sandia assumes an increasingly pivotal role in sustaining the nation's nuclear deterrent.





Roles:

- Design
- Production
- Warhead systems engineering



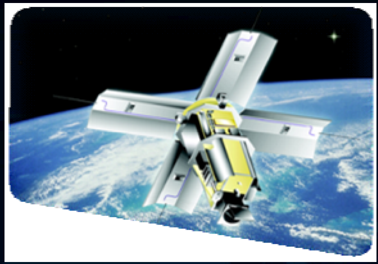
Global Security

Nonproliferation

Critical Asset Protection

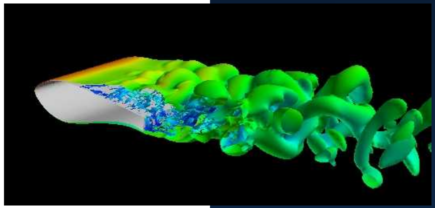
Global Security

Remote Sensing



Energy & Climate

- Energy Security
  - Climate Security
    - ture Security
    - g Capabilities
    - ewable Energy



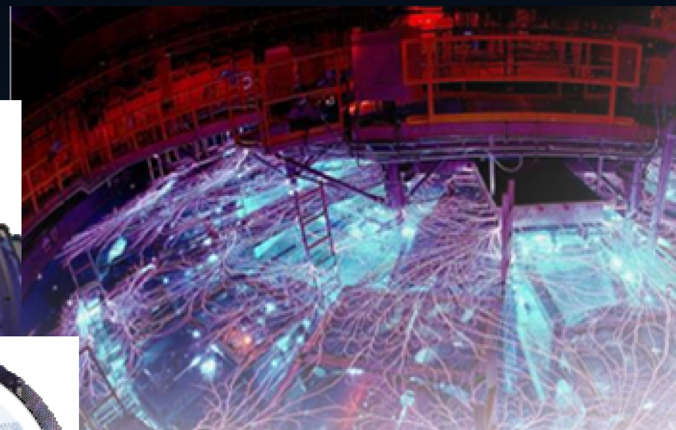
Defense Systems & Assessments

We support our troops arc … *d help to keep them safe*

Our Foundations in Research

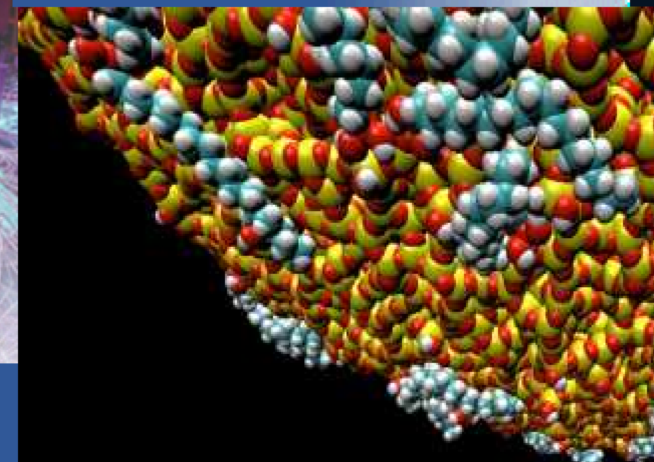
We support essential research-and-discovery activities that translate into invention, innovation, entrepreneurship, economic opportunity, and public benefit.

Computing & Information Sciences

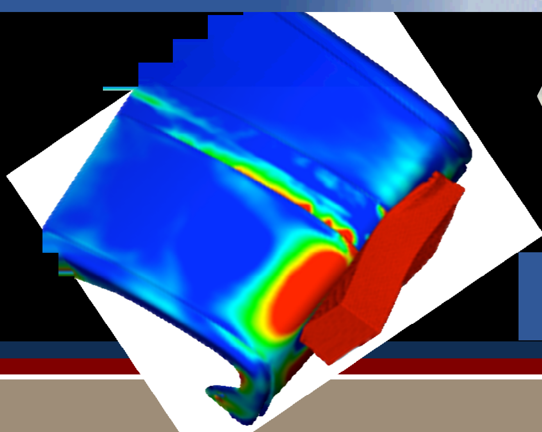


Radiation Effects & High Energy Density Science

Materials Science

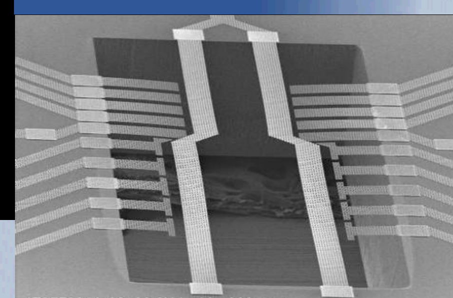


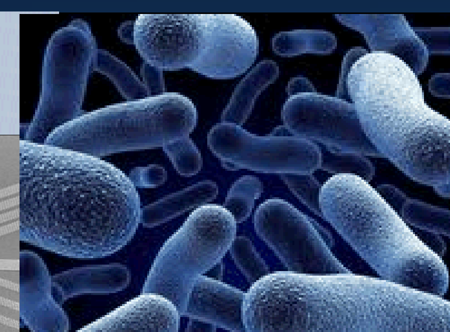
Engineering Sciences



Geoscience

Nanodevices & Microsystems





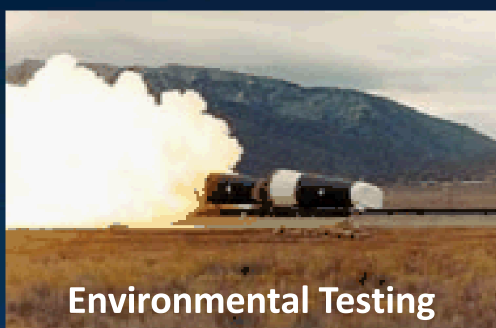
Bioscience

We Steward Key R&D Facilities for the Nation


Combustion Research Facility

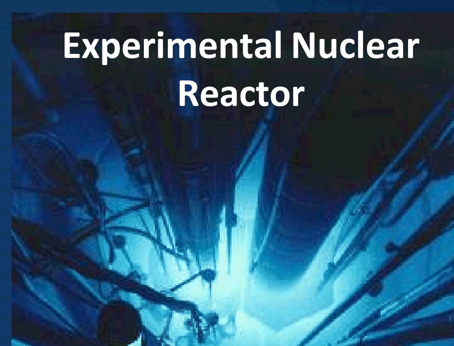

High Performance Computing


Ion Beam Laboratory


Environmental Testing


Microelectronics Fabrication


Z Machine


Experimental Nuclear Reactor

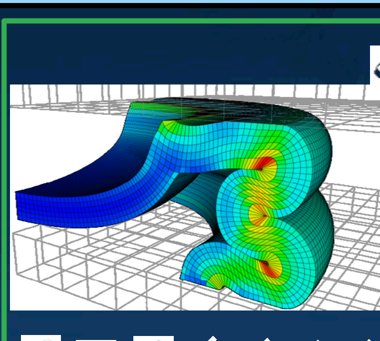

Center for Integrated Nanotechnologies (CINT)

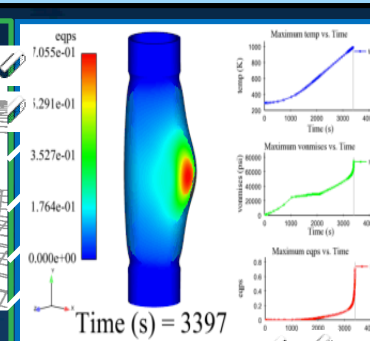
Engineering Sciences Center

Mission: *To provide validated, science-based engineering expertise and solutions across the life cycle of products to inform engineering decisions.*

- We integrated theory, computational simulation and experimental discovery/validation across length and time scales is critical to develop the technical basis for complex systems.
- We partner internally and externally to advance our knowledge base and tool sets to provide physical and computational simulation capabilities that support the development and deployment of innovative, mission-driven products and services.

Engineering Analysis





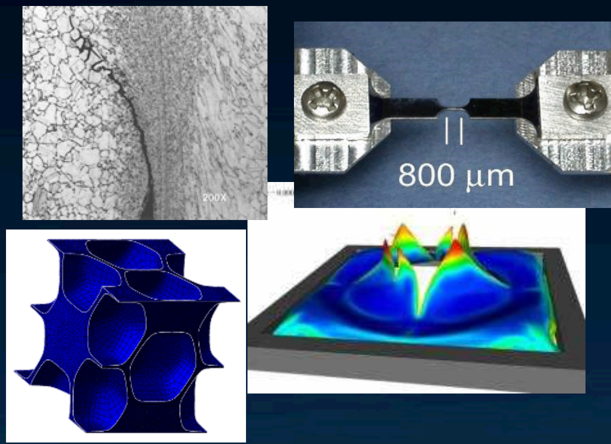
Engineering Science Physical Phenomena

Environmental Simulation & Test

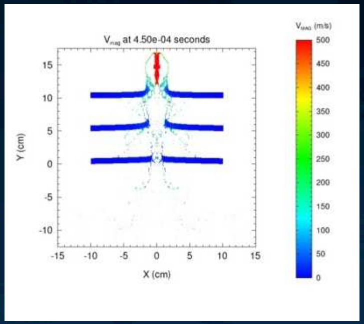
Computational Simulation Technology

Engineering Sciences Core Technical Areas

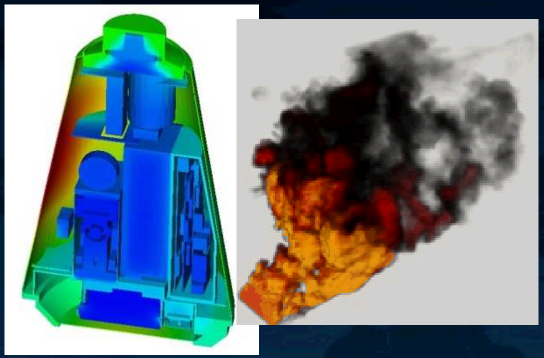
Solid Mechanics



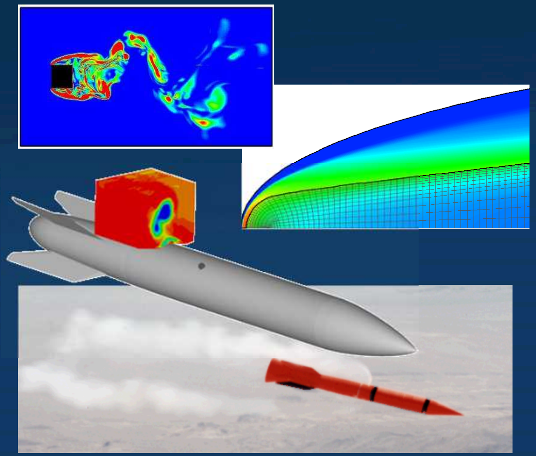
Shock Physics and Energetics



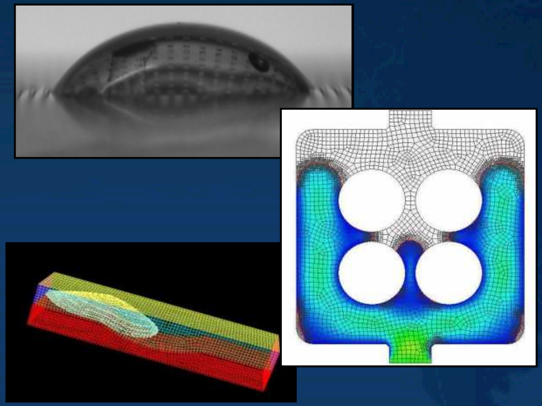
Thermal and Combustion Sciences



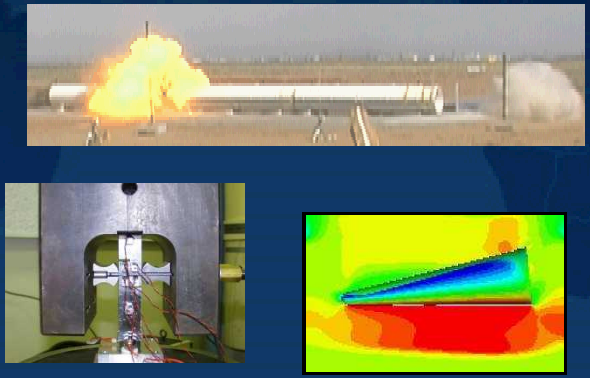
Aerosciences



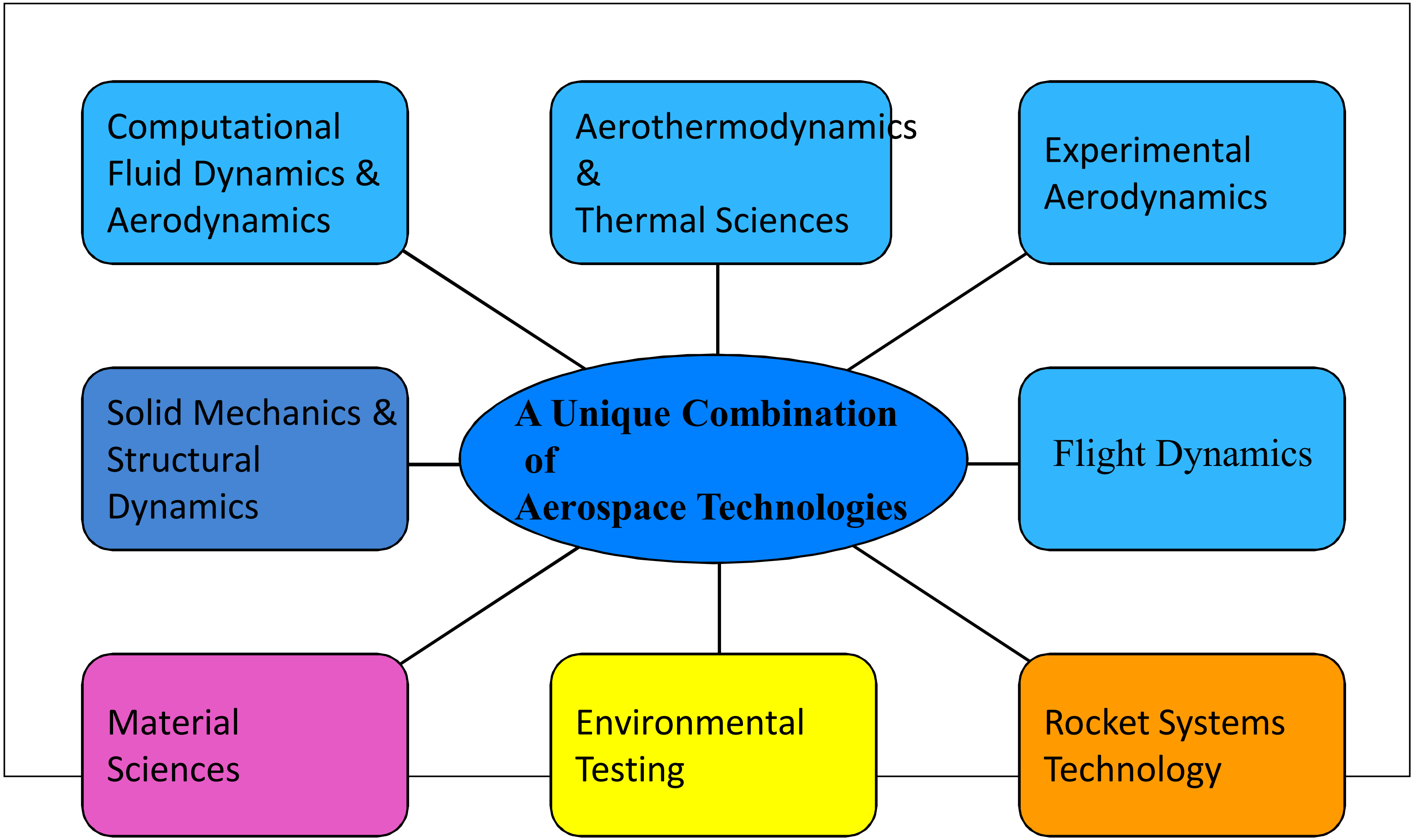
Fluid Mechanics



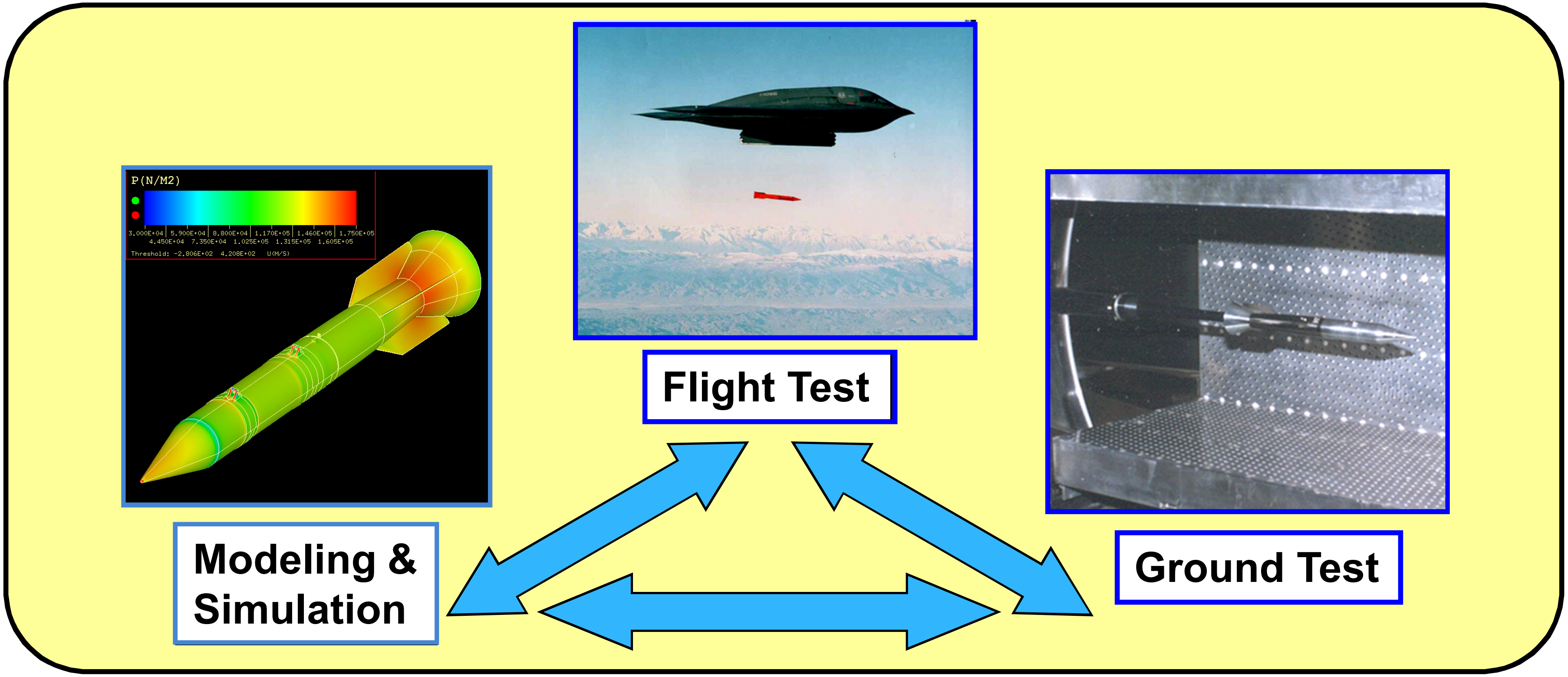
Structural Dynamics



Aerosciences and *Aerospace Technologies* at Sandia



Aeroscience at Sandia



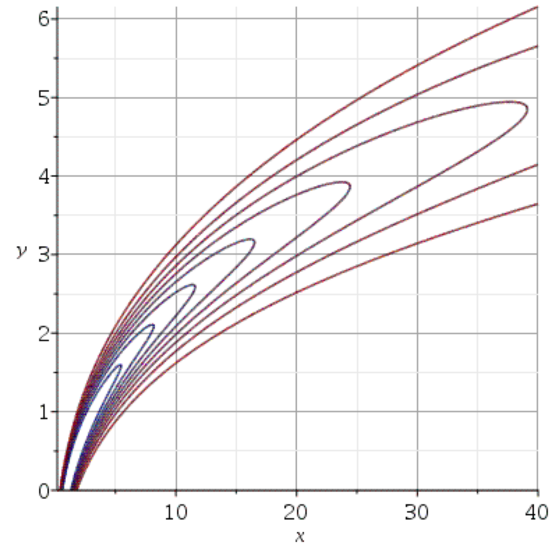
Engineering Solution to Complex Problems:

- Through a sustained R->D->A effort
- By applying combination of ground testing, modeling and simulation and flight testing

- Mod-Sim:
- High Performance Computing Fluid Dynamic Simulation
- Classical Fluid Mechanics

Analytical Methods in Fluid Mechanics

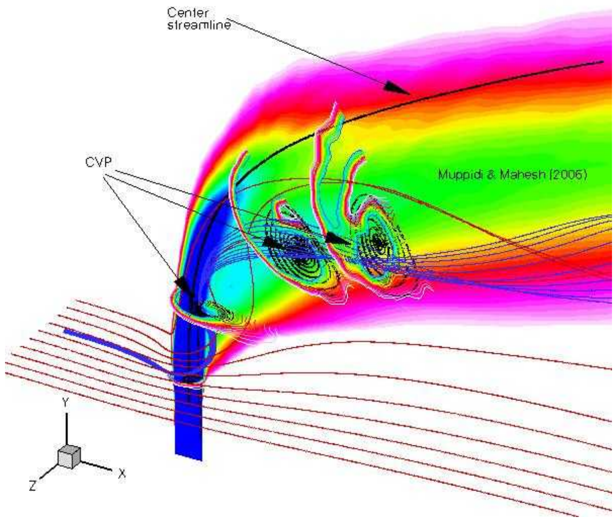
- **Fluid Dynamics Problems**
  - **Experimental Measurements**
  - **Computational Fluid Dynamics (CFD)**
  - **Analytical methods**

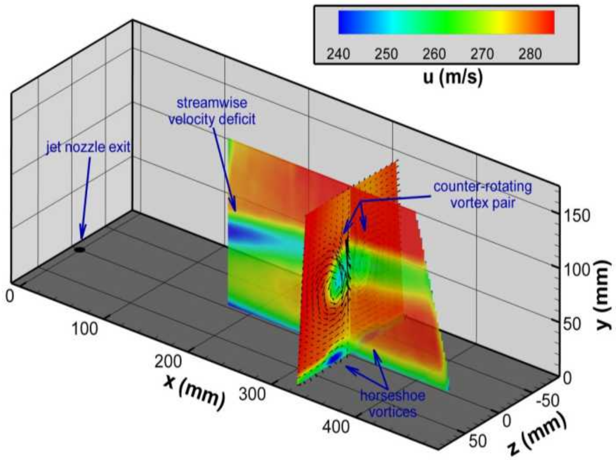


- **Analytical Methods**
  - **Unique type of insight**
  - **Limited applicability**
  - **Often asymptotic**
  - **Virtually always approximate in terms of formulation, solution or (likely) both**

$$\frac{V(x,y)}{V_j} = \frac{1}{2}\left[erf\left(\frac{2x^{1/3} - y - 2\left(\frac{1}{2}\right)^{1/3}}{(2K)^{1/2} x^{2/3}} \right) - erf\left(\frac{2x^{1/3} - y - 2\left(\frac{3}{2}\right)^{1/3}}{(2K)^{1/2} x^{2/3}} \right) \right]$$

Jet-in-Crossflow: Turbulence Parameters





- **Calibration of turbulence model parameters using data(computational/measurements) can be a highly effective procedure (Ray et. al. 2016)**
- **Turbulence model parameters have traditionally been estimated by demanding recovering of simplified/canonical flows**
- **Here we utilize a classical self-similar, axisymmetric wake/jet solution to provide estimates for a k-ε turbulence model implementation**
- **Simplified methods interacting with computational approaches**

JIC Simplified Governing Equations

- **Approximate axisymmetric wake Model (Following Tennekes-Lumley, 1972)**

$$U\frac{\partial u}{\partial x} = \frac{1}{y}\frac{\partial}{\partial y}(yC_\mu \frac{k^2}{\varepsilon}\frac{\partial u}{\partial y})$$

- **Turbulence model (k-ε)**

$$U\frac{\partial k}{\partial x} = \frac{1}{y}\frac{\partial}{\partial y}(yC_\mu \sigma_k \frac{k^2}{\varepsilon}\frac{\partial k}{\partial y}) + C_\mu \frac{k^2}{\varepsilon}\left(\frac{\partial u}{\partial y}\right)^2 - \varepsilon$$

$$U\frac{\partial \varepsilon}{\partial x} = \frac{1}{y}\frac{\partial}{\partial y}(yC_\mu \sigma_\varepsilon \frac{k^2}{\varepsilon}\frac{\partial \varepsilon}{\partial y}) + C_{\varepsilon 1}C_\mu k\left(\frac{\partial u}{\partial y}\right)^2 - C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

- **Momentum constraint**

$$\frac{\pi}{4}\rho_j V_j^2 d^2 = const = 2\pi\rho_\infty \int_0^\infty Uuydy$$

$$= 2\pi\rho_\infty U u_s l^2 \int_0^\infty f\xi d\xi$$

Classical Self-Similar Solution: Far-Field

- Traditional length and velocity scales (axisymmetric wake analogy)

$$u_s = A^* U d^{2/3} x^{-2/3} \quad ; \quad l = B^* d^{2/3} x^{1/3}$$

- Connection to turbulence model

$$k_s = C A^{*2} U^2 d^{4/3} x^{-4/3} \qquad \varepsilon_s = D \frac{A^{*3}}{B^*} \frac{U^3}{d} d^{7/3} x^{-7/3}$$

- Where $k = k_s(x) g(\xi) \quad ; \quad \varepsilon = \varepsilon_s(x) h(\xi) \qquad u = u_s(x) f(\xi)$

- Tennekes and Lumley solution for f(ξ) assume $\frac{g^2}{h} = 1$ define $\alpha = 1$

$$\alpha\left(2f + \xi \frac{df}{d\xi}\right) = \frac{d}{d\xi}\left(\frac{g^2}{h}\frac{df}{d\xi}\right) \qquad f = \exp\left(-\frac{1}{2}\xi^2\right)$$

Classical Self-similar Solution: Far-Field

- Using empirical input (effective viscosity)

$$\mathrm{Re}_T = \frac{u_s l}{\nu} = 14.1$$

- Compute length(spreading) and velocity decay

$$\frac{u_s}{U} = A^*(\frac{d}{x})^{2/3} \approx \frac{1}{2}(\frac{\mathrm{Re}_T}{3})^{2/3} J^{1/3}(\frac{d}{x})^{2/3}$$

$$\frac{l}{d} = B^*(\frac{x}{d})^{1/3} = \frac{1}{2}(\frac{3}{\mathrm{Re}_T})^{1/3} J^{1/3}(\frac{x}{d})^{1/3}$$

- These are axisymmetric wake scaling laws

Jet Trajectory: Classical 1/3 law scaling

- Counter-rotating vortex pair CVP induce velocity

$$W = \frac{dz}{dt} = \frac{\Gamma}{4\pi L}$$

- Jet impulse (circulation)

$$\frac{\pi}{4}\rho_j V_j^2 d^2 = 2\rho_\infty U \Gamma L$$

- Combine with spreading rate: $\frac{l}{d} = 0.3 J^{1/3} (\frac{x}{d})^{1/3}$

$$(\frac{z}{d}) = \begin{cases} 3(0.54) J^{1/3} (\frac{x}{d})^{1/3} = 1.62 J^{1/3} (\frac{x}{d})^{1/3} & ; \quad L = 0.8l \\ 3(0.71) J^{1/3} (\frac{x}{d})^{1/3} = 2.13 J^{1/3} (\frac{x}{d})^{1/3} & ; \quad L = 0.7l \end{cases}$$

- Good agreement with measurement and theory: Broadwell and Breidenthal[12], Greitzer, et. al.[19]and Durando[20]

Jet-in Crossflow: Near Field

- Classical far-field behavior is well modeled via axisymmetric wake scaling

$$u_s = A^* U d^{2/3} x^{-2/3} \quad ; \quad l = B^* d^{2/3} x^{1/3}$$

- But a different near-field scaling has also been observed (Hasslebrink and Mungal (2001))

$$u_s = A^* U d^{1/2} x^{-1/2} \quad ; \quad l = B^* d^{1/2} x^{1/2}$$

- This law reverts to the wake scaling far-downstream
- How can we reconcile two different scaling laws in a self-similar analysis?
- **We can compute turbulence equation parameters (constants) that honor near field**
- **But solve the flow problem using the classical far-field**

Near Field: K-ε

- Use near field scaling

$$u_s = A^* U d^{1/2} x^{-1/2} \quad ; \quad l = B^* d^{1/2} x^{1/2}$$

- TKE and ε scaling

$$k_s = C A^{*2} U^2 d^1 x^{-1} \qquad \varepsilon_s = D \frac{A^{*3}}{B^*} \frac{U^3}{d} d^2 x^{-2}$$

- Where

$$k = k_s(x) g(\xi) \quad ; \quad \varepsilon = \varepsilon_s(x) h(\xi)$$

- Effective viscosity constraints

$$\frac{g^2}{h} \approx const \approx 1 \qquad \frac{D}{C_\mu C^2} = \mathrm{Re}_T = const$$

Near Field: K-ε Equations and Constraints

- **Substitute into k-ε**

$$\alpha(2g+\xi\frac{dg}{d\xi})+\frac{1}{\xi}\frac{d}{d\xi}(\xi\frac{dg}{d\xi})+\frac{1}{C}\left(\frac{df}{d\xi}\right)^2-\mathrm{Re}_T\frac{D}{C}h=0$$

$$\alpha(4h+\xi\frac{dh}{d\xi})+\frac{1}{\xi}\frac{d}{d\xi}(\xi\frac{dh}{d\xi})+\frac{C_{\varepsilon 1}}{C}\left(\frac{df}{d\xi}\right)^2-C_{\varepsilon 2}\mathrm{Re}_T\frac{D}{C}\frac{h^2}{g}=0$$

- **To obtain bounded solution for ξ→∞ require that dissipation terms cancel homogeneous term so that:**

$$f(M)g_0\mathrm{Re}_T\frac{D}{C}=2 \qquad C_{\varepsilon 2}\mathrm{Re}_T\frac{D}{C}g_0=4$$

- **Where we have used the linearization** $\frac{h^2}{g}=\frac{g_0 g}{g}h\approx g_0 h$

K-ε Solutions and Constraints

- **With constraint TKE equations can be solved:**

$$g = \frac{1}{2C}\left(2E_{i\_1}(\frac{1}{2}\xi^2) - 2E_{i\_1}(\xi^2) - \exp(-\xi^2)\right)$$

- **Where E_{i_1} is the exponential integral** $E_{i\_1}(x) = \int_x^\infty \frac{e^{-u}}{u} du$

- **Solution permits us to estimate g_0 used previously**

$$g_0 = \frac{1}{2}(g(0) + g(\infty)) = \frac{1}{4C}\left(2\ln(2) - 1\right)$$

- **Algebraic constraints; solve for C_μ**

$$\frac{D}{C_\mu C^2} = \mathrm{Re}_T \quad ; \quad \frac{2\ln(2)-1}{4C}\mathrm{Re}_T \frac{D}{C} = 2$$

K-ε Parameter Estimates

- solve for C_μ

$$C_\mu = \frac{8}{(2\ln(2)-1)}\mathrm{Re}_T^{-2} = 0.1$$

- Dissipation constraint $C_{\varepsilon 2}\,\mathrm{Re}_T \frac{D}{C} g_0 = 4$ lets us estimate $C_{\varepsilon 2}$

$$C_{\varepsilon 2} = 2$$

- Finally solve dissipation to give:

$$C_{\varepsilon 1} = g_0 = \left(\frac{2\ln(2)-1}{4(0.072)}\right) \approx 1.34$$

- Where the Bradshaw constraint: $u'v' = \frac{2}{3}(0.45)k_s = 0.3k_s$ has been used.

K-ε Turbulence Model Parameter Estimates

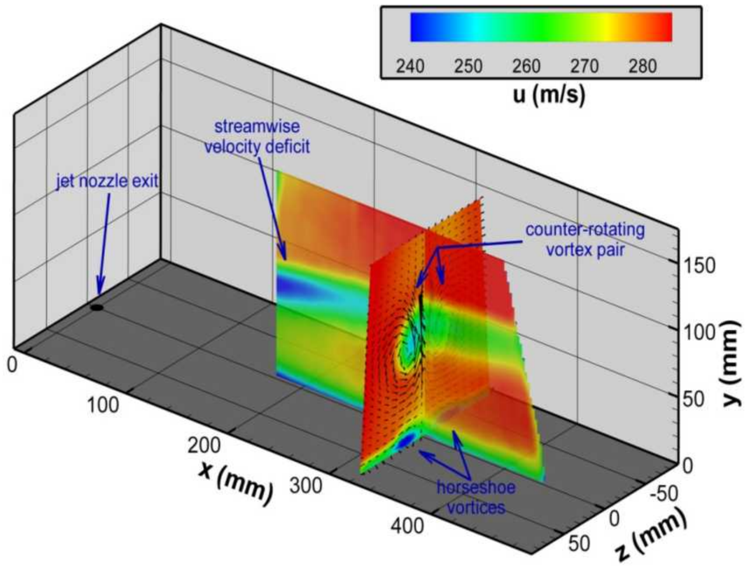
- Parameter estimates

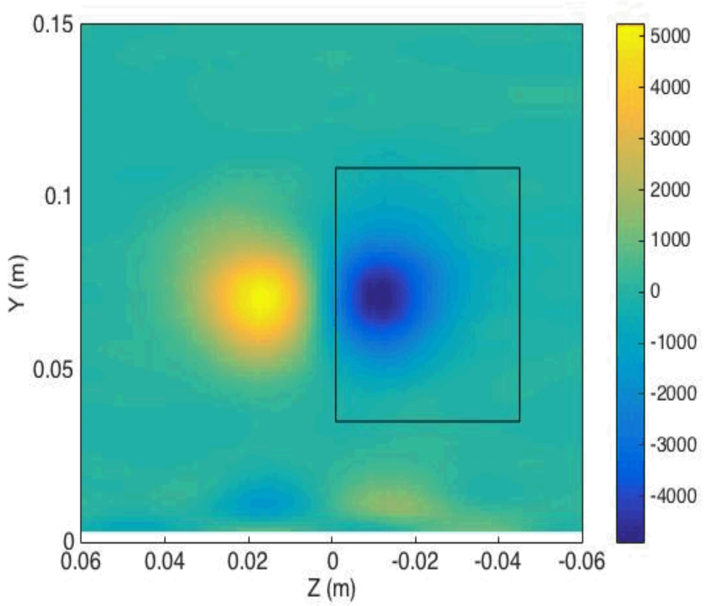
Self-Similar Model (current) (M=0)	**0.10**	**1.34**	**2.00**
Bayesian Model (M=0.8)	**0.10**	**1.42**	**2.10**
Relative Error ($SS_{M=0}$-B)/B(100%)	**0%**	**-6%**	**-5%**
Nominal	**0.09**	**1.44**	**1.92**
Relative Error (SS-N)/N(100%)	**11%**	**-7%**	**4%**

- Analytical solution based parameter estimates agree well with Bayesian calibration approach.
- Compressibility appears to have minimal effect

Computation Using Analytical Parameters

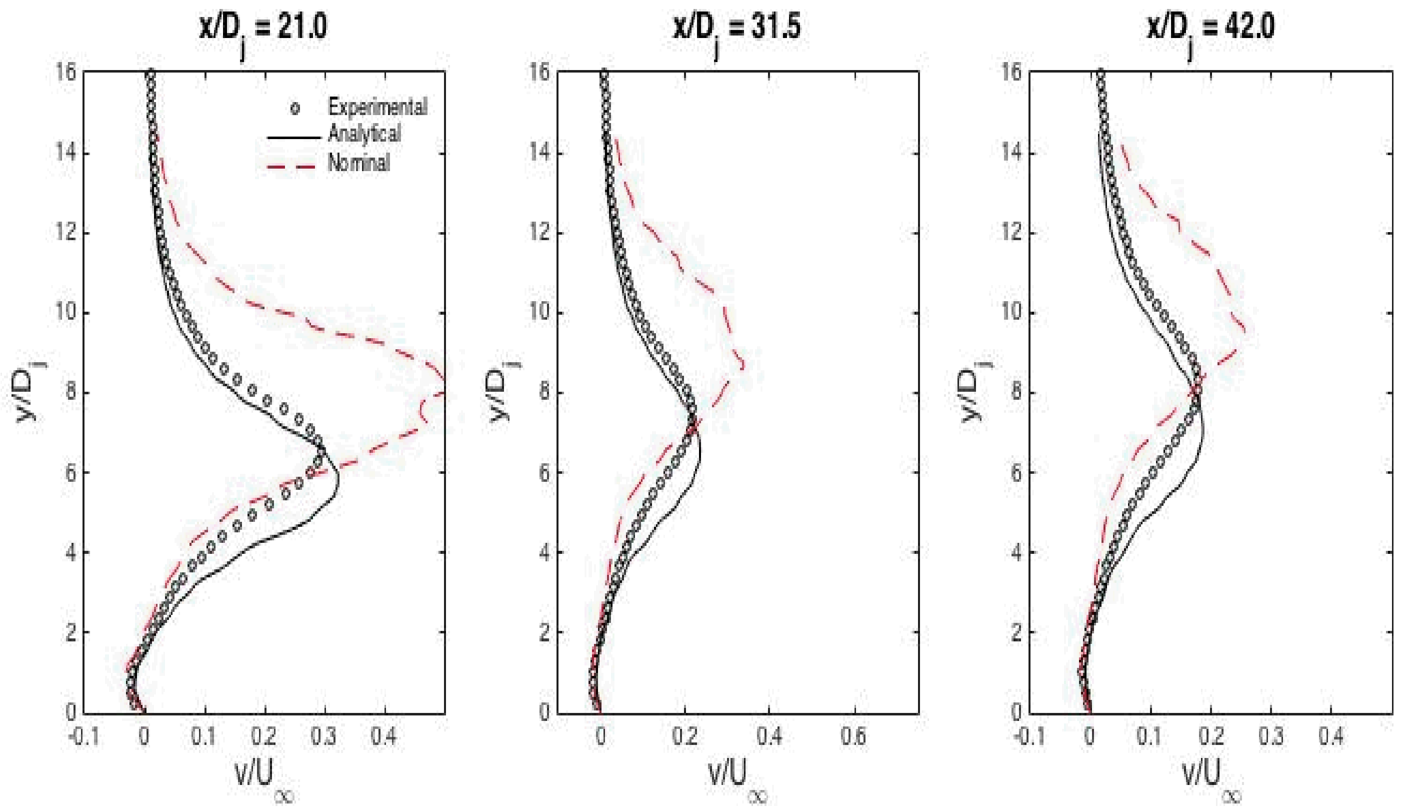
- **JIC RANS computation Sigma; J. Ray, S. Lefantzi, S. Arunajatesan**
- **Measurements: Beresh et. al. (2005)**
- **"v" velocity; <u>Improvement over nominal</u>**





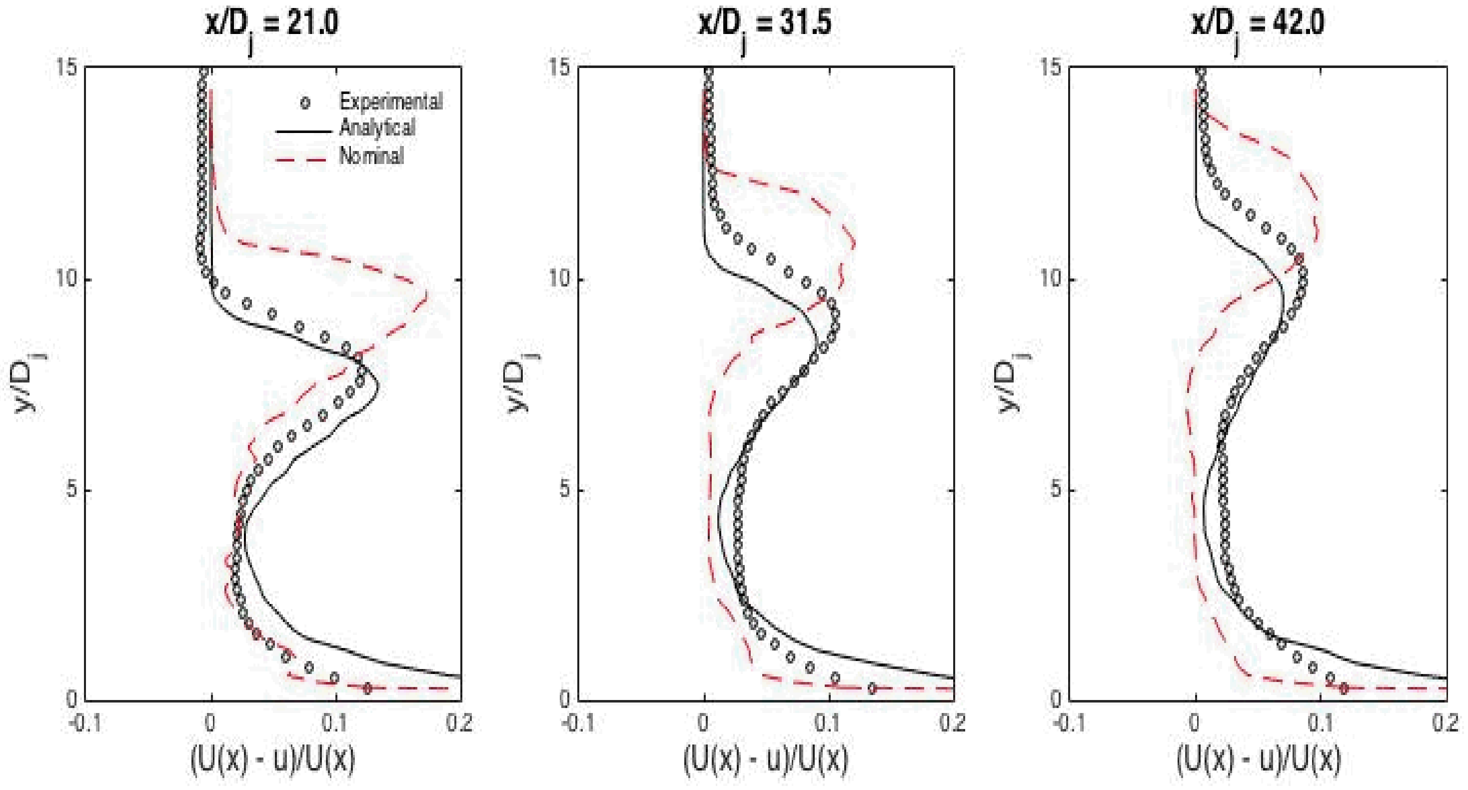
Computation Using Analytical Parameters

- **JIC RANS computation Sigma; J. Ray, S. Lefantzi, S. Arunajatesan**
- **Measurements: Beresh et. al.**
- **"v" velocity, M=0.8; <u>Improvement over nominal</u>**



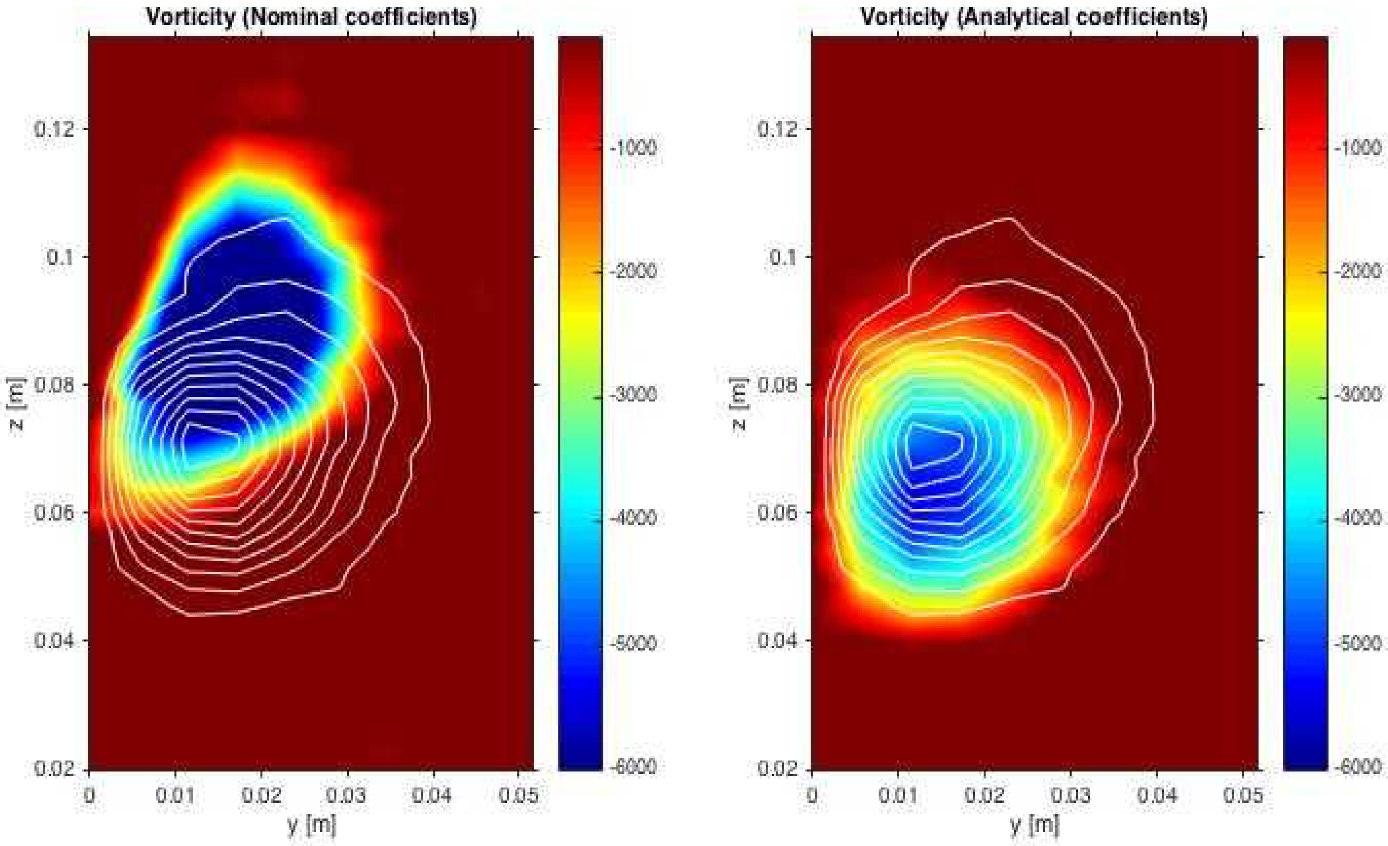
Computation Using Analytical Parameters

- **JIC RANS computation Sigma; J. Ray, S. Lefantzi, S. Arunajatesan**
- **Measurements: Beresh et. al.**
- **Velocity Deficit, M=0.8; <u>Improvement over nominal</u>**



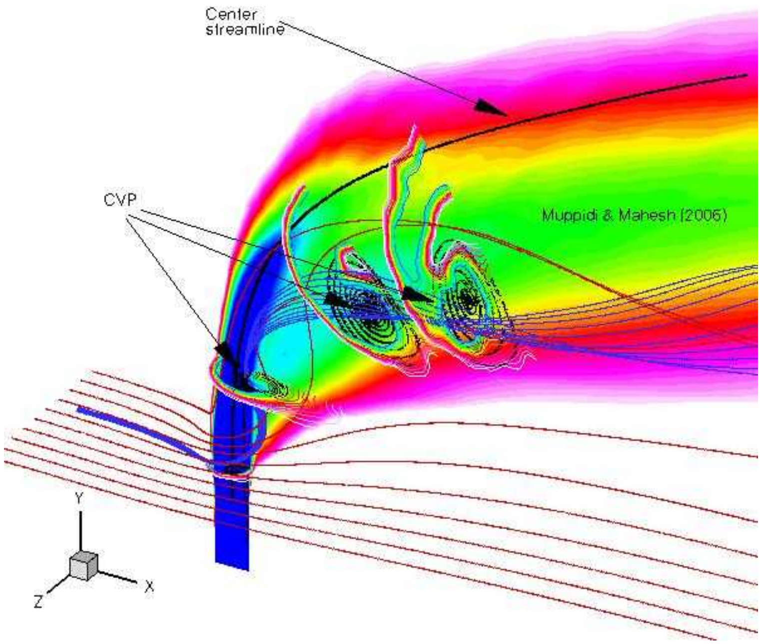
Computation Using Analytical Parameters

- **Vorticity location:**



Jet-in-Crossflow: Turbulence Parameters

- **Comments:**
- **Selection of jet-in-crossflow turbulence model parameters can be improved by utilization of approximate analytical, axisymmetric wake/jet solution**
- **Estimates support Bayesian turbulence model calibration calibration (Ray et. al. 2016)**
- **Analytical modeling supports computational modeling**



Conclusions

- **Jet-in-Crossflow/Analytical Models**
  - **Examined approximate analytical models for turbulent flow problems**
  - **Analytical approaches can provide a useful role in fluid dynamic modeling**
  - **They support experimental and computational studies**

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