Addressing the Challenges of the Design of Hypersonic Vehicles with Simulations

Valerio Viti, PhD, Lead Engineer
Scott Marinus, Senior Engineer
Jeff Tharp, PhD, Principal Engineer
Craig Miller, PhD, Principal Engineer

Ansys, Inc.

Ansys

Ansys technical panel

Valerio Viti, PhD

Lead Application Engineer,
Fluids SME

Scott Marinus

Senior Application Engineer,
Mechanical SME

Jeff Tharp, PhD

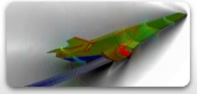
Principal Application Engineer,
Electromagnetic SME

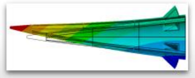
Craig Miller, PhD

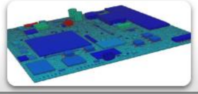
Principal Application Engineer.
Mechanical/Workflow/DT SME

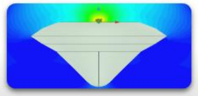
Webinar outline

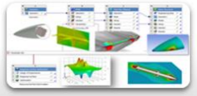
- Introduction
  - Why hypersonics, why now
- The Ansys hypersonic solution: an overview
- Hypersonic case studies


Aerothermodynamic environment


Structural integrity and deformation for a hypersonic vehicle

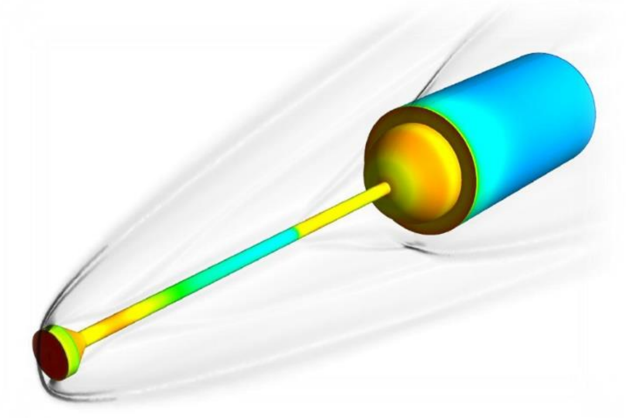

Sensor reliability in high heat-flux environment

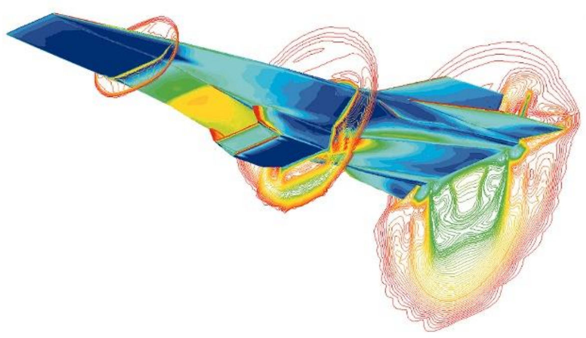

Predicting communication degradation and blackout


Tool-chaining and workflow assembly for hypersonics

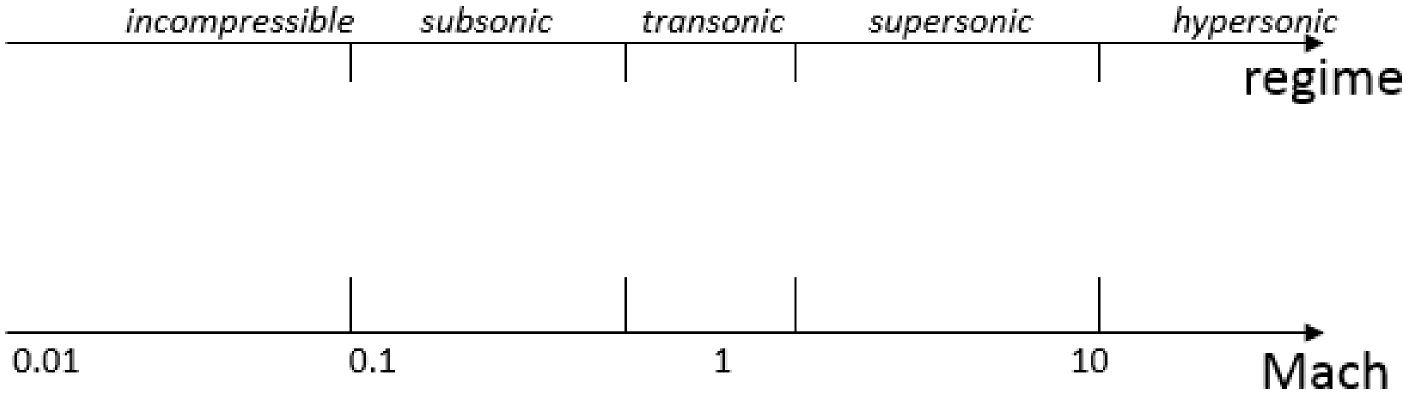
What is hypersonics?

- In aerodynamics, a hypersonic speed is one that is highly supersonic. Since the 1970s, the term has generally referred to speeds of Mach 5 and above.





CFD analysis of X43 courtesy of NASA



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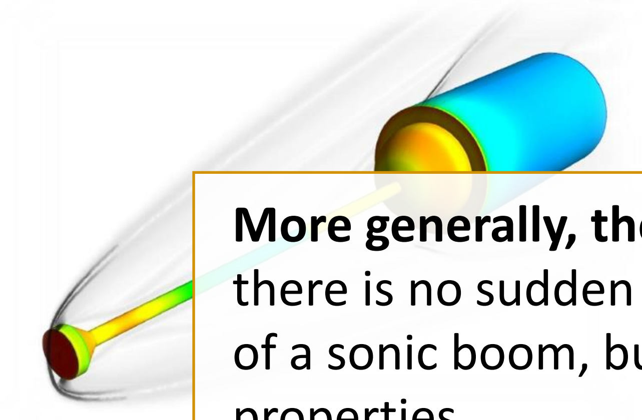
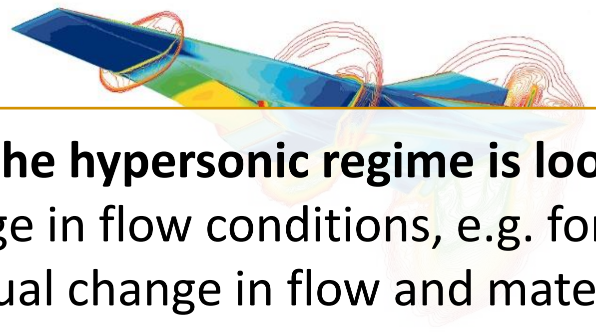
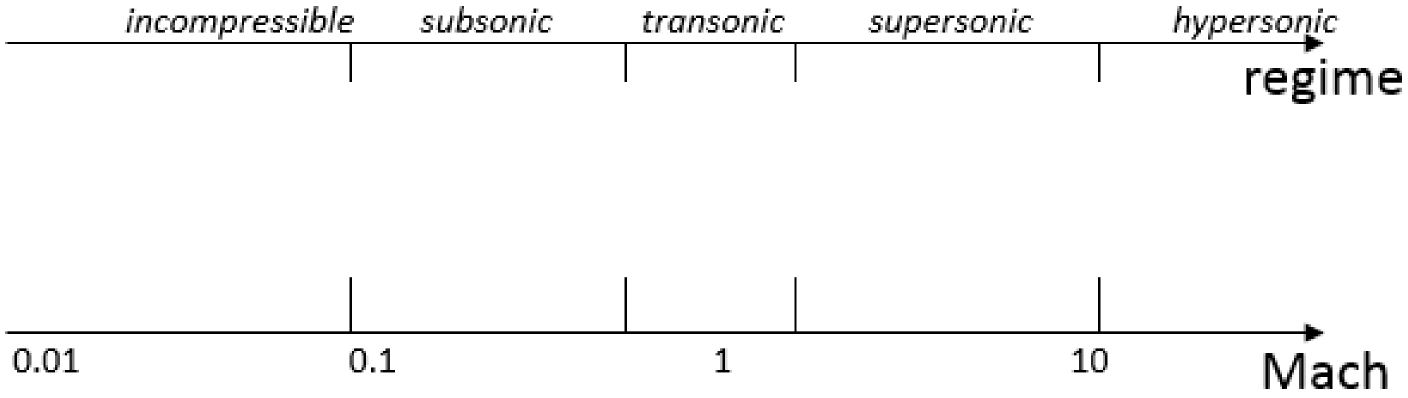


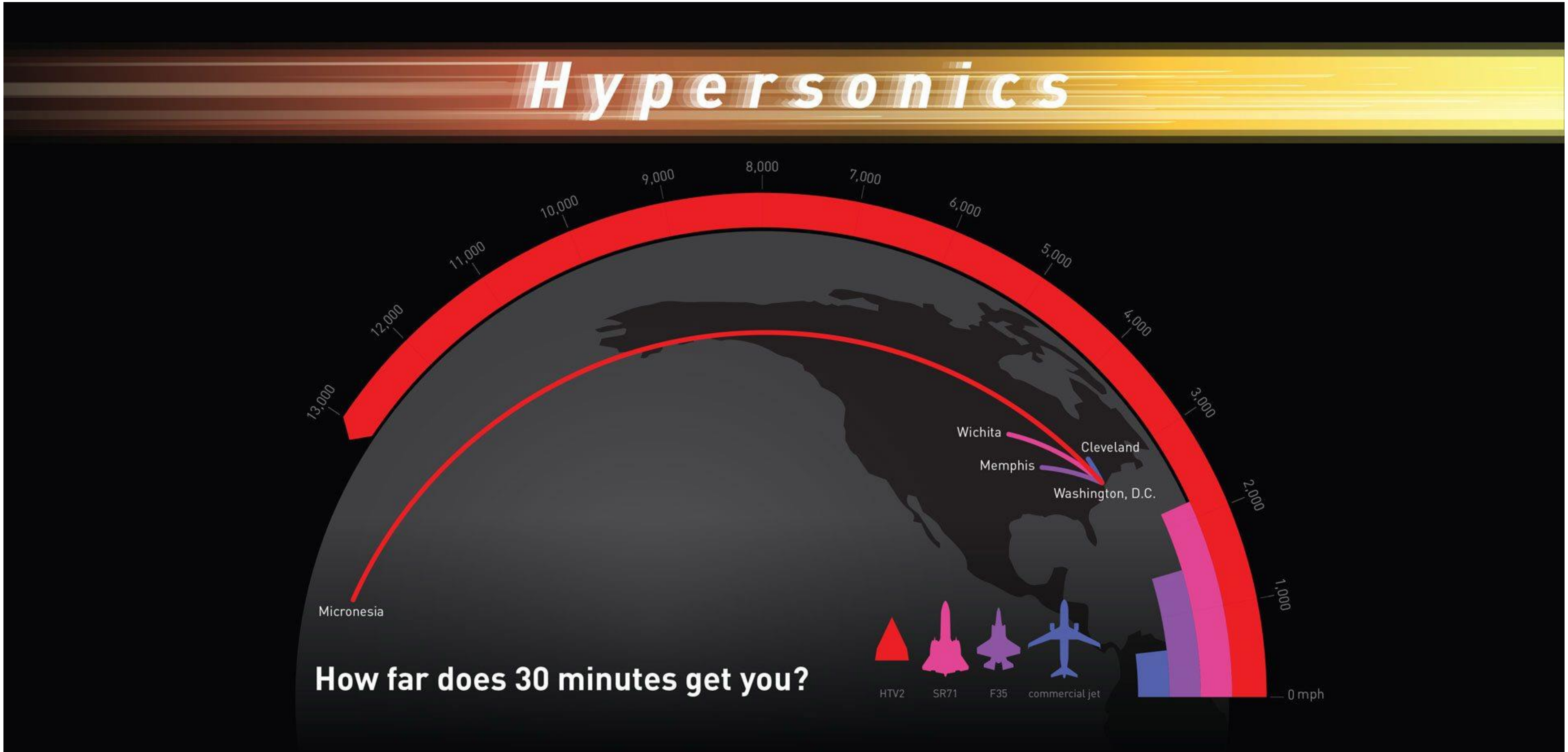


CFD analysis of X43 courtesy of NASA

More generally, the definition of the hypersonic regime is loose; there is no sudden and clear change in flow conditions, e.g. formation of a sonic boom, but rather a gradual change in flow and material properties.

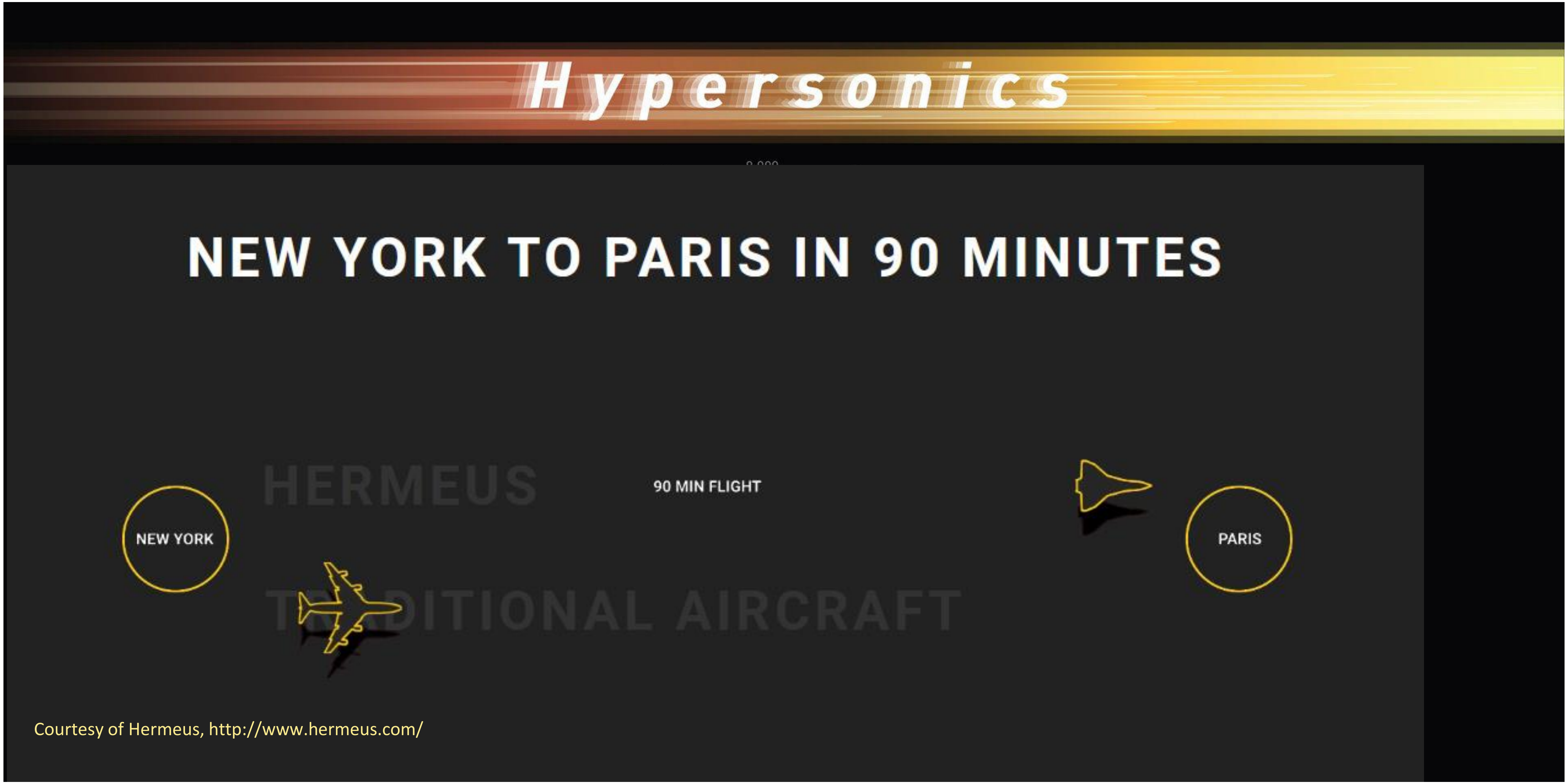


Why the interest in hypersonics



Courtesy of Lockheed-Martin, https://www.lockheedmartin.com/en-us/capabilities/hypersonics.html

Why the interest in hypersonics



Why now?

- **Differently form other times in the past 30+ year, the current impetus behind the development of hypersonic vehicles is coming from the changed global hypersonic scenario.**

BUSINESS INSIDER

TECH | FINANCE | POLITICS | STRATEGY | LIFE | ALL

Russia, China, and the US are in a hypersonic weapons arms race — and officials warn the US could be falling behind

Ben Brimelow Apr. 30, 2018, 9:13 AM

TECH

China Just Launched a Hypersonic Aircraft That Could Slip a Nuke Past US Defences

BI RYAN PICKRELL, BUSINESS INSIDER
8 AUG 2018

European States Plan For Hypersonic Defense

Tony Osborne January 10, 2020

AVIATION WEEK NETWORK

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NATIONAL SECURITY

Nations Rush Ahead With Hypersonic Weapons Amid Arms Race Fear

5:03

+ QUEUE

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TRANSCRIPT

October 23, 2018 · 5:00 AM ET
Heard on Morning Edition

GEOFF BRUMFIEL

Sep 8, 2020, 02:00am EDT | 55,656 views

India Goes Hypersonic: New Missile Technology May Be Answer To China's Navy

H I Sutton Former Contributor
Aerospace & Defense
I cover the changing world of underwater warfare.

China Daily

Russian Ministry of Defense/Sputnik News

Hypersonic global market

Global market forecast for hypersonic weapons by regions, 2019-2027, US $BN

	2019	2020	2021	2022	2023	2024	2025	2026	2027	∑19-27	CAGR 19-27
Americas	4.3	4.5	4.9	5.5	5.5	6.0	6.0	5.9	7.2	49.8	6.7%
Europe	1.7	1.8	1.9	2.2	2.2	2.4	2.4	2.3	2.5	19.3	5.0%
Asia	3.1	3.3	3.6	4.0	4.0	4.4	4.4	4.2	5.0	35.9	6.1%
Middle East	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.5	2.0	13.3	7.4%
Africa	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.1	1.3	8.9	6.3%
TOTAL	11.0	11.5	12.6	14.0	14.2	15.5	15.5	15.0	18.0	127.3	6.3%

Notes:

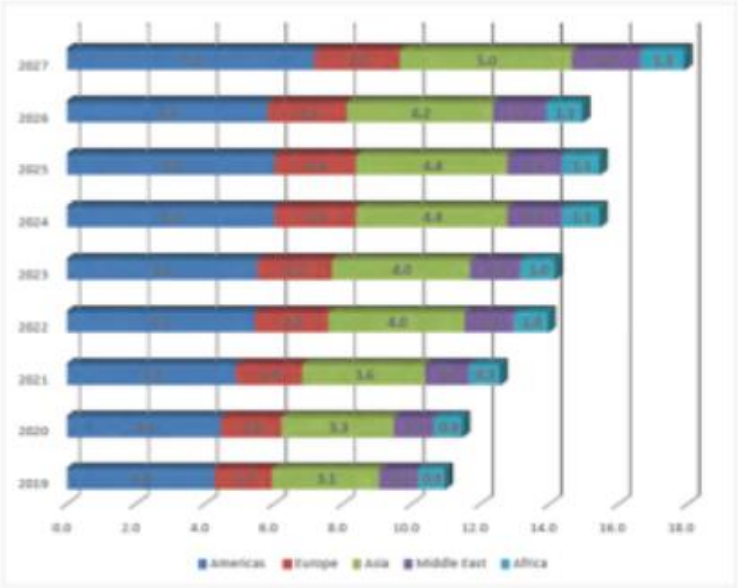
Americas Market Forecast will grow by 6.7% CAGR from 2019-2027, with a cumulative US $49.8 billion during this period.

Europe Market Forecast with grow by 5.0% CAGR from 2019-2027, with a Cumulative US $19.3 Billion during this period

Asia Market Forecast with brow by 6.1% CAGR from 2019-2029, with a cumulative US$35.9 Billion during this period

Middle East Market Forecast will grow by 7.4% CAGR from 2019-2027, with a cumulative US$13.3 Billion during this period

Africa Market Forecast will grow by 6.3% CAGR From 2019-2027, with a cumulative US$8.9Billion during this period



Source: Hypersonic Missiles Report 2019-2027, Institute for Defense and Government, 2019

<u>Estimated global tot: ~ US$127.3B over the next 8 years</u>

What is happening in North America?

STARS AND STRIPES

Military services to work together to speed hypersonic weapon development

"China's hypersonic weapons development outpaces ours," Harris told lawmakers on Capitol Hill. "We're falling behind."

Another top Pentagon official, Michael Griffin, the undersecretary of defense for research and engineering, said in March that the Defense Department must do more than catch up to its adversaries on this technology.

Hypersonic weapons race

AEROSPACE AMERICA

BY KEITH BUTTON | JUNE 2018

Feeling behind, the Trump administration proposes pouring hundreds of millions of dollars into a game of urgent catch-up led in part by Michael Griffin, the Pentagon's chief technology officer and under secretary for research and engineering. Much of the emphasis will be on boost-glide concepts, although air-breathing will still be vigorously pursued.

GOVCON WIRE

Draper Awarded $110M Navy Hypersonic Missile Guidance Research Support Extension

Brenda Marie Rivers November 12, 2018 Contract Awards, News

Charles Stark Draper Laboratory has received a $109.5M contract modification to support the U.S. Navy's research into hypersonic guidance technologies for the common missile compartment of U.S. *Columbia*-class and U.K. *Dreadnought*-class submarines.

The Defense Department said Friday Draper will also provide technical and engineering services for a guidance, navigation and control system for use in hypersonic flight experiments.

The full obligated amount will come from the fiscal 2019 Navy weapons procurement and operations and maintenance funds along with U.K. government funds.

Draper was originally awarded a $13.4M cost-plus-fixed-fee contract in October.

The nonprofit company will perform work in Cambridge, Mass., and El Segundo, Calif., through Sept. 30 of next year.

AVIATION WEEK NETWORK | MARKETS | PRODUCTS | SERVICES | EVENTS | ABOUT

Raytheon Seen As Better Hypersonics Bet Than Lockheed

Michael Bruno August 06, 2019

Credit: Tactical Boost Glide: Raytheon

Tucson Tech: Raytheon deeply involved in next-gen hypersonic weapons

David Wichner Feb 15, 2020

The Washington Post

Democracy Dies in Darkness

Business

Air Force awards massive hypersonic-weapon contract to Lockheed Martin

By Aaron Gregg

April 18

After repeated warnings that Russia and China have each developed a hypersonic missile that could punch through U.S. missile defenses, the U.S. Air Force says it will spend an estimated $1 billion to develop one of its own.

The service announced Wednesday that it has awarded Bethesda, Md.-based defense giant Lockheed Martin a $928 million contract to design, develop and test an air-launched hypersonic strike weapon, which would travel far faster than the speed of sound.

THE WARZONE

Navy Spends Millions On Sub-Launched Hypersonics As USAF Touts New Hypersonic X-Plane

The U.S. military as a whole has a voracious appetite for the fast-flying vehicles and there's no sign it will be satiated anytime soon.

BY JOSEPH TREVITHICK OCTOBER 4, 2018

July 18 (UPI) -- The Johns Hopkins University Applied Physics Laboratory has received a $93 million contract to continue its engineering and research work with the Air Force Nuclear Weapons Center, the Department of Defense announced Monday.

Hypersonic NA funding

Unclassified Pentagon Hypersonic Spending Plan (U.S. $ millions)	Fiscal Year					
	2020	2021	2022	2023	2024	Totals
Conventional Prompt Strike (Navy)	$718.148	$1,169.92	$1,404.29	$1,462.66	$994.888	$5,749.902
Land-Based Hypersonic Missile (Army)	228	181	137	359	274	1179
Hypersonic Conventional Strike Weapon (Air Force)	290	0	0	0	0	290
Air-Launched Rapid Response Weapon (Air Force)	286	201.2	28.5	0	0	515.7
Tactical Boost Glide (DARPA)	162					162
Operational Fires (DARPA)	50					50
Hypersonic Air-breathing Weapon Concept (DARPA)	10					10
TOTAL	$1,744.148	$382.2	$1,569.79	$1,821.66	$1,268.888	$7,956.602

Source: Defense Department Budget

+ $700M for MDA through 2024
+ $222 (x4 yrs) for DARPA (DARPA does not release 5-year cycles)
+ 2.5B of classified work through 2024
+ $157M for hypersonic defensive weapons (2020, most likely to grow)

Tot: ~ $11.4B over the next 5 years

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“It is the sense of Congress that development of hypersonic capabilities is a key element of the National Defense Strategy.”
Section 219 of 2020 SASC draft

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Not only the military. Civilian market too.

FlightGlobal
Pioneering Aviation Insight

NEWS > MANUFACTURER & MRO > AIRCRAFT PROGRAMMES > BOEING UNVEILS LONG-TERM CONCEPT FOR HYPERSONIC AIRLINER

Boeing unveils long-term concept for hypersonic airliner

26 JUNE, 2018 | SOURCE: FLIGHT DASHBOARD | BY: STEPHEN TRIMBLE | WASHINGTON

Flight Global/Boeing

INSIDER

An aerospace startup just won a contract to develop an Air Force One jet that can travel at Mach 5. Here's an early look at the engine that could rocket from New York to Paris in 90 minutes.

David Slotnick Aug 6, 2020, 12:42 PM

Photo: Courtesy of Business Insider/Hermeus

GeekWire

Paul Allen's Stratolaunch Systems lays out a roadmap for hypersonic rocket planes

BY ALAN BOYLE on September 20, 2018 at 4:43 pm

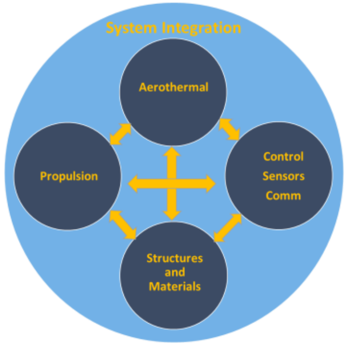
Courtesy of Stratolaunch

Planetary atmospheric re-entry

Photo: Courtesy of NASA

Photo: Courtesy of ESA

Simulation technology for hypersonics



- **The design of these maneuverable hypersonic interceptors requires extensive understanding of all of the physics involved and their interaction**
  - aerothermodynamics, structure, electromagnetic, sensors, guidance and control, etc.

- **Physical testing capabilities for very high-speed aerodynamics are limited:**

Ground Testing
- Few specialized facilities
- Limited time duration and physical scale
- Difficult, if not impossible, to match actual flight conditions
- Expensive to develop and to run

Photo: NASA Langley

Flight Testing
- Extremely expensive
- Often test cycles lasts 5+ years
- Limited instrumentation
- Most realistic scenario

Photo: US Air Force/Reuters

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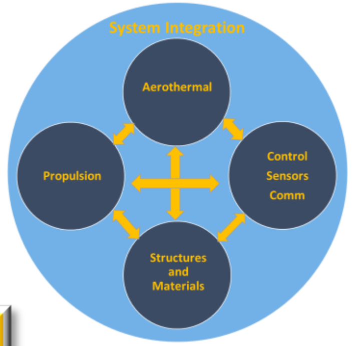

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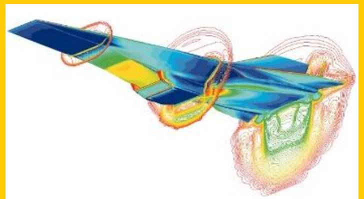
- **Physi**

Physics-based simulation is a key enabling technology for the development of this class of vehicles



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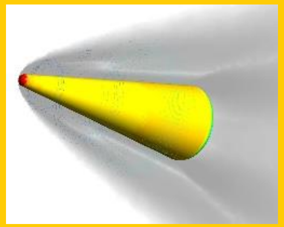

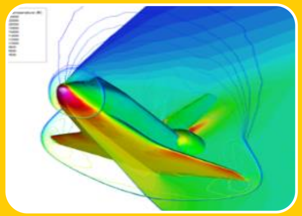

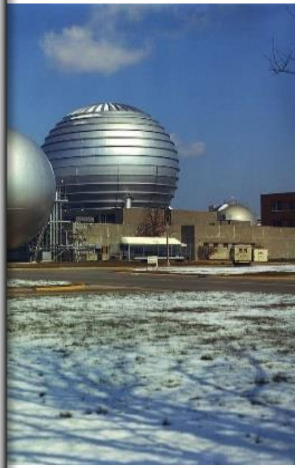

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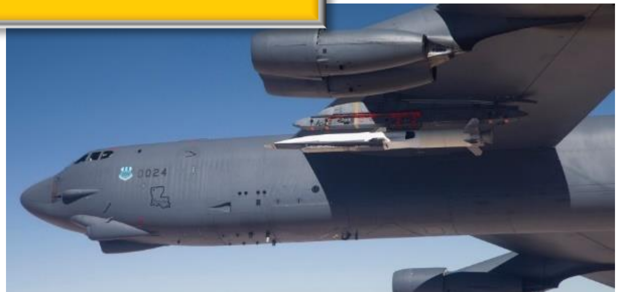
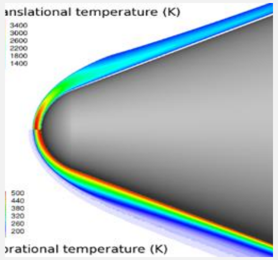


Photo: US Air Force/Reuters

Ansys Hypersonic solution

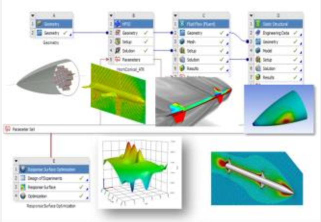
Platform and workflow

- Platform agnostic
- Data and process management
- Traceability



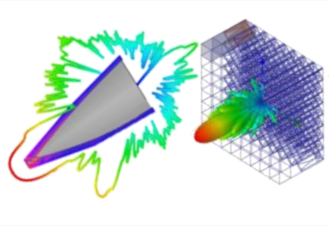
Aerothermodynamics

- Heat fluxes and aero forces
- Shock location and behavior
- Laminar-Turbulent transition
- Flow control
- Chemical non-equilibrium
- Thermodynamic non-equilibrium
- Ablation
- Aero optics



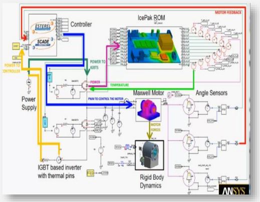
Process Integration and Design Optimization

- Platform agnostic
- Multiphysics
- Parametric analysis
- Design optimization
- Data and process mngt
- Traceability



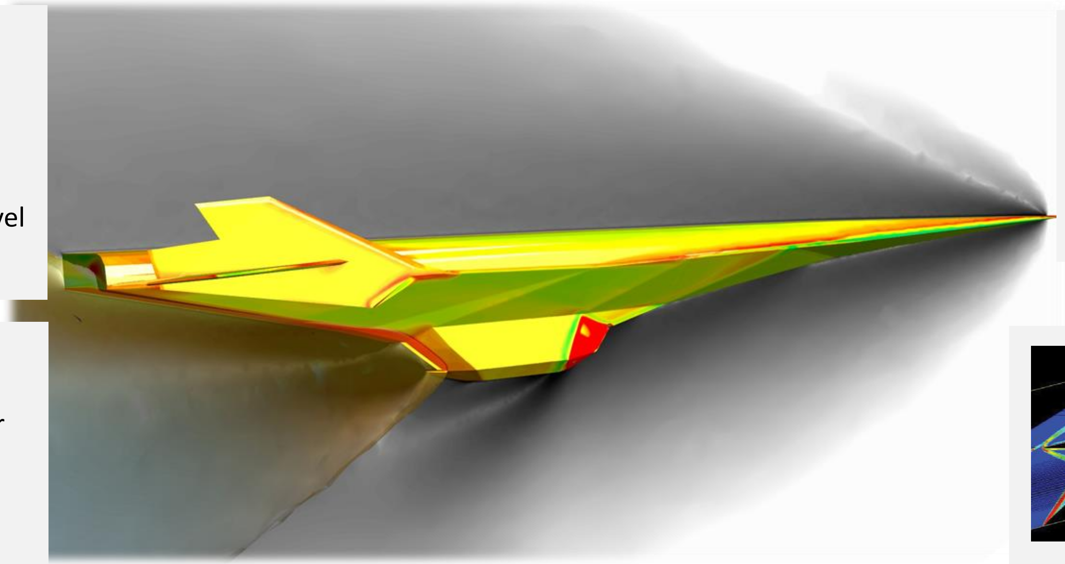
Communication and tracking

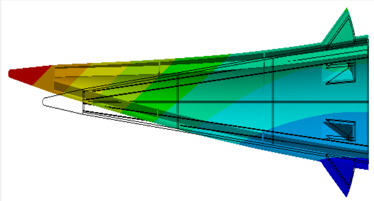
- Antennas and sensors
- Radio/GPS jamming
- Radar/IR signature
- Structural deformation
- Vibration impact
- Communication black-out



System integration

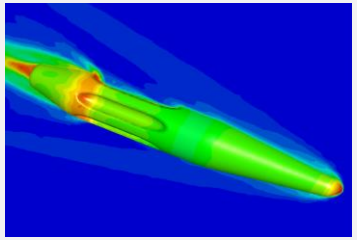
- Control system integration
- Sensor fusion and actuation
- Navigation, guidance and control
- "Wargaming" and mission-level simulation: AGI





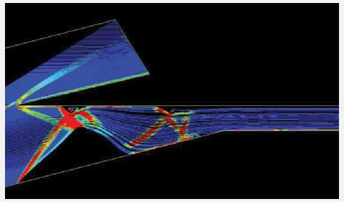
Structure and materials

- FSI/Deformation:
  - ✓ steady-state
  - ✓ transient
- Fracture and fatigue
- Structural integrity
- Material intelligence



Thermal management

- Radiation, Conv., Cond.
- Conjugate Heat Transfer
- Active cooling
- Phase change: boiling, evapor./condensation
- Melting/solidification
- Electronics cooling



Propulsion

- RAM/SCRAMJET combustion
- Solid/Liquid rocket
- Gas, liquid and solid fuels
- Thermal loads
- Structural deformation

New Ansys R&D collaborations in hypersonics

- **University of Texas, Arlington**
  - Aerodynamic Research Lab (ARC): Director Prof Maddalena
  - The only US academic institution with arc-jet facility.
  - Inaugurated in summer 2019, with $1.5M funding from US Navy/DARPA
  - Cutting-edge experimental research in hypersonics (aerothermodynamics, SCRAMJET propulsion, ablation)
  - Currently working with AFRL/NRL/DARPA

- **Missouri S**
  - Aerodyna
  - Research
    - Simu
    - Effe
    - Unc
  - ARL has recently won an NSF grant for ~$2M to deploy a supercomputer dedicated to computer simulations.

These universities and Ansys are members of the <u>University Consortium for Applied Hypersonics</u>

- **University of Colorado, Boulder**
  - Collaboration with UC Boulder's Non-Equilibrium Gas and Plasma Dynamics Lab on hybrid coupling of CFD and DSMC methods for rarefied flows.

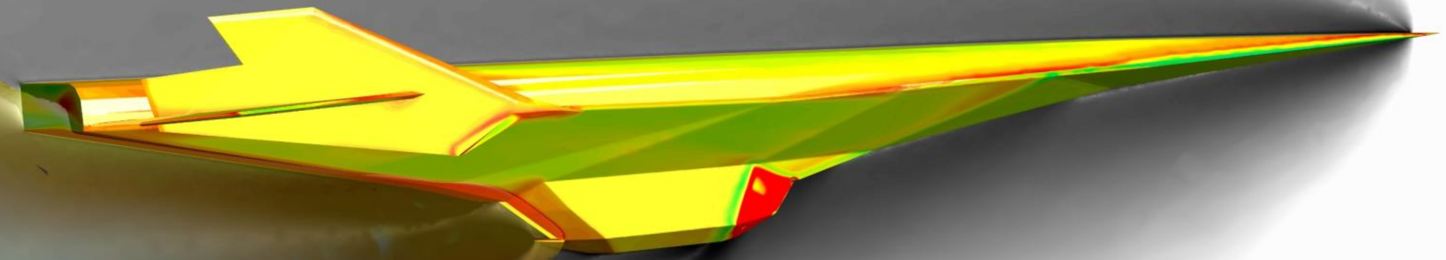
Ansys

Ansys CFD Hypersonic Training

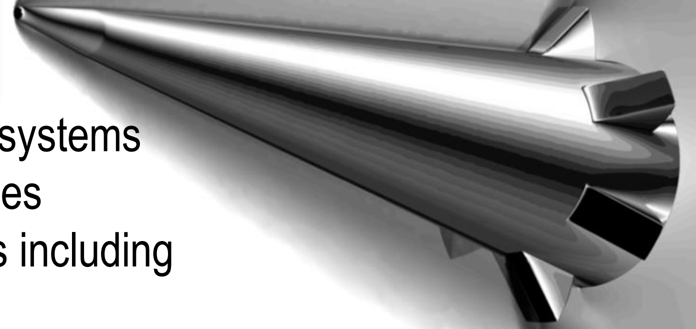
Improve engineering productivity using advanced engineering simulation

Learn how to use Ansys CFD to design and analyze hypersonic systems

- 2-day on-site course (1-week mentoring project total)
- Combination of lectures and hands-on workshops
- Work on your own problem on the second day
- Maximum 10 students per class



Extending training material to include **structural** and **electromagnetic** modules

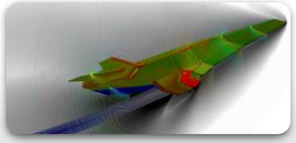


What you will learn

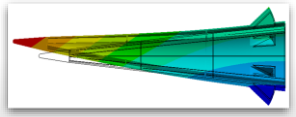
- The value of simulation for hypersonic systems
- Using Ansys CFD for hypersonic vehicles
- Modeling advanced physical processes including chemical non-equilibrium
- Simulation strategies to improve productivity

Contact: Rodger.Zhao@ansys.com

Outline



Aerothermodynamic environment and propulsion



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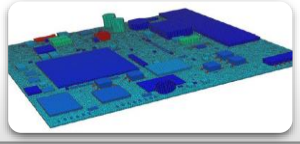

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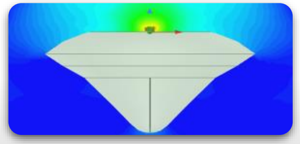

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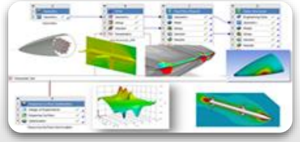

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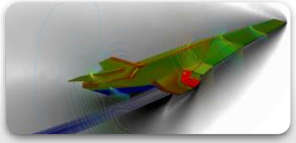
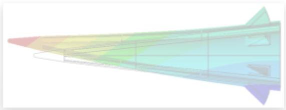
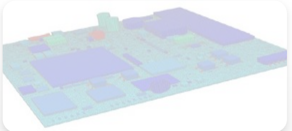


Aerothermodynamic environment and propulsion



Structural integrity and deformation for a hypersonic vehicle



Sensor reliability in high heat-flux environment

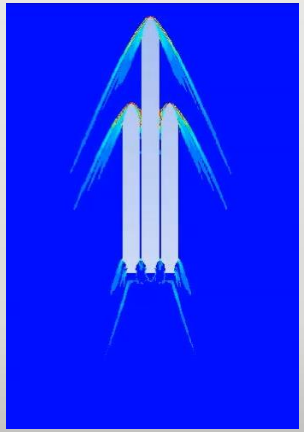
Predicting communication degradation and blackout

Tool-chaining and workflow assembly for hypersonics

Valerio Viti

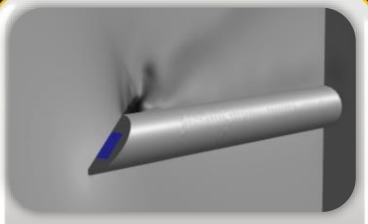
ANSYS Technology Stack for Hypersonics

Aerodynamics	Propulsion	Materials & Structures	Communication & Tracking	System Integration



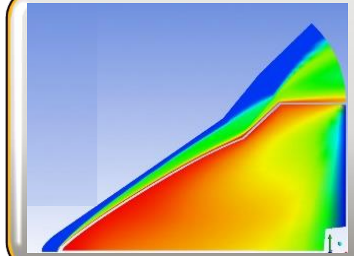
Aircraft/booster Separation

- Trajectory computation
- Aerodynamic interference
- Shock impingement



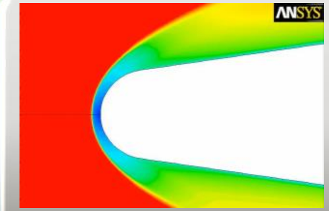
Aero optics

- Shock and turbulence
- OPL/OPD computation



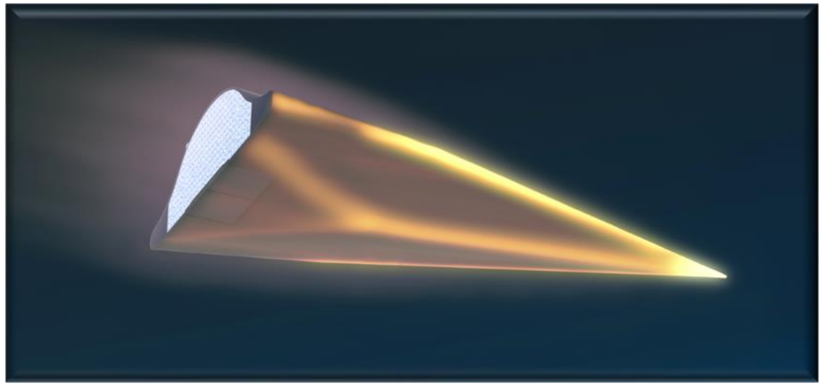
Aerothermodynamics

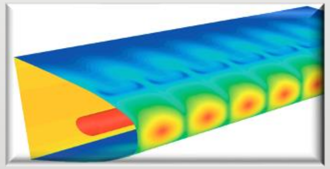
- Shock capturing and location
- Pressure distribution
- Skin friction, Wall heat flux
- Inlet conditions for engines
- Turbulence transition
- Flow control



Ablation

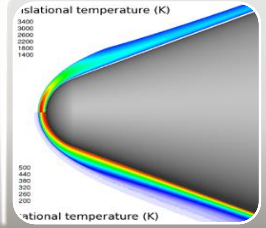
- Surface finite-rate reactions
- Charring and erosion
- Surface recession
- LE/Nose/flap shape change





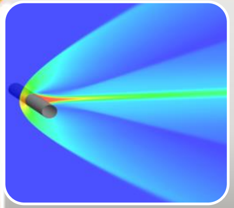
Active cooling

- Single/Multi-phase
- Radiation, Convection, Cond
- Phase change: boiling, evaporation/condensation
- Jet impingement



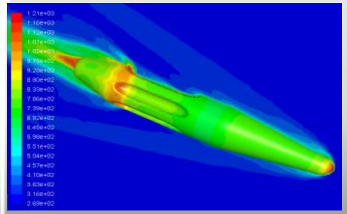
Chemical non-equilibrium

- Species transport, finite-rate reactions
- Dissociation, ionization, recombination
- Equilibrium and non-equilibrium
- Flexible and powerful chemical solver



Plasma activation

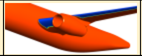
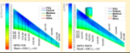
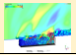
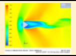
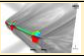
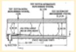
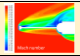
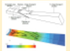
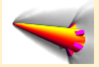
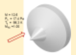
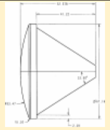
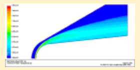
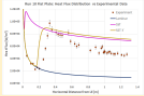
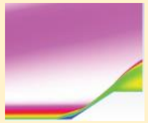
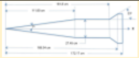
- Ion concentration
- Lorentz forces
- Communication blackout



Conjugate HT

- Radiation, Convection, Cond
- Surface and structure conduction
- Melting/solidification

Extensive suite of validations for hypersonic flows

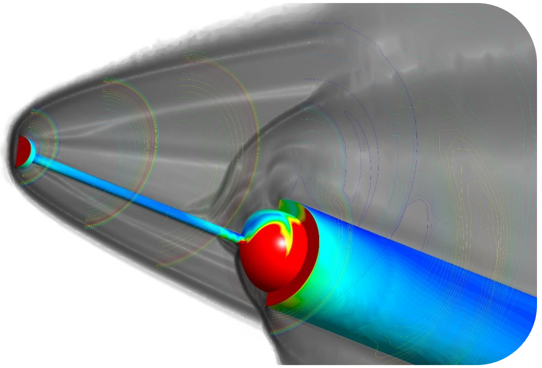
case	flow regime	Mach No.	AoA	geometry	image	Publication	Exp Reference
T-1	Transonic	0.6 to 0.8	Range from -5 to +2	DLR-F6 wing-body and wing-body-nacelle-pylon		Eisenhut, S. & Frank, T. 2nd AIAA Drag Prediction Workshop, DLR-F6 Aircraft Model, WB and WBNP Configuration, Orlando, FL, June 21-22, 2003.	2nd AIAA CFD Drag Prediction Workshop
T-2	Transonic	0.85	2.5 to 2.7	CRM wing-body and wingbody-nacelle-pylon		Zore, K., Sasanapuri, B., Shah, S., Bish, E., & Sotkes, J. ANSYS Simulation Results for the 6th AIAA Drag Prediction Workshop, Washington , DC, June 16-17, 2016.	6th AIAA CFD Drag Prediction Workshop
T-3	Transonic	0.85	-	Transonic Cavity Noise		Kurtabatskii, K., Menter, F., Schuetze, J., & Fujii, A. Numerical Simulation of Transonic Cavity Noise using Scale-Adaptive Simulation (SAS) Turbulence Model, Internoise 2011, Osaka, Japan, September 4-7, 2011.	M. J. Henshaw, "M219 Cavity Case," Verification and Validation Data for Computational Unsteady Aerodynamics, Tech. Rep. RTO-TR-26, AC/323(AVT)TP/19 (2000).
T-4	Transonic	0.4, 0.8, 0.9	2	RAE wing body		Ansys internal validation	Treadgold, D., Jones, A., and Wilson, K., "Pressure Distribution Measured in the RAE 8ft x 6ft Transonic Wind Tunnel on RAE Wing 'A' in Combination with an Axi-Symmetric Body at Mach Numbers of 0.4, 0.8 and 0.9," AGARD-AR-138, Appendix B4.
T-5	Transonic	0.95, 1.2	0	store drop - delta wing		Snyder, D.O., Koutsavdis, E.K., Anttonen, J.S.R.: "Transonic store separation using unstructured CFD with dynamic meshing", Technical Report AIAA-2003-3913, 33th AIAA Fluid Dynamics Conference and Exhibition, American Institute of Aeronautics and Astronautics, 2003.	Heim, E. : "CFD wing/pylon/finned store mutual interference wind tunnel experiment", DTIC Document, (1991).
Sup-1	Supersonic	1.2	165, 180	Apollo capsule		Ansys internal validation	Moseley, W. Graham, R., & Hughes, J., Aerodynamic Stability Characteristics of the Apollo Command Module, NASA-TN D-4688, August 1968.
Sup-2	Supersonic	3.48	0	re-entry capsule w/ counter-flowing jet		Ansys internal validation	Daso, O. E. et. al., " Dynamics of Shock Dispersion and Interactions in Supersonic Freestreams with Counterflowing Jets," AIAA Journal, Vol. 47, No. 6, June 2009.
Sup-3	Supersonic	2.5,3.5	Range from -5 to +18	tandem canard missile		Rao, V., Viti, V., & Abanto, J. CFD simulations of super/hypersonic missiles: validation, sensitivity analysis, and improved design, AIAA SciTech Forum, 6-10 January 2020, Orlando, FL, January 2020.	Blair, Jr., A. B., Allen, J. M., Hernandez, G., Effect of tail-fin span on stability and control characteristics of a canardcontrolled missile at supersonic Mach number, NASA Technical Paper 2157, June 1983.
Sup-4	Supersonic	2.4	-	SCRAMJET supersonic combustion		Ansys internal validation	Burrows, M. C. and Kurkov, A. P., "Analytical and Experimental Study of Supersonic Combustion of Hydrogen in a Vitiated Airstream," NASA-TM-X-2828, Sep. 1973.
Hyp-01	Hypersonic	6	0,10	Aerospike		Rao, V., Viti, V., & Abanto, J. CFD simulations of super/hypersonic missiles: validation, sensitivity analysis, and improved design, AIAA SciTech Forum, 6-10 January 2020, Orlando, FL, January 2020.	Huebner, L., et al., Experimental results on the feasibility of an aerospike for hypersonic missiles, 33rd Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings, Reno, NV, 1995.
Hyp-02	Hypersonic	6.5	-	Hypersonic SCRAMJET		Babu, V., Run Like the Wind, ANSYS Advantage, Volume VIII, Issue 1, 2014.	Kumaran, K. & Babu, V., Mixing and combustion characteristics of kerosene in a model supersonic combustor, Journal of Propulsion and Power 25 (3), 583-592.
Hyp-03	Hypersonic	7.93	0	Hypersonic flow over Mars Pathfinder (70 degree sphere cone)		Ansys internal validation	Paterna, D., Monti, R., Savino, R., & Esposito, A., Experimental and Numerical Investigation of Martian Atmosphere Entry, Journal of Spacecraft and Rockets, Vol. 39, No. 2, March-April 2002.
Hyp-04	Hypersonic	8.3	-	Hypersonic double fin inlet		upcoming AIAA paper Viti, V., Crawford, B., Arguinzoni, C., Rao, V., & Zori, L. Numerical simulations of four hypersonic vehicles using a density-based CFD solver: validation, analysis and sensitivity to material properties 2020.	Kussoy, M.I., Horstman, K. C., Horstman, C. C., Hypersonic Crossing Shock-Wave/Turbulent Boundary-Layer Interactions, AIAA Journal 31 No. 12, 2197-2203, 1993
Hyp-05	Hypersonic	10	0	Hyperboloid Flare		Kurbatskii, K.A, Kumar, R., and Mann, D., "Simulation of External Hypersonic Problems Using Fluent 6.3 Density-Based Coupled Solver", 2nd European Conference for Aerospace Sciences	Sagnier, Ph., Joly, V, and Marmignon, C., "Analysis of Nonequilibrium Flow Calculations and Experimental Results Around a Hyperboloid-flare Configuration", 2nd European Symposium on Aerodynamics for Space Vehicles, 1995.
Hyp-06	Hypersonic	10.3		Biconic Reentry Vehicle with Six Extended Flaps		upcoming AIAA paper Viti, V., Crawford, B., Arguinzoni, C., Rao, V., & Zori, L. Numerical simulations of four hypersonic vehicles using a density-based CFD solver: validation, analysis and sensitivity to material properties 2020.	Jordan, T.M., Buffington, R.J., Aerodynamic Model for a Hemispherically-Capped Biconic Reentry Vehicle with Six Drag Flaps. AIAA Paper 87-2364, 1987.
Hyp-07	Hypersonic	12.6	0	sharp-nosed double cone		upcoming AIAA paper Viti, V., Crawford, B., Arguinzoni, C., Rao, V., & Zori, L. Numerical simulations of four hypersonic vehicles using a density-based CFD solver: validation, analysis and sensitivity to material properties 2020.	Effect of Vibrational Non-Equilibrium on Hypersonic Double-Cone Experiments Ioannis Nompelis and Graham V. Candler (AIAA Journal Vol.41, No.11, Nov 2003
Hyp-08	Hypersonic	19.4	0	FIRE II re-entry vehicle		upcoming AIAA paper Viti, V., Crawford, B., Arguinzoni, C., Rao, V., & Zori, L. Numerical simulations of four hypersonic vehicles using a density-based CFD solver: validation, analysis and sensitivity to material properties 2020.	Hash, D., Olejniczak, J., Wright, M., Prabhu, D., Pulsonetti, M., Hollis, B., Gnoffo, P., Barnhardt, M., Nompelis, I., FIRE II Calculations for Hypersonic Nonequilibrium Aerothermodynamics Code Verification: DPLR, LAURA,and US3D, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, AIAA Paper 2007-605, January 2007. Wright, M., Loomis, M., Papadopoulos, P., Aerothermal Analysis of the Project Fire II Afterbody Flow, Journal of Thermophysics and Heat Transfer, vol. 17 No.2, April-June 2003.
Hyp-09	Hypersonic	25	0	blunt axisymmetric sphere-cone		Ansys internal validation	Lee, K. & Gupta, R. , Viscous-Shock-Layer Analysis of Hypersonic Flows over Long Slender Vehicles, NASA Contractor Report 189614 March 1992.
Hyp-10	Hypersonic	29	0	sphere		Kurbatskii, K.A, Kumar, R., and Mann, D., "Simulation of External Hypersonic Problems Using FLUENT 6.3 Density-Based Coupled Solver", 2nd European Conference for Aerospace Sciences.	Widhopf, G. F., and Wang, J. C. T., "A TVD Finite-Volume Technique for Nonequilibrium Chemically Reacting Flows", AIAA Paper 1988-2711 Dellinger, T. C., "Computation of Nonequilibrium Merged Stagnation Shock Layers by Successive Accelerated Replacement", AIAA Journal, 9(2):262-269, 1971.
Hyp-11	Hypersonic	10.6, 11.1	0	Hypersonic transition on a Flat Plate		Aliaga, C., Guan, K., Selvanayagam, J., Sokes, J., Viti, V., & Menter, F. Hypersonic Applications of the Laminar-Turbulent Transition SST Model in ANSYS Fluent AIAA Hypersonic Transition Paper to be published in 2020.	Holden, M., MacLean, M., Wadhams, T., and Mundy, E., "Experimental Studies of Shock Wave/Turbulent Boundary Layer Interaction in High Reynolds Number Supersonic and Hypersonic Flows to Evaluate the Performance of CFD Codes", AIAA 2010-4468, 40th Fluid Dynamics Conference and Exhibit, Chicago, Illinois, June 28, 2010. Marvin, J.G., Brown, J.L., and Gnoffo, P.A., "Experimental Database with Baseline CFD Solutions: 2-D and Axisymmetric Hypersonic Shock-Wave/Turbulent-Boundary-Layer Interactions", NASA/TM-2013-216604, NASA: Ames Research Center, Moffett Field, CA, November 2013.
Hyp-12	Hypersonic	7.19	0	2d axisymmetric Hypersonic transition on a Blunt Cone Cylinder Flare junction		same as above	MacLean, M., Wadhams, T., Holden, M., and Johnson, H., "A Computational Analysis of Ground Test Studies of HIFiRE-1 Transition Experiment," AIAA 2008-641, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 7, 2008. Wadhams, T., Mundy, E., MacLean, M., and Holden, M., "Pre-Flight Ground Testing of the Full-Scale HIFiRE-1 Vehicle at Fully Duplicated Flight Conditions: Part II, AIAA 2008-639, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 7, 2008.
Hyp-13	Hypersonic	7.16	0	2d axisymmetric Hypersonic transition on a Sharp Cone Cylinder Flare junction		same as above	same as above
Hyp-14	Hypersonic	7.19	0	3d Hypersonic transition on a Blunt Cone Cylinder Flare junction		same as above	same as above
Hyp-15	Hypersonic	Vel ~ 7.8 km/s		RF Blackout during Space Probe Reentry		validation work-in-progress	Bendoukha, S., Okuyama, K., & Szasz, B. A Study of Radio Frequency Blackout for Space Probe During Atmospheric Reentry Phase, International Journal of Research Granthaalayah, Vol. 5 (Iss. 3): March, 2017.

Ansys public literature/journal/conference papers on hypersonics

- Shah, S., Zore, K., Stokes, J., Zori, L., Ansys Fluent Scale-Resolving Simulations with SBES & Validation of a Re-Entry Capsule at Hypersonic Speed, AIAA 2021-1073, AIAA Scitech, Virtual Event, Jan 11-15, 2021.
- Viti, V., Rao, V., Crawford, B., Arguinzoni, C, Zori, L., "Numerical simulations of four canonical hypersonic vehicles and test cases", AIAA 2020-2723, AIAA Aviation 2020, Nashville, TN, June, 2020.
- Aliaga, C., Guan, K., Selvanayagam, J., Stokes, J., Viti, V., Menter, F., Hypersonic Applications of the Laminar-Turbulent Transition SST Model in ANSYS Fluent, AIAA Hypersonics 2020, Montreal, QC, Canada, March 2020.
- Tiliakos, N., DeSorbo, J., Martin, N., Viti, V., Laurence, S., Rabin, O., "A Roadmap for Obtaining and Implementing Heat Flux Measurements in the Hypersonic Environment", AIAA Hypersonics 2020, Montreal, QC, Canada, March 2020.
- Rao, V., Viti, V., Abanto, J., "CFD simulations of super/hypersonic missiles: validation, sensitivity analysis and improved design", AIAA 2020-2123, AIAA ScitTech 2020, Orlando, FL, January 6-10th, 2020.
- Kumar, A., Kumar, V., Nakod, P., Rajan, A., Schütze, J., Multiscale Modelling of a Doublet Injector Using Hybrid VOF-DPM Method, AIAA 2020-2284, AIAA ScitTech 2020, Orlando, FL, January 6-10th, 2020.
- Viti, V., Svihla, K., Marinus, S., Dodd, E., Tharp, J., Crawford, B., Miller, C., Staggs, E., "Development and validation the ANSYS hypersonic prototype", Hypersonic Technology and Systems Conference, Alexandria, VA, 26-29 August, 2019.
- Babu, V., Flight like the wind, ANSYS Advantage, Vol.8, 2014.
- Ground, C., Vergine, F., Maddalena, L., Viti, V., "Flow characteristics of a strut injector for scramjets: numerical and experimental analysis", TFAWS2014-I-02, NASA Thermo and Fluids Analysis Workshop, Cleveland, OH, August 4-8th, 2014.
- Ground, C., Vergine, F., Maddalena, L., Viti, V., "Experimental and numerical investigation of the flow characteristics of a strut injector for scramjets", AIAA 2014-3217, 19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Atlanta, GA, 16-20 June, 2014.
- Kurbatskii, K., Montanari, F., Application of Pressure-Based Coupled Solver to the Problem of Hypersonic Missiles with Aerospikes, 45th AIAA Aerospace Sciences Meeting and Exhibit 8 - 11 January 2007, Reno, Nevada, AIAA Paper 2007-462.
- Kurbatskii, K., Kumar, R., Mann, D., Simulation of External Hypersonic Problems Using FLUENT 6.3 Density-Based Coupled Solver, 2ND EUROPEAN CONFERENCE FOR AEROSPACE SCIENCES EUCASS, Brussell, Belgium, 1-6 June 2007.
- Paterna, D., Monti, R., Savino, R., Esposito, A., "Experimental and numerical investigation of Martian atmosphere entry". Journal of spacecraft and rockets, Vol. 39, No.2, March-April 2002.
- Savino, R., De Stefano Fumo,M., Paterna, D., Serpico, M., Aerothermodynamic study of UHTC-based thermal protection systems, Aerospace Science and Technology, Volume 9, Issue 2, pp.151-160, March 2005.
- Savino,R., Paterna,D.,Blunted cone–flare in hypersonic flow, Computers & Fluids, Volume 34, Issue 7, pp. 859-875, August 2005.

Ansys improvements for high-speed flows

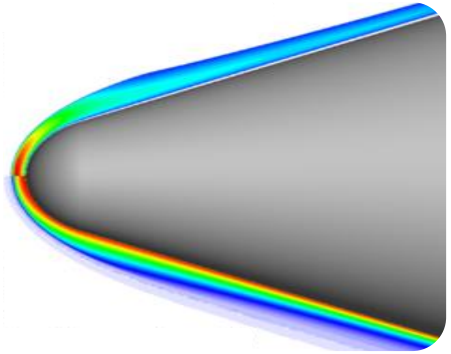
Improved high-speed solver



- HSNs
- Enhanced-PMNs
- Non-reflecting BCs

3X speed up

Hypersonics



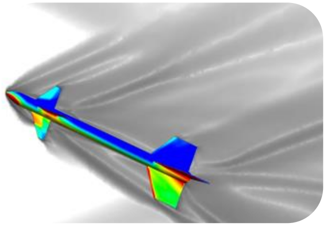
- Thermodynamic non-eq
- Built-in NASA 9-coeff curve fits for material properties
- Slip-wall BC
- Chemkin mechanisms for reactions with DBNS

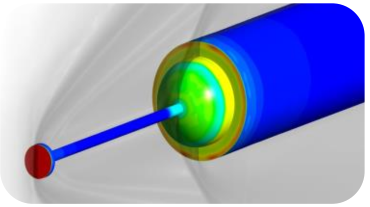
GUI and workflow tailored for external aero

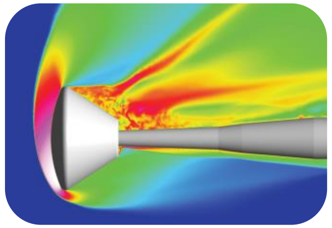
Ansys validation matrix for hypersonics

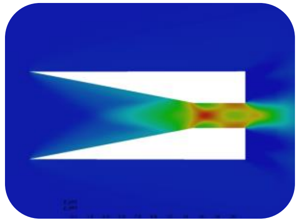
Ideal gas | Flight test | Chemical non-equilibrium | Combustion

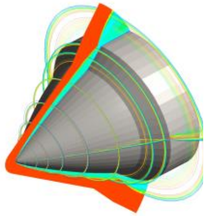

Re-entry capsule with counter-flow jet, Mach 3.5, Turbulent, Air as ideal-gas (Daso case)

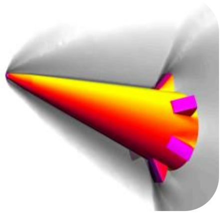

NASA TCM, Mach 2.5 and 3.5, Turbulent. Air as ideal-gas

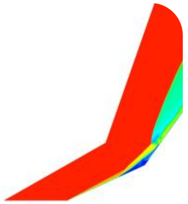

Aerospike at Mach 6, Turbulent. Air as ideal gas

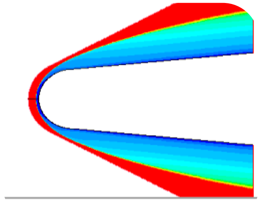

Orion Capsule at Mach 6.4 Turbulent, Air as ideal gas, Transient

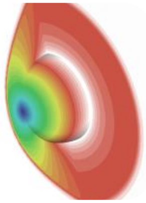

Kussoy Hypersonic inlet at Mach 8.3, Turbulent. Air as ideal-gas

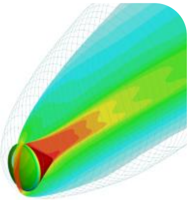

Hyperboloid, Mach 9.85, laminar. Chemical non-equilibrium (Park II)

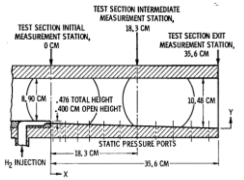

Biconic with flaps at Mach 10.3, Turbulent. N_2 as ideal-gas

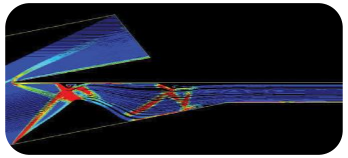

Double cone at Mach 12.6, Laminar, Thermodynamic non-equilibrium. N_2.

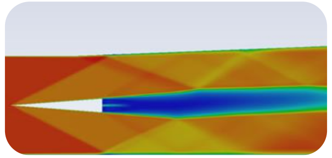

Blunt-cone at Mach 25, Laminar, Chemical non-equilibrium. Air. (Park II)

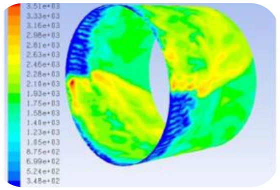

Sphere at Mach 29, Laminar, Chemical non-equilibrium. Air (Widhopf model)


FIRE II, Re-entry capsule, Turbulent, Mach 35.7. Chemical non-equilibrium. Air(Gupta)


Burrow's SCRAMJET, Mach 2.44, Turbulent, H_2


Bapu's SCRAMJET at Mach 3.45, Turbulent, Hydrocarbon


DLR SCRAMJET, Mach 2. Turbulent, H2

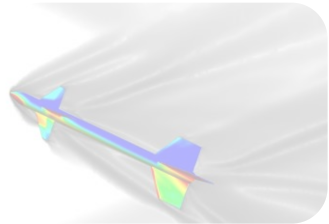

NETL RDE, Turbulent, H_2

Ansys

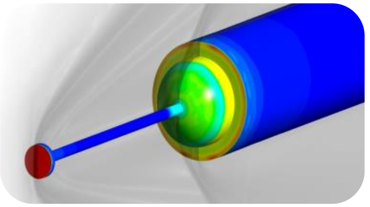
Ansys validation matrix for hypersonics

Ideal gas | Flight test | Chemical non-equilibrium | Combustion

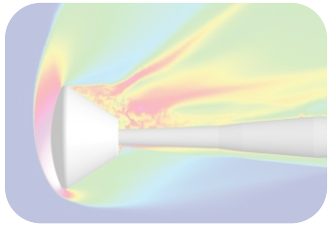
Re-entry capsule with counter-flow jet, Mach 3.5, Turbulent, Air as ideal-gas (Daso case)



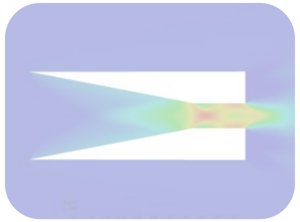
NASA TCM, Mach 2.5 and 3.5, Turbulent. Air as ideal-gas



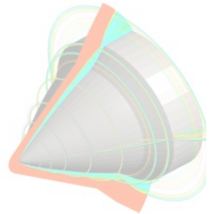
Aerospike at Mach 6, Turbulent. Air as ideal gas



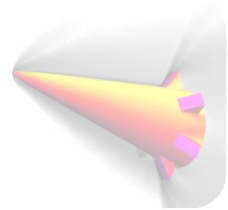
Orion Capsule at Mach 6.4 Turbulent, Air as ideal gas, Transient



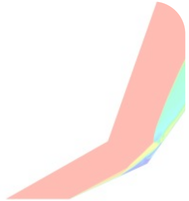
Kussoy Hypersonic inlet at Mach 8.3, Turbulent. Air as ideal-gas



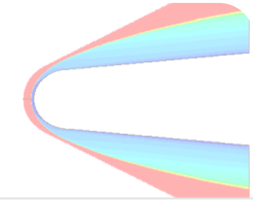
Hyperboloid, Mach 9.85, laminar. Chemical non-equilibrium (Park II)



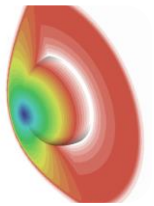
Biconic with flaps at Mach 10.3, Turbulent. N_2 as ideal-gas



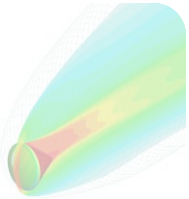
Double cone at Mach 12.6, Laminar, Thermodynamic non-equilibrium. N_2.



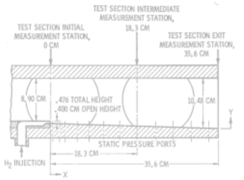
Blunt-cone at Mach 25, Laminar, Chemical non-equilibrium. Air. (Park II)



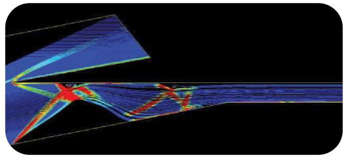
Sphere at Mach 29, Laminar, Chemical non-equilibrium. Air (Widhopf model)



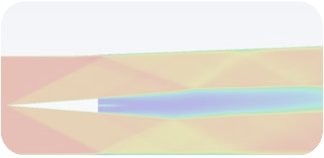
FIRE II, Re-entry capsule, Turbulent, Mach 35.7. Chemical non-equilibrium. Air(Gupta)



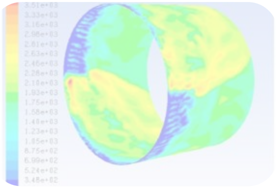
Burrow's SCRAMJET, Mach 2.44, Turbulent, H_2



Bapu's SCRAMJET at Mach 3.45, Turbulent, Hydrocarbon



DLR SCRAMJET, Mach 2. Turbulent, H2



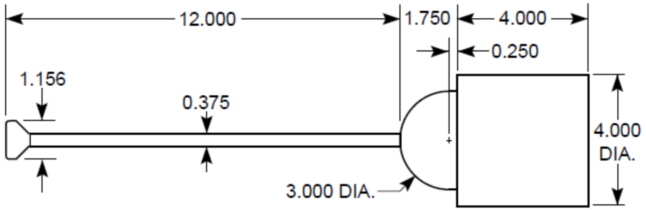
NETL RDE, Turbulent, H_2

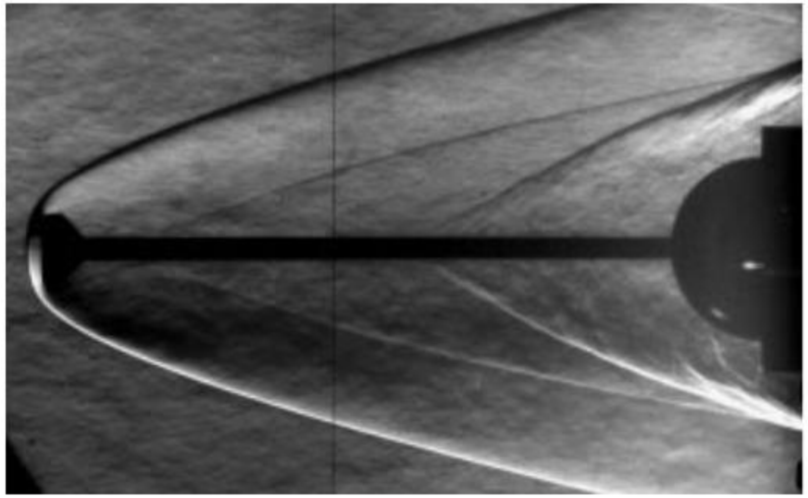
Ansys

Case study: validation of aerospiked missile at Mach 6

Work based on an aerospike geometry with and aerodisk proposed by Hubner et Al. at NASA Langley, mid 1990s.

Mach number =6.06, turbulent, non-reacting air

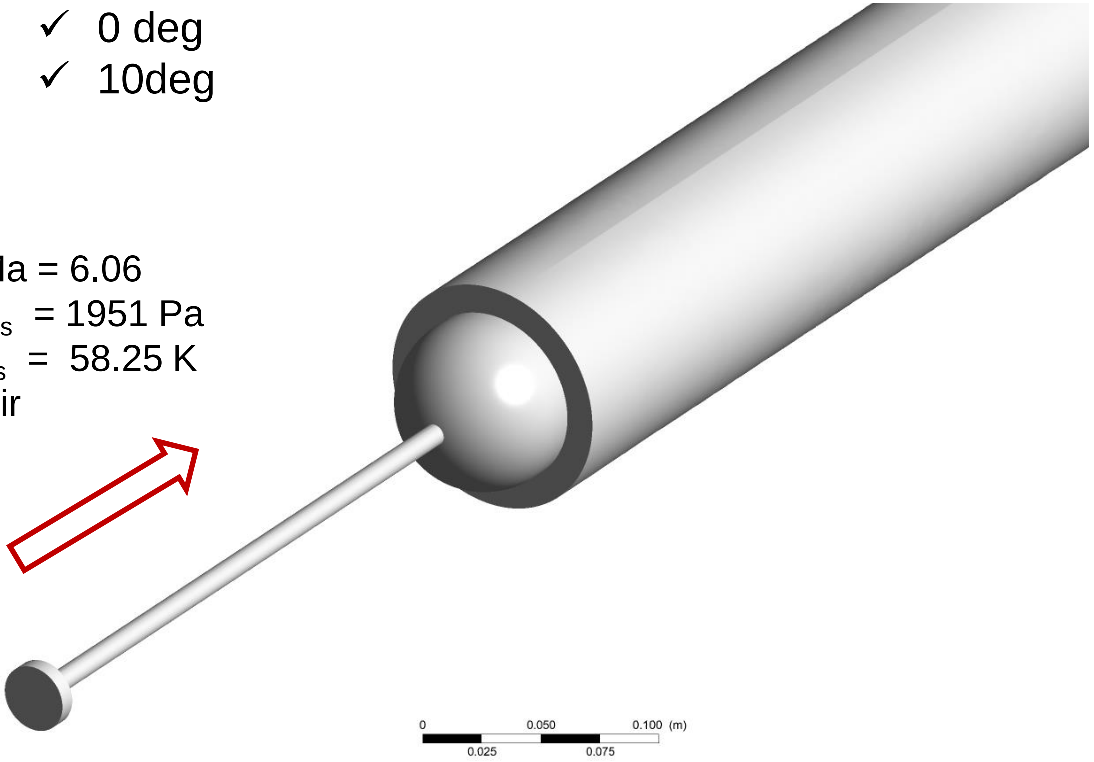




2 Angles of Attack

- ✓ 0 deg
- ✓ 10deg

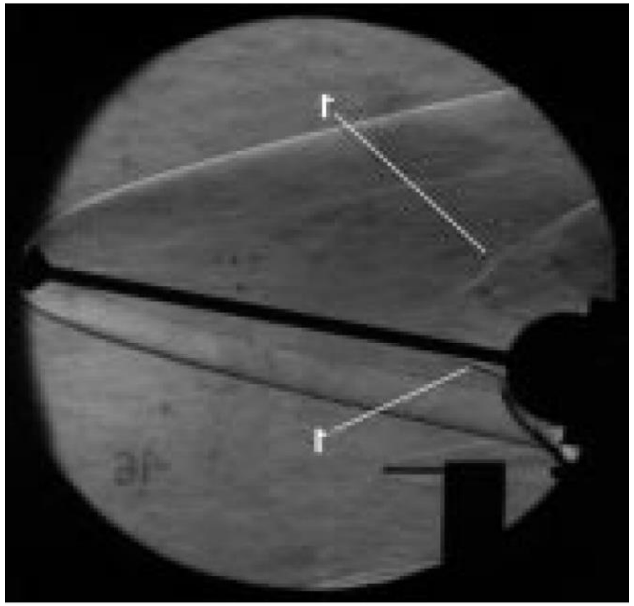
Ma = 6.06
P_s = 1951 Pa
T_s = 58.25 K
Air

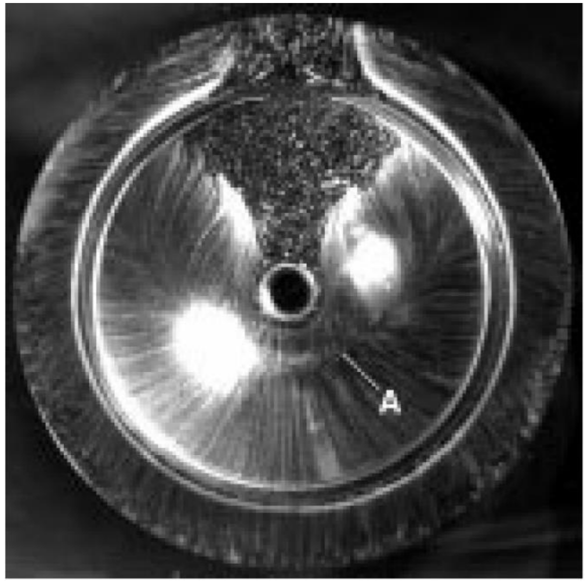


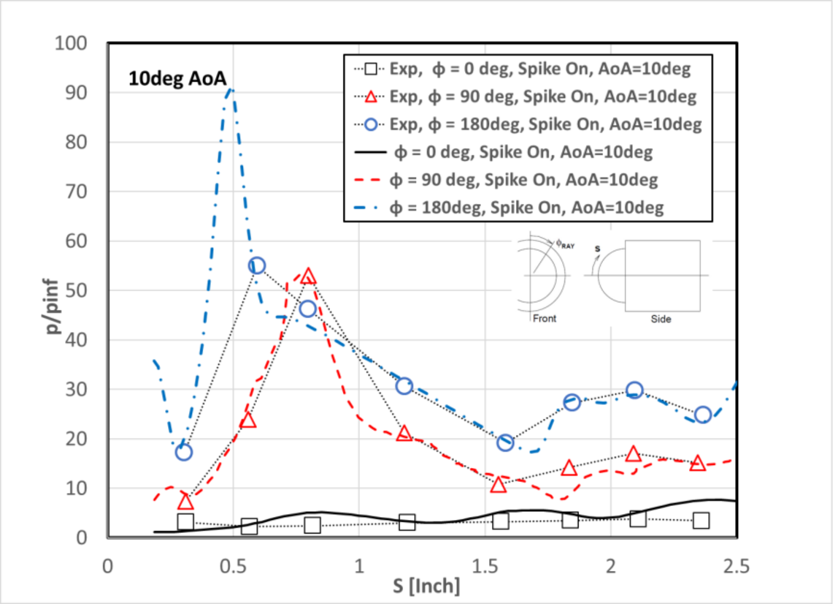
Reference: Huebner, L., et al., Experimental results on the feasibility of an aerospike for hypersonic missiles, 33rd Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings, Reno, NV, 1995.

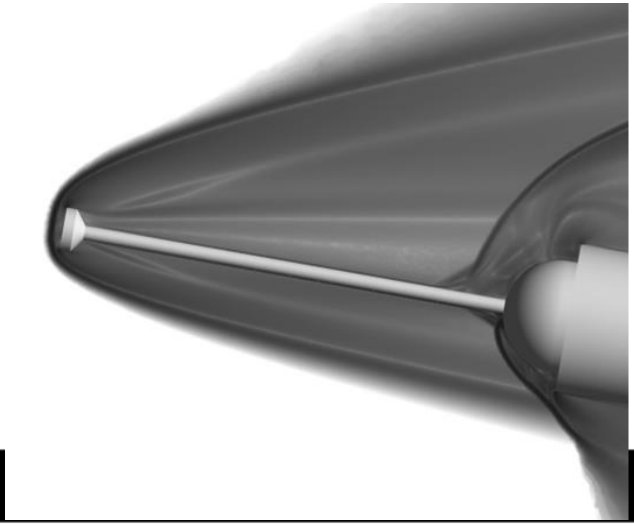
Case study: validation of aerospiked missile at Mach 6: 10deg AoA

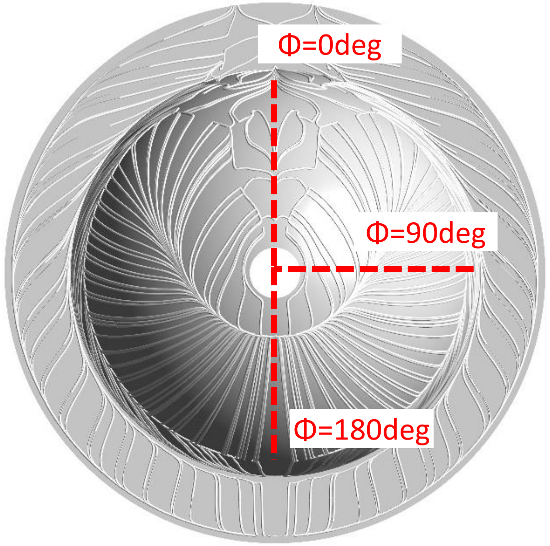
Reference: Rao, V., Viti, V., Abanto, J., "CFD simulations of super/hypersonic missiles: validation, sensitivity analysis and improved design", AIAA 2020-2123, AIAA SciTech 2020, Orlando, FL, January 6-10th, 2020.

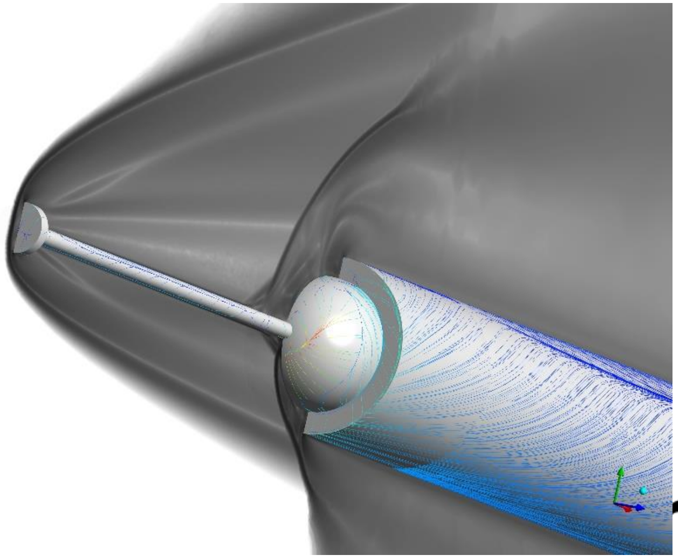








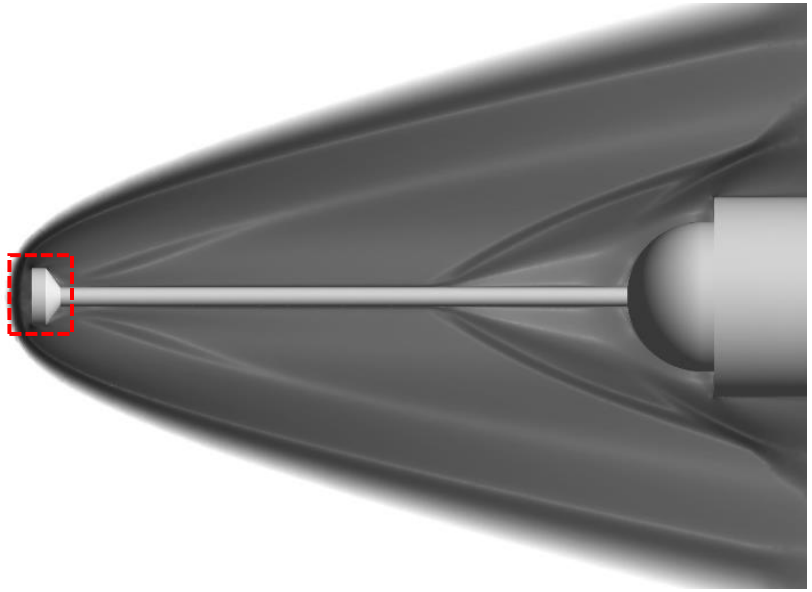




Case study: Optimization of aerodisk using Adjoint solver

Improve performance of aerospike

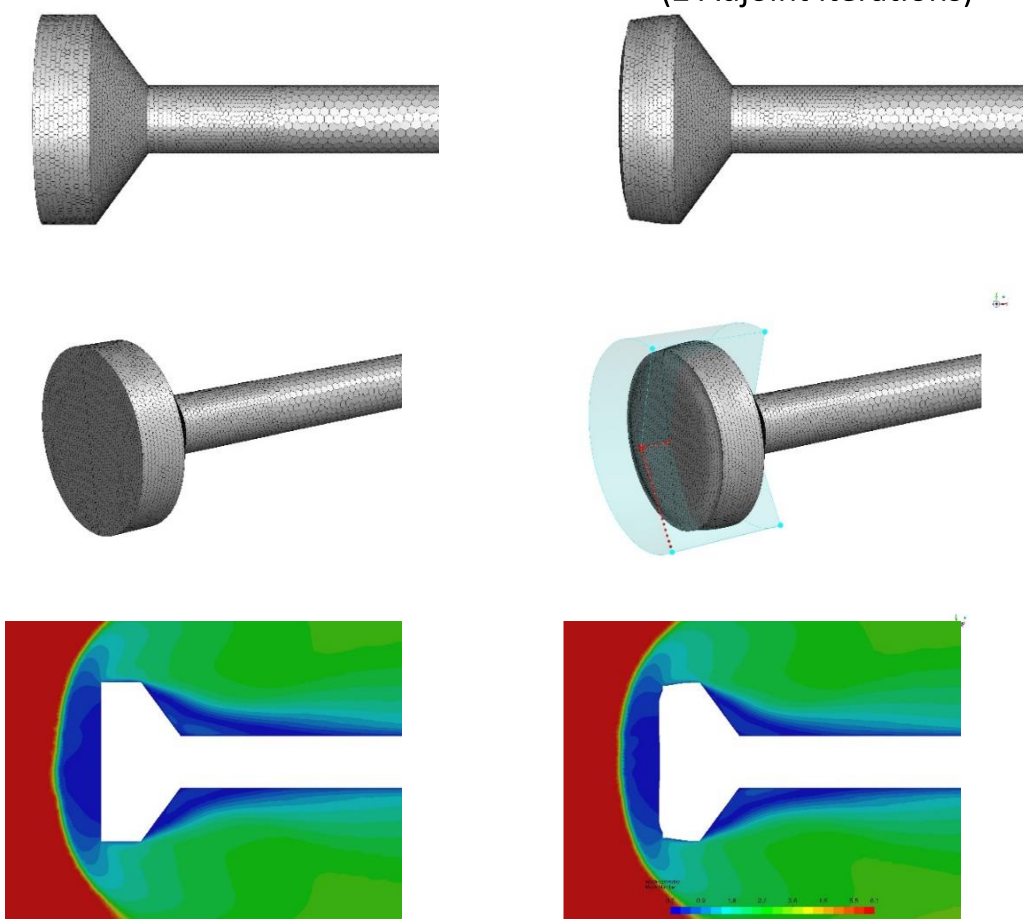
- Modify only aerodisk shape
- Reduce overall vehicle drag (Target: -2%)
- Maintain leading shock wave away from radome



Original

Optimized

(2 Adjoint iterations)

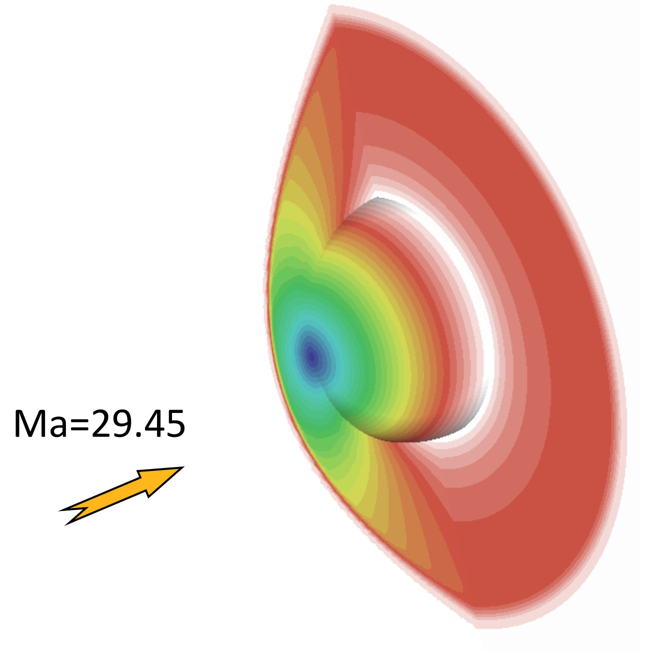


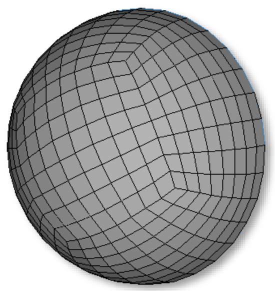
Drag=95.7N

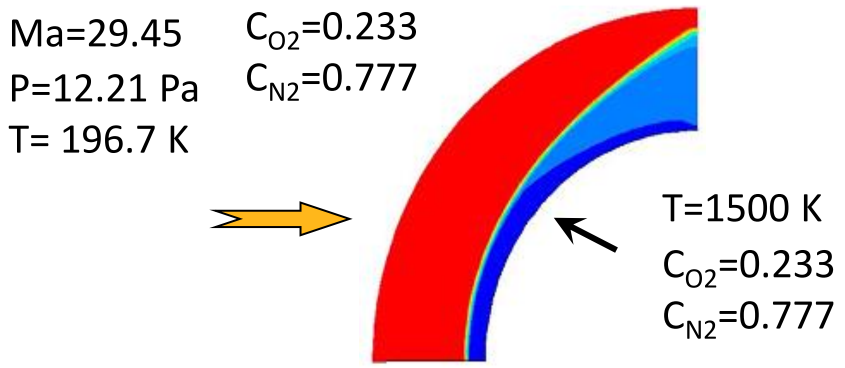
Drag=94.1N

Case study: Mach 29 Flow Over a Sphere

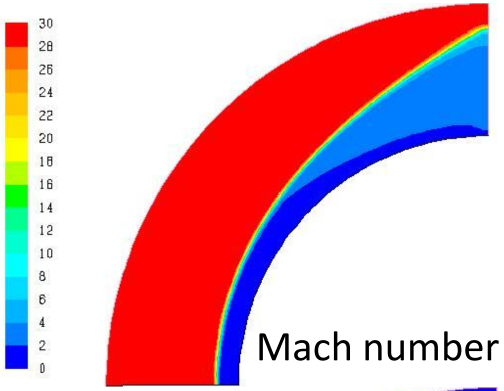
- Laminar flow over 60.96 mm diameter hemisphere
- Free-stream static pressure and temperature:
  p_s = 12.21 Pa, T_s = 196.7 K
- Laminar finite-rate model to compute chemical sources in energy equation: Gupta model
- Reacting dissociated mixture of 11 species and 21 reactions (N_2, O_2, O, N, NO, N^+, O^+, NO^+, N_2^+, O_2^+, e^-)
- Isothermal 1500 K condition at sphere wall
- Structured 2-D mesh: 64,00 quad cells
- Assume axisymmetric flow

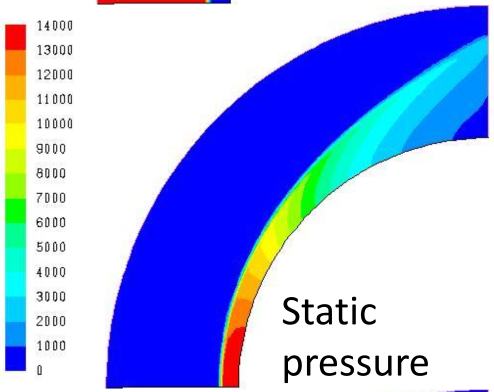


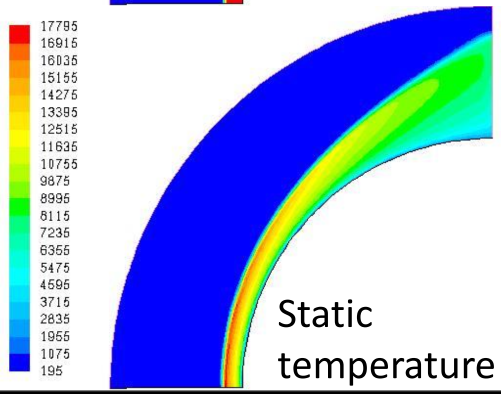


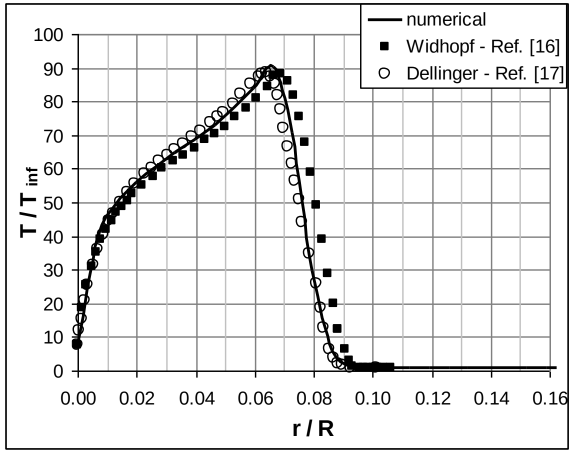


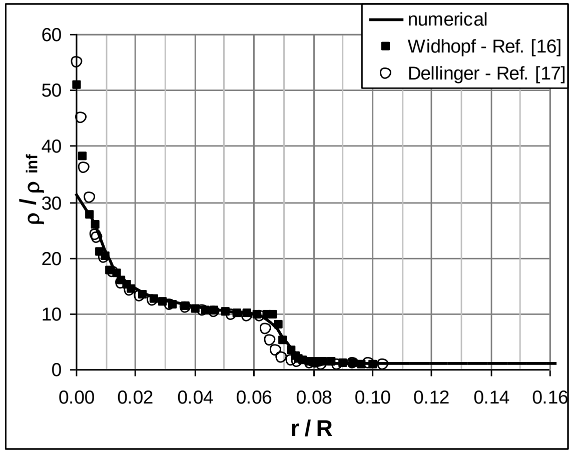
Case study: Mach 29 Flow Over a Sphere



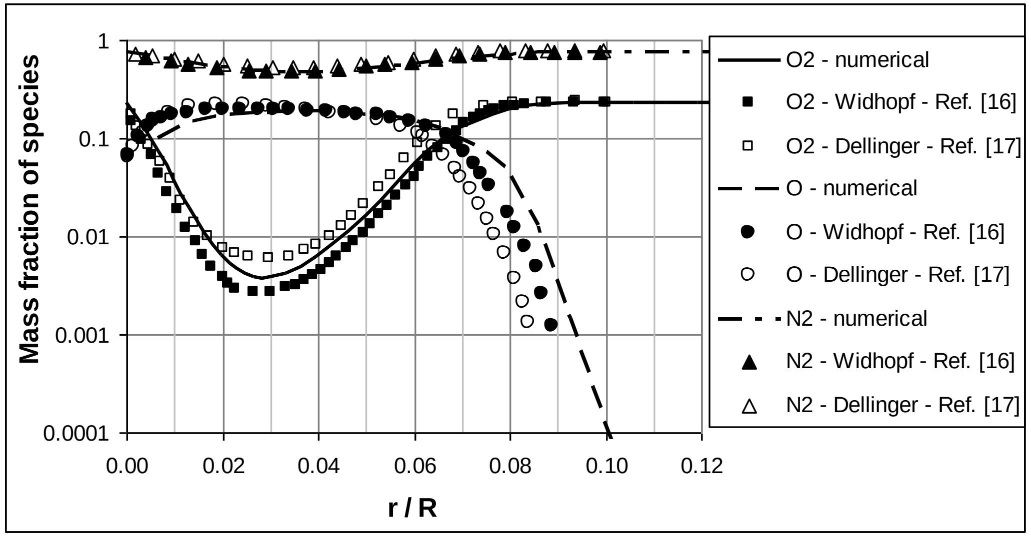








Distributions of normalized static temperature, density, and mass fraction of O_2, O and N_2 along the stagnation streamline



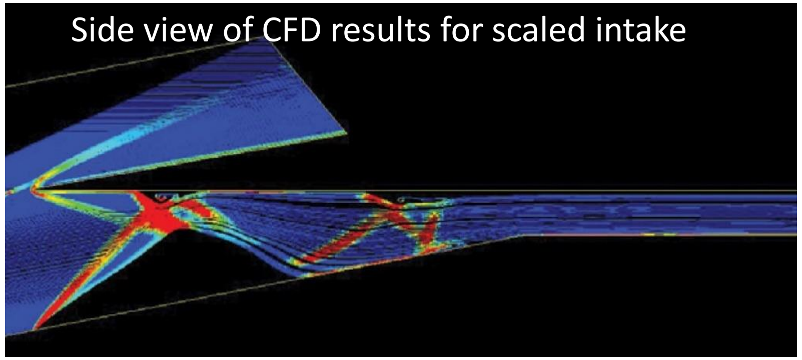
Case study: SCRAMJET design for Mach 6.5 cruise

IIT MADRAS
Indian Institute of Technology Madras

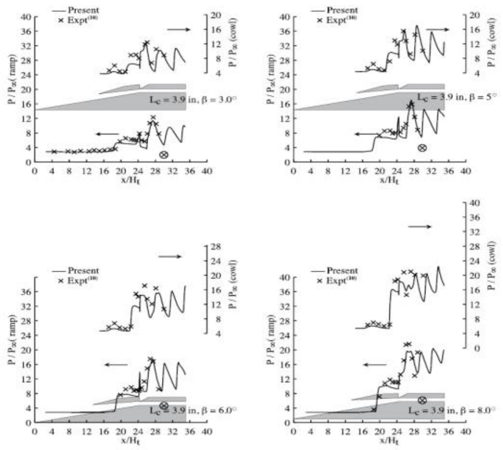
Hypersonic technology demonstrator vehicle (HSTDV) tested and simulated at IIT Madras by Professor V. Babu

Reference: V Babu, "Flight like the wind", ANSYS Advantage, Vol.8, 2014

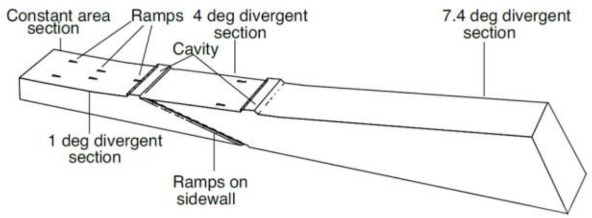
Initial validation on scaled-down wind tunnel model

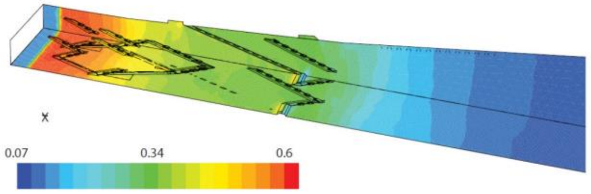


Validation of pressure recovery for 2 cowl angles

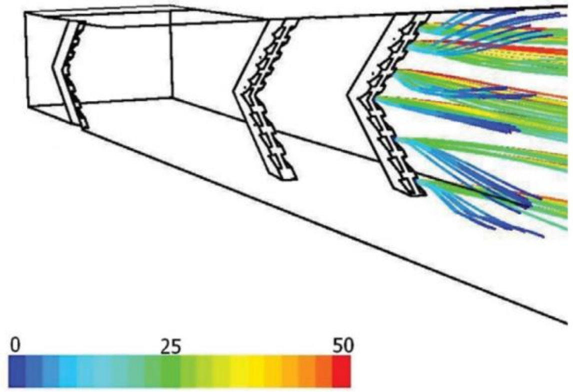


Full-scale SCRAMJET model





CFD simulation of original full-scale design



Fuel injection via DPM model in original design

Case study: SCRAMJET design for Mach 6.5 cruise

IIT MADRAS
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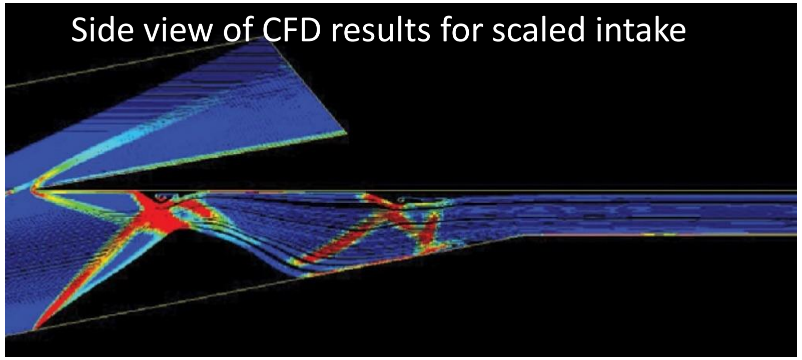
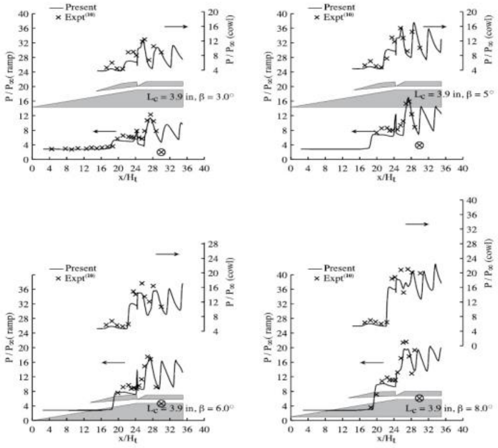
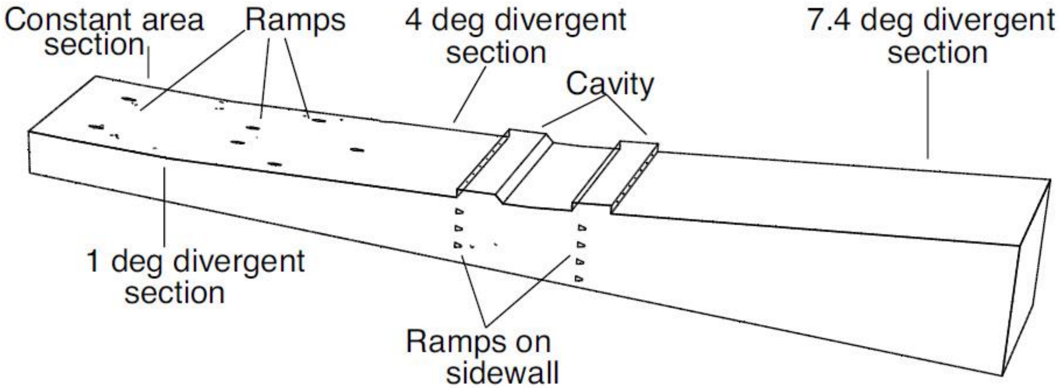
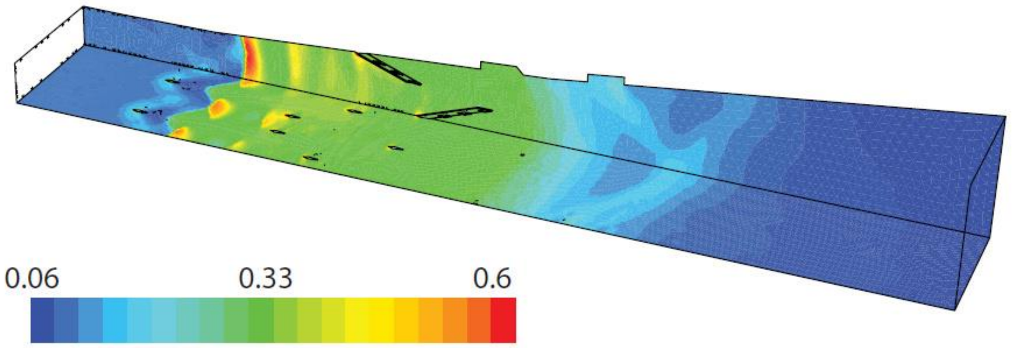


Validation of pressure recovery for 2 cowl angles



Modified full-scale design





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Ansys

Case study: SCRAMJET design for Mach 6.5 cruise

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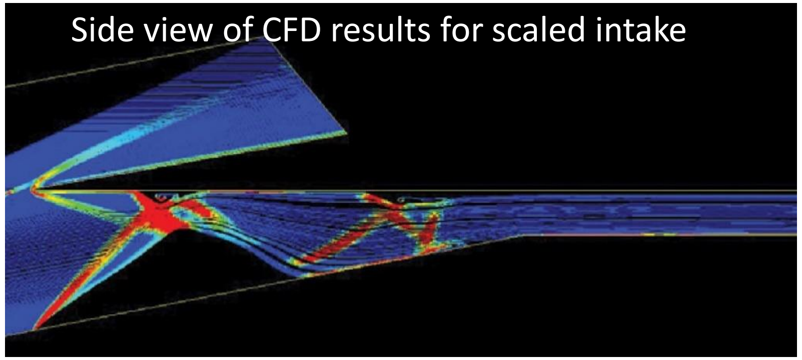
Initial validation on scaled-down wind tunnel model

Side view of CFD results for scaled intake



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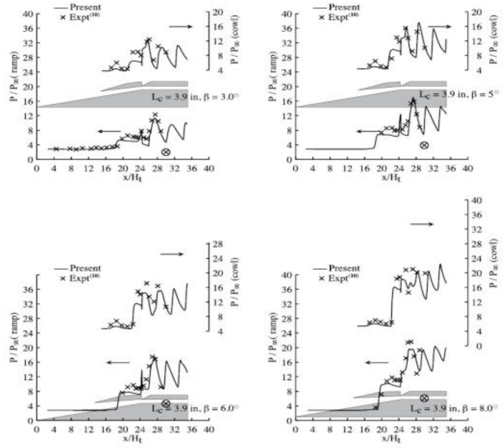
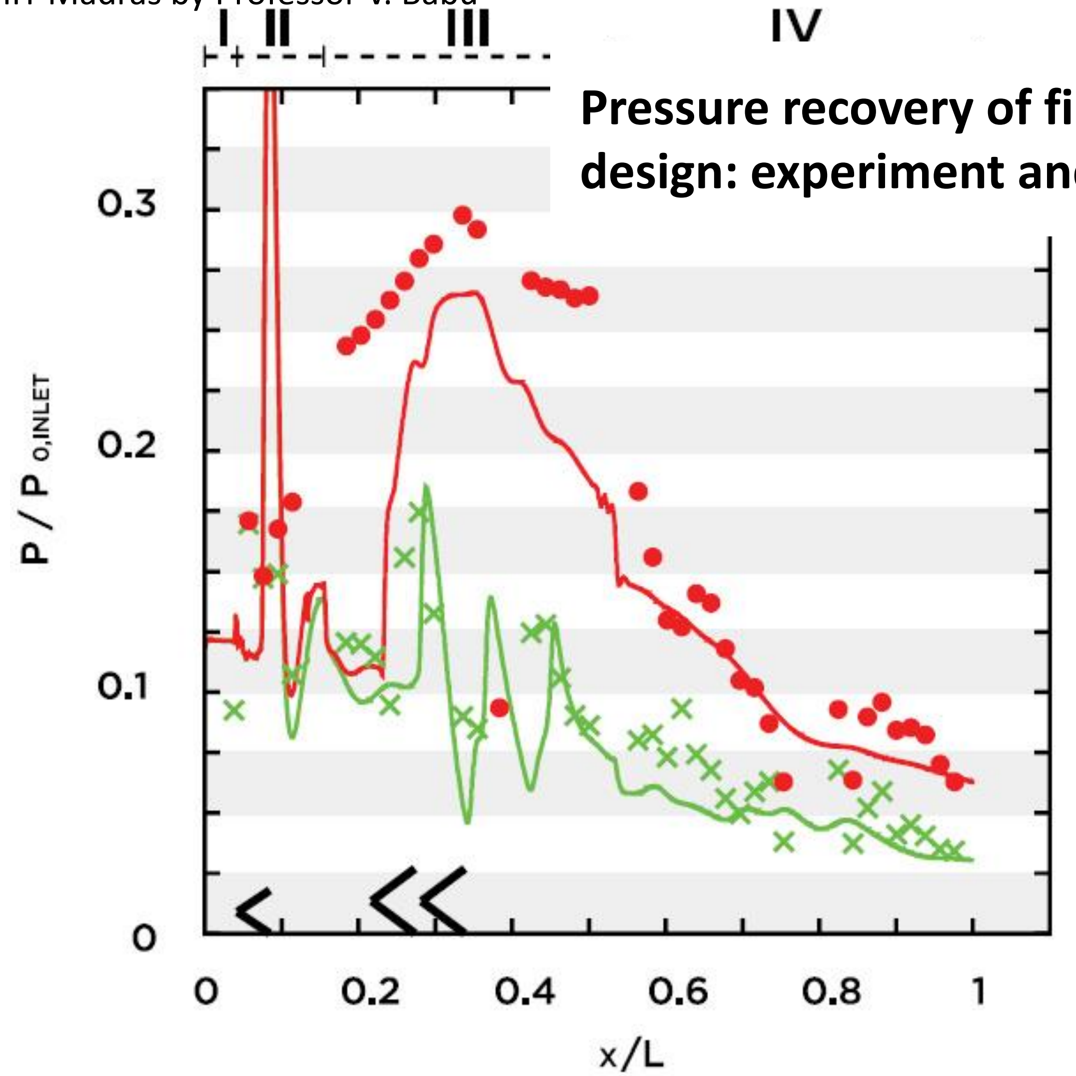
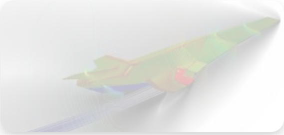


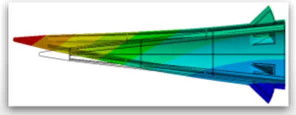
Pressure recovery of final design: experiment and CFD



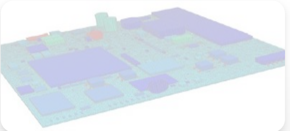
Outline



Aerothermodynamic environment



Structural integrity and deformation for a hypersonic vehicle



Sensor reliability in high heat-flux environment

Predicting communication degradation and blackout

Tool-chaining and workflow assembly for hypersonics

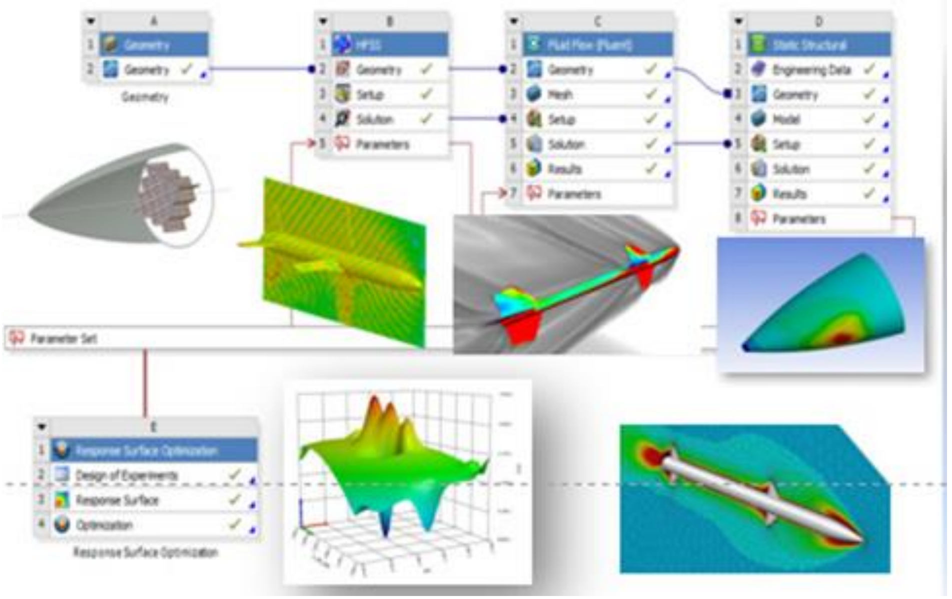
Scott Marinus

Ansys

Hypersonic FSI Workflow(s)

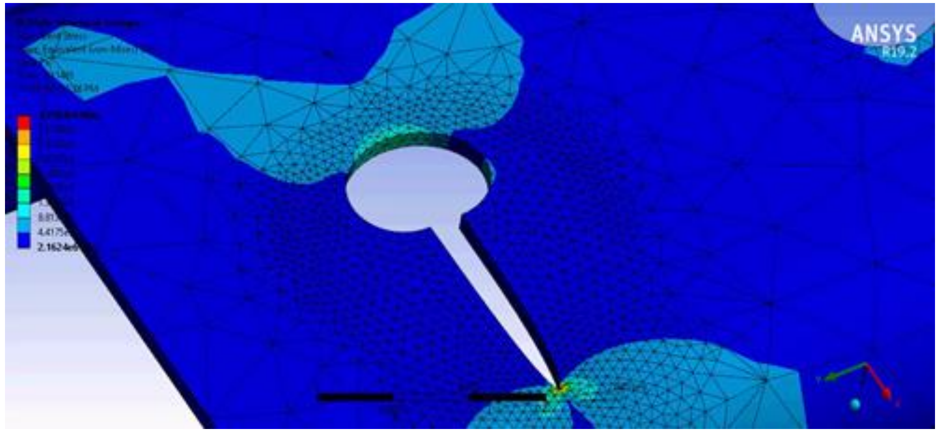
ANSYS Strengths

- Breadth and depth of physics
- Open platform; can integrate other tools/solvers
- Tool connectivity and Inter-operability (FSI, Emag, Systems, Digital Twin)
- Multiphysics ease of use
- Optimization across all tools
- Industry-wide name recognition

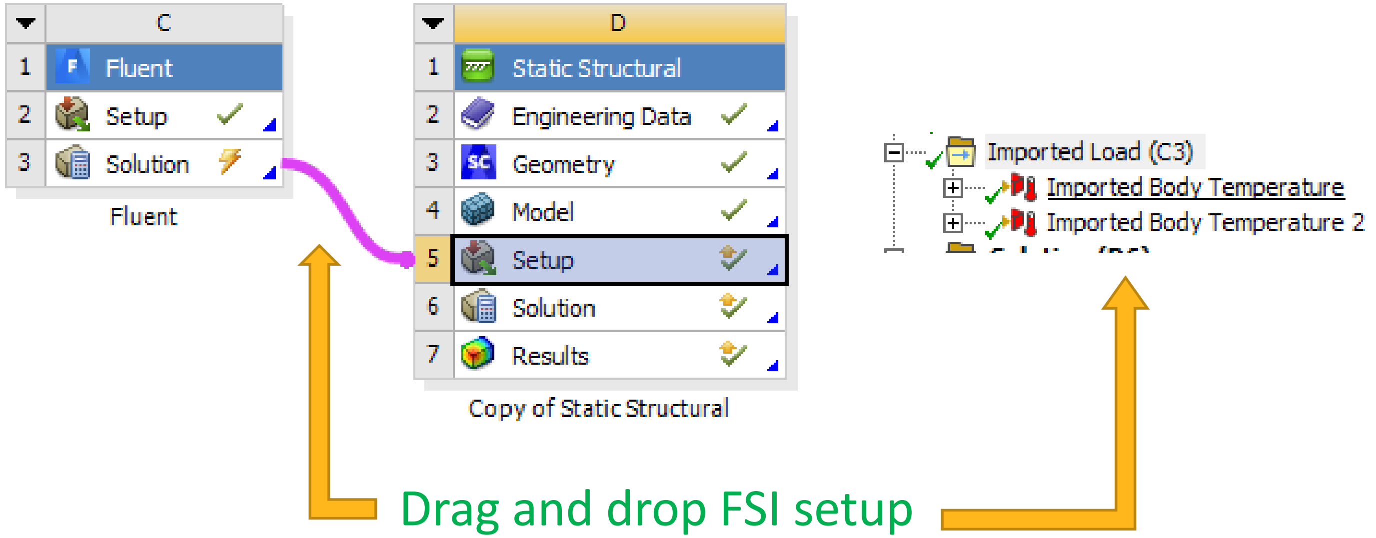


ANSYS Weaknesses

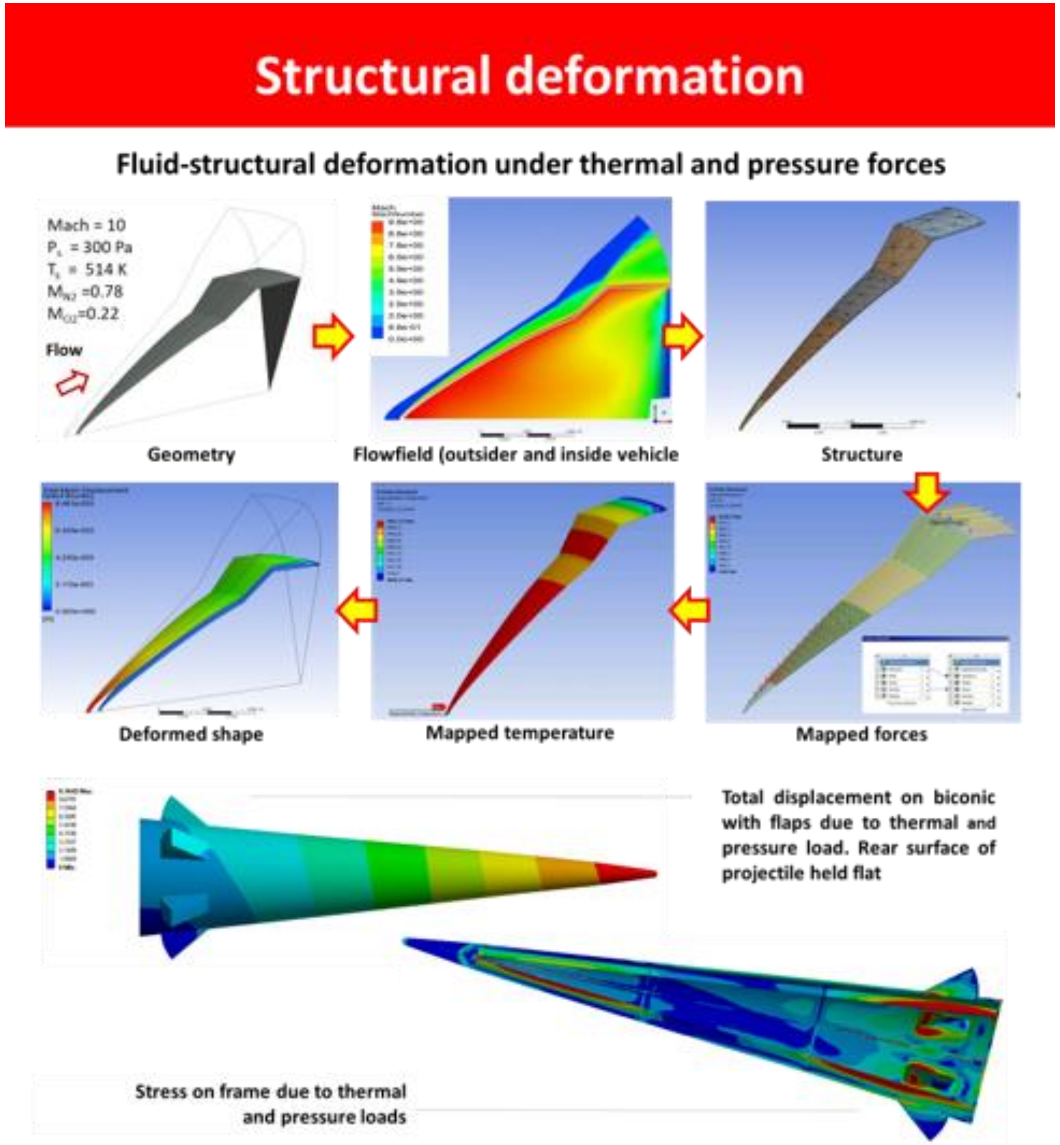
- Generic solver, not specific to Hypersonics
- Lacking some hypersonic-specific capabilities (Development aware, requirements shared)
- Lack of in-depth knowledge of customer pains



Hypersonic FSI Workflow

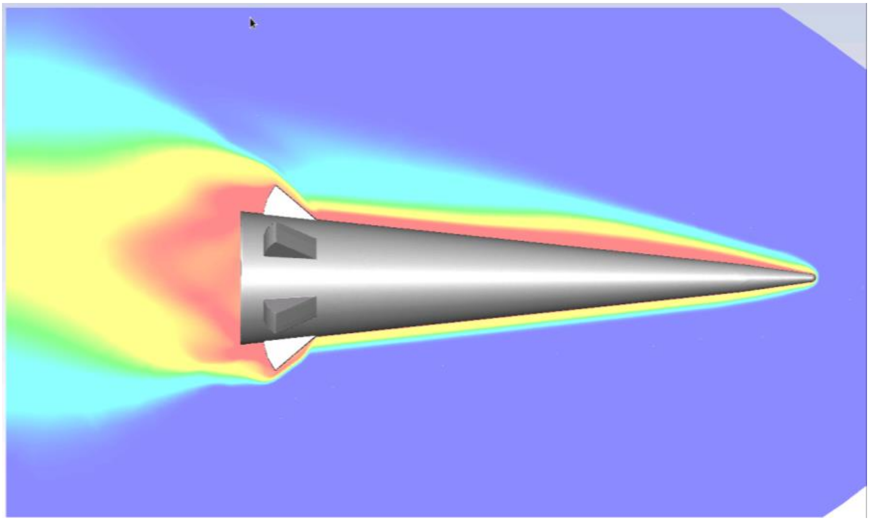


Automated import of files from fluids code simplifies process.



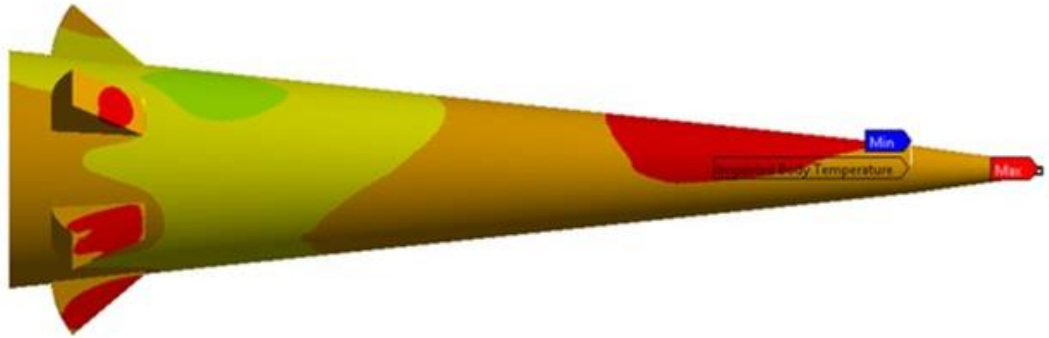
Hypersonic FSI Workflow

Ansys can map fluid data from:
- Ansys fluid solver
- 3rd party solvers
- Generic data files

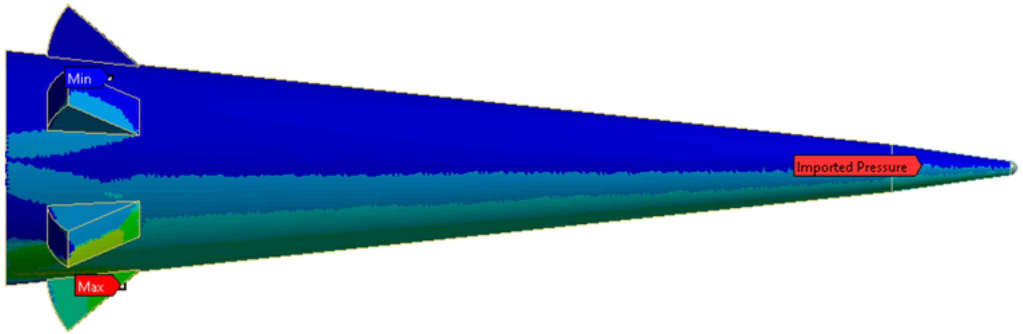


Mapping fluid solution to mechanical solution

Temperature

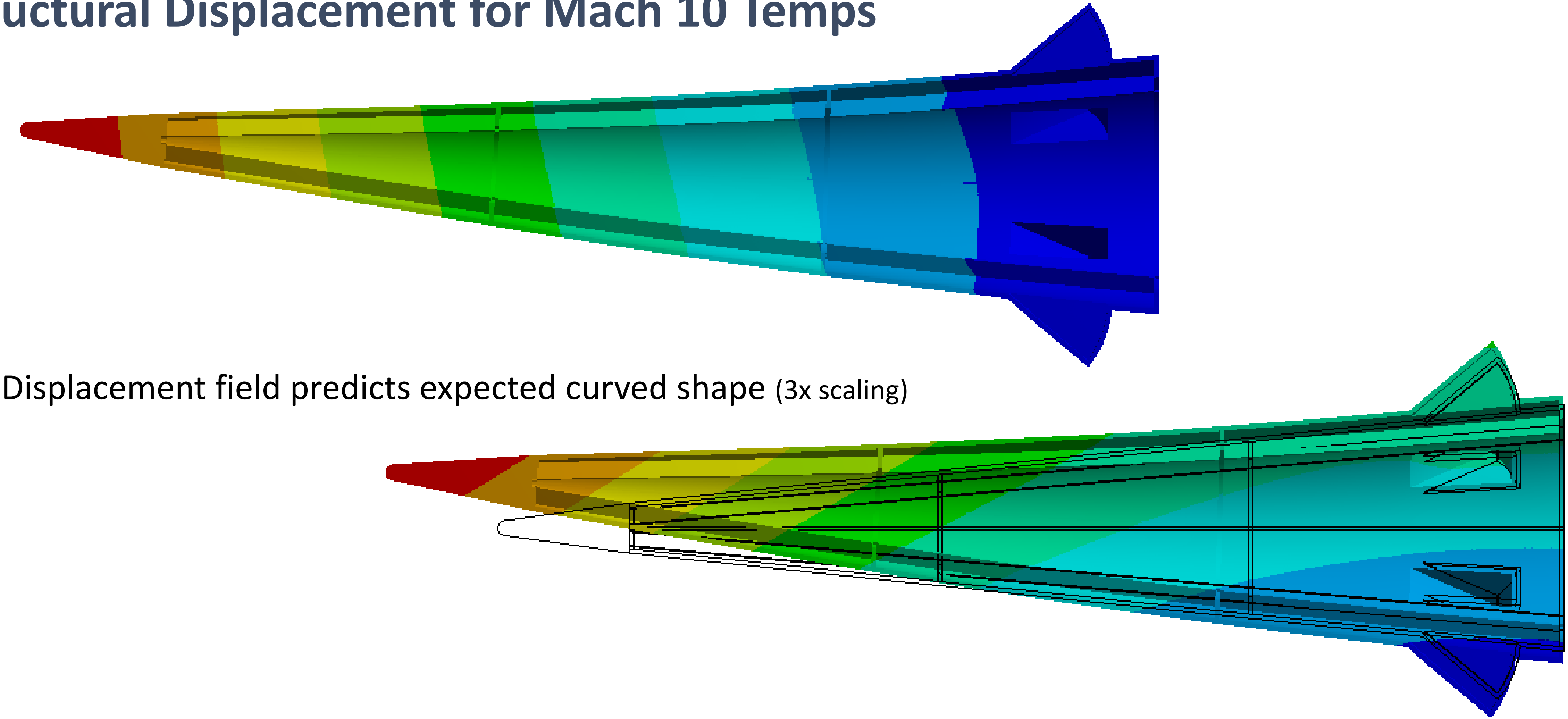


Pressure



Mechanical Solution

Structural Displacement for Mach 10 Temps

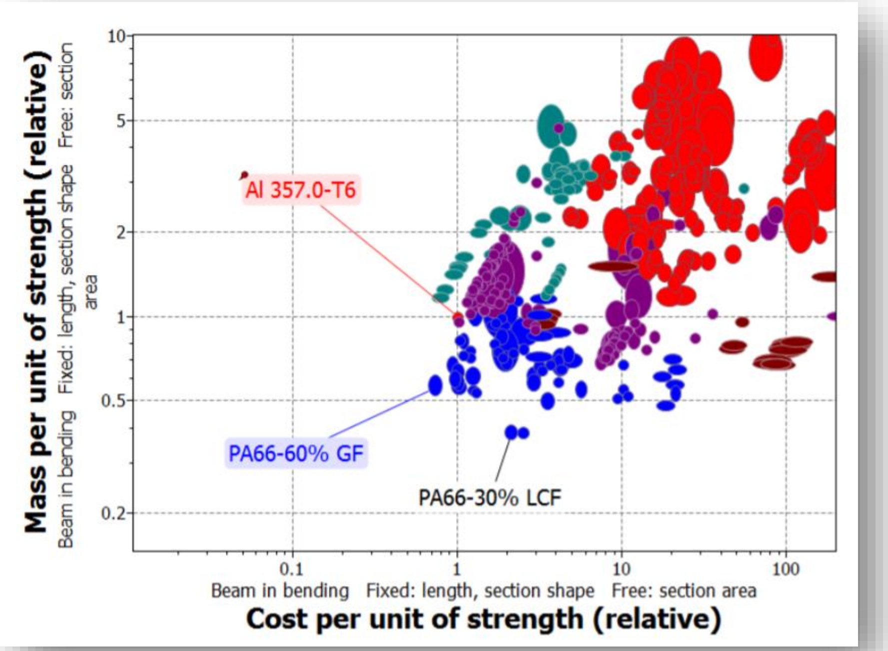


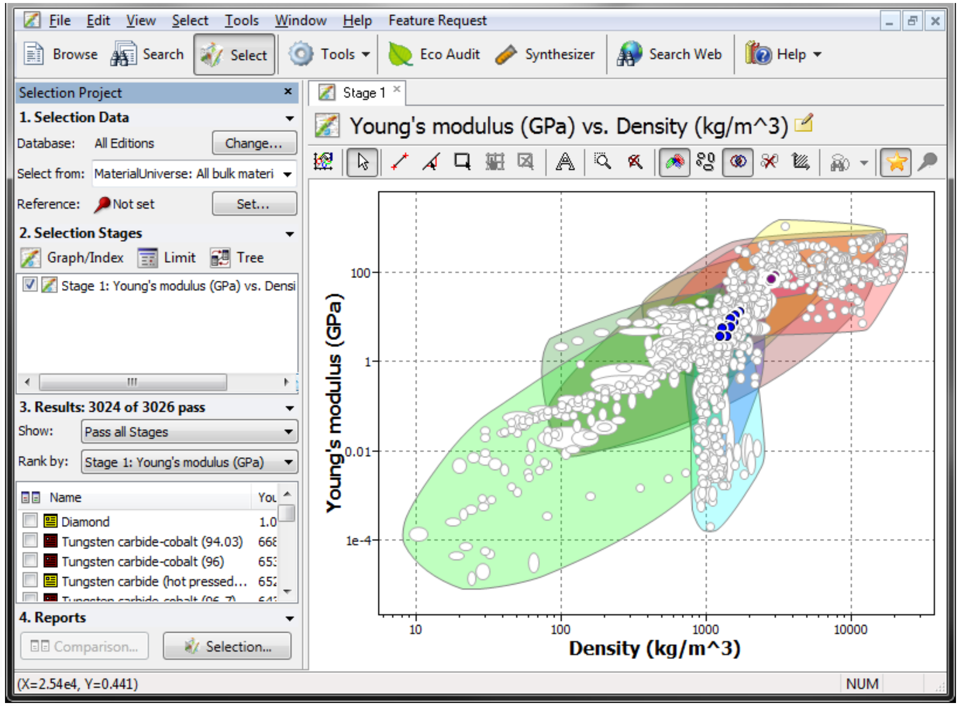
*Displacement field predicts expected curved shape (3x scaling)

Ansys

Ansys

Material Selection



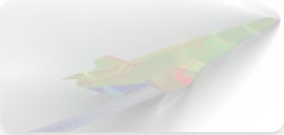


Current material: Al 357-T6

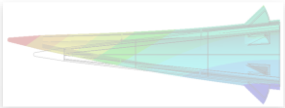
New material:
glass fiber reinforced polyamide
(4MID 9A22160)

- Properties for extreme environments
- Compare materials based on their performance
- Identify replacement material and specific grade
- Reduce weight by 45% and cost by 25%
- Communicate results with rationale and justifications.

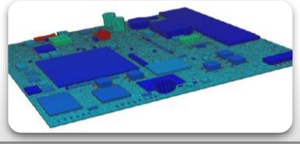
Outline



Aerothermodynamic environment



Structural integrity and deformation for a hypersonic vehicle



Sensor reliability in high heat-flux environment

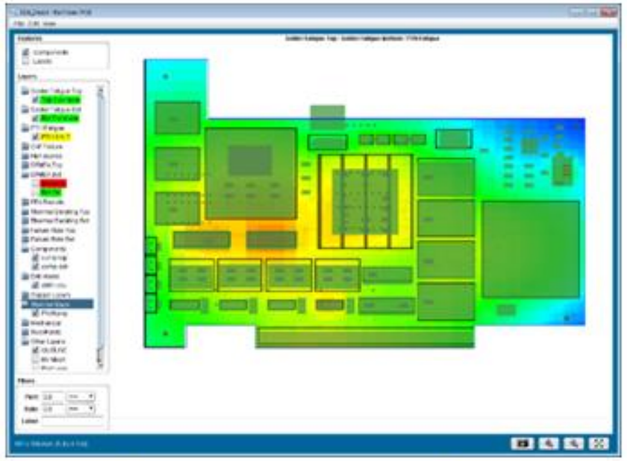
Predicting communication degradation and blackout

Tool-chaining and workflow assembly for hypersonics

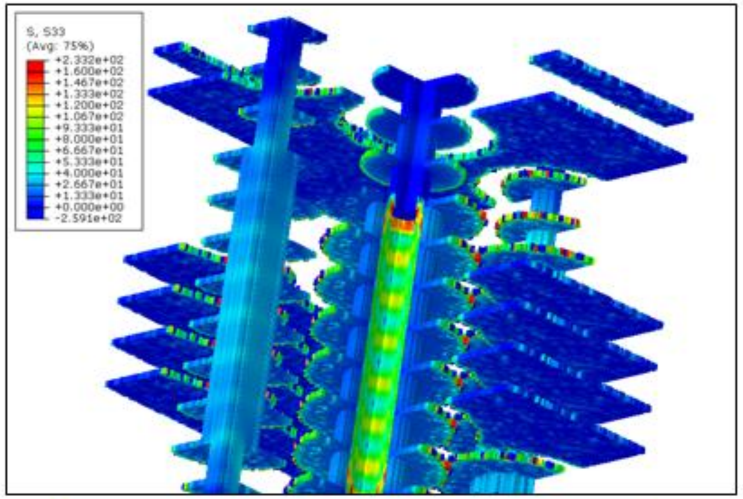
Scott Marinus

Sherlock – Electronics Reliability

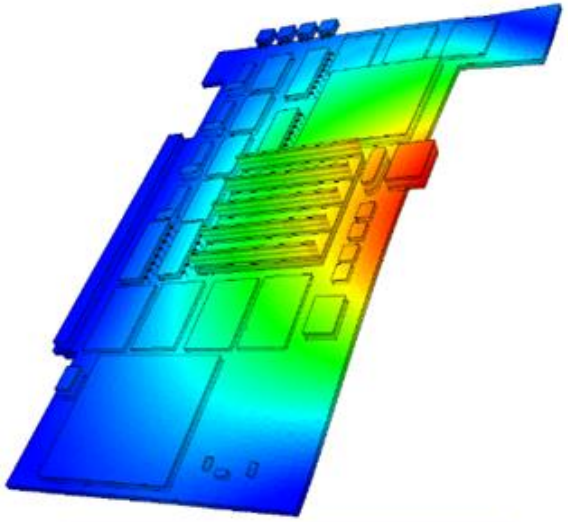
- Electronics-focused Reliability Physics Analysis (RPA) tool
- Predicts product failure early in design process, quickly and accurately
- Mitigates thermal, mechanical, and manufacturing risks



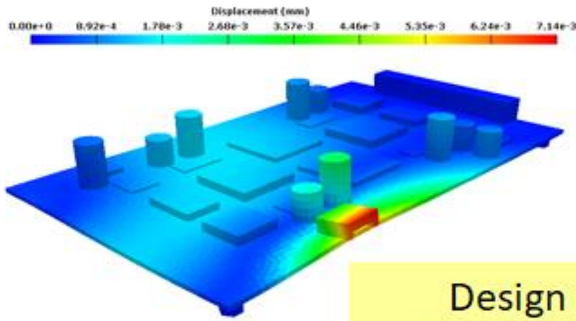
Thermal Cycle Fatigue



Predict solder reflow failures



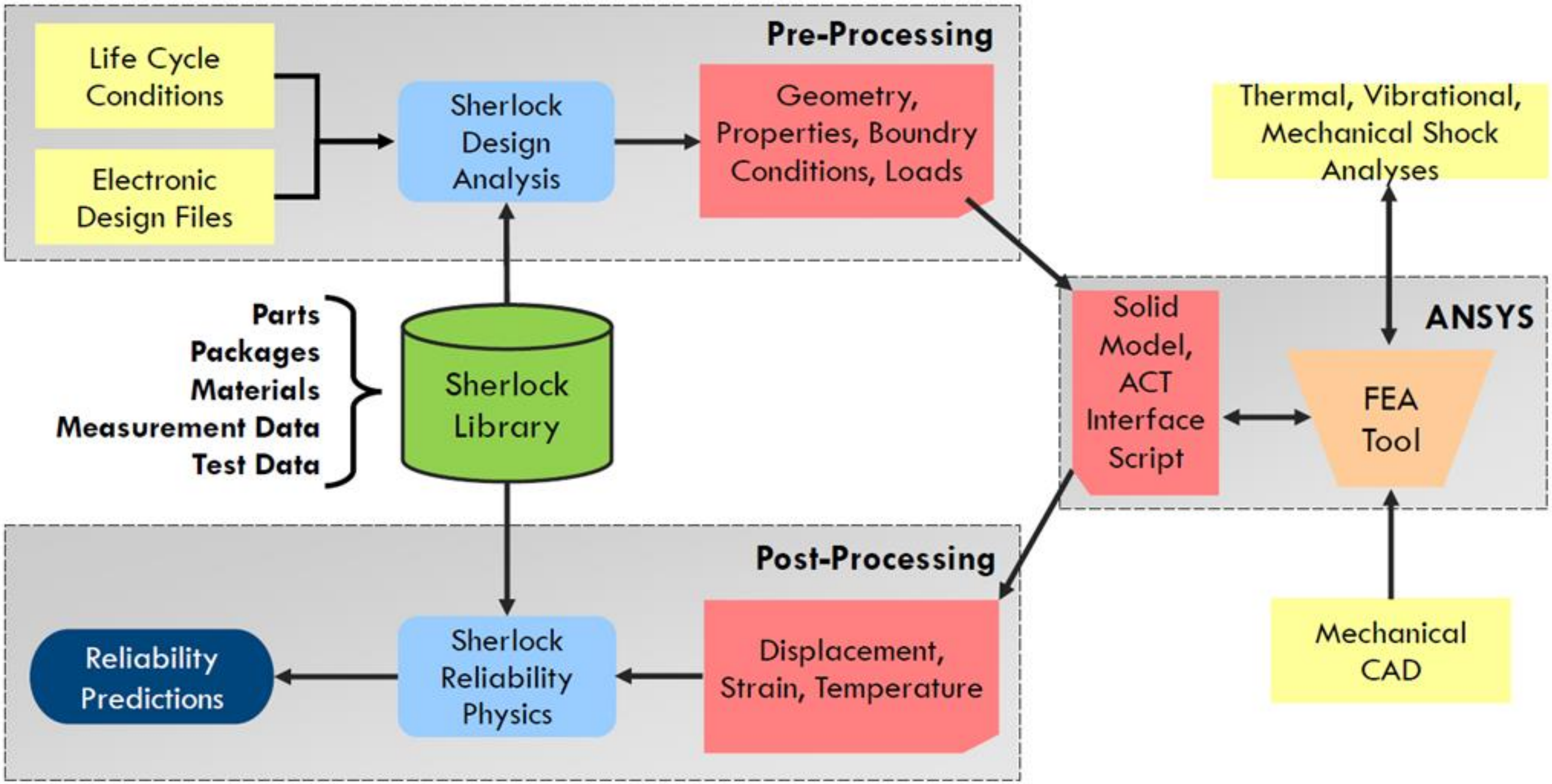
Vibration/Mechanical Shock



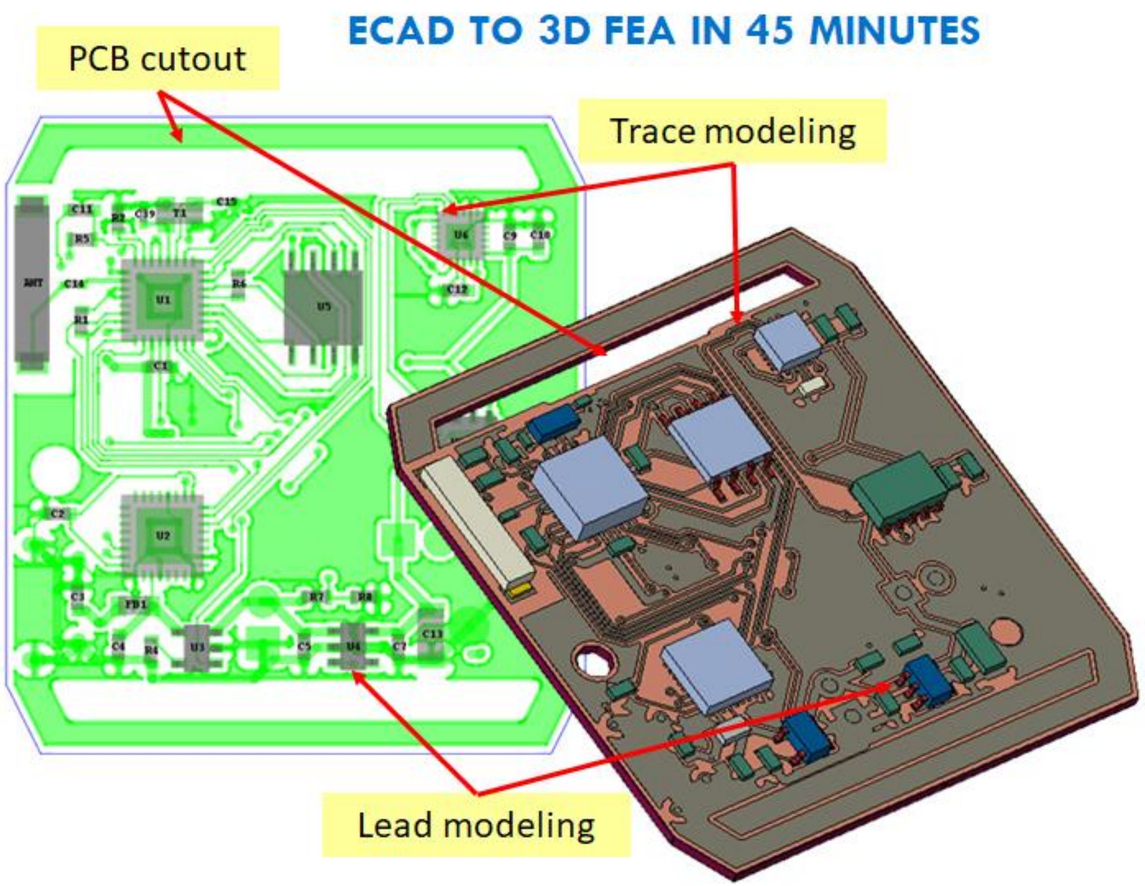
Design for Manufacturing

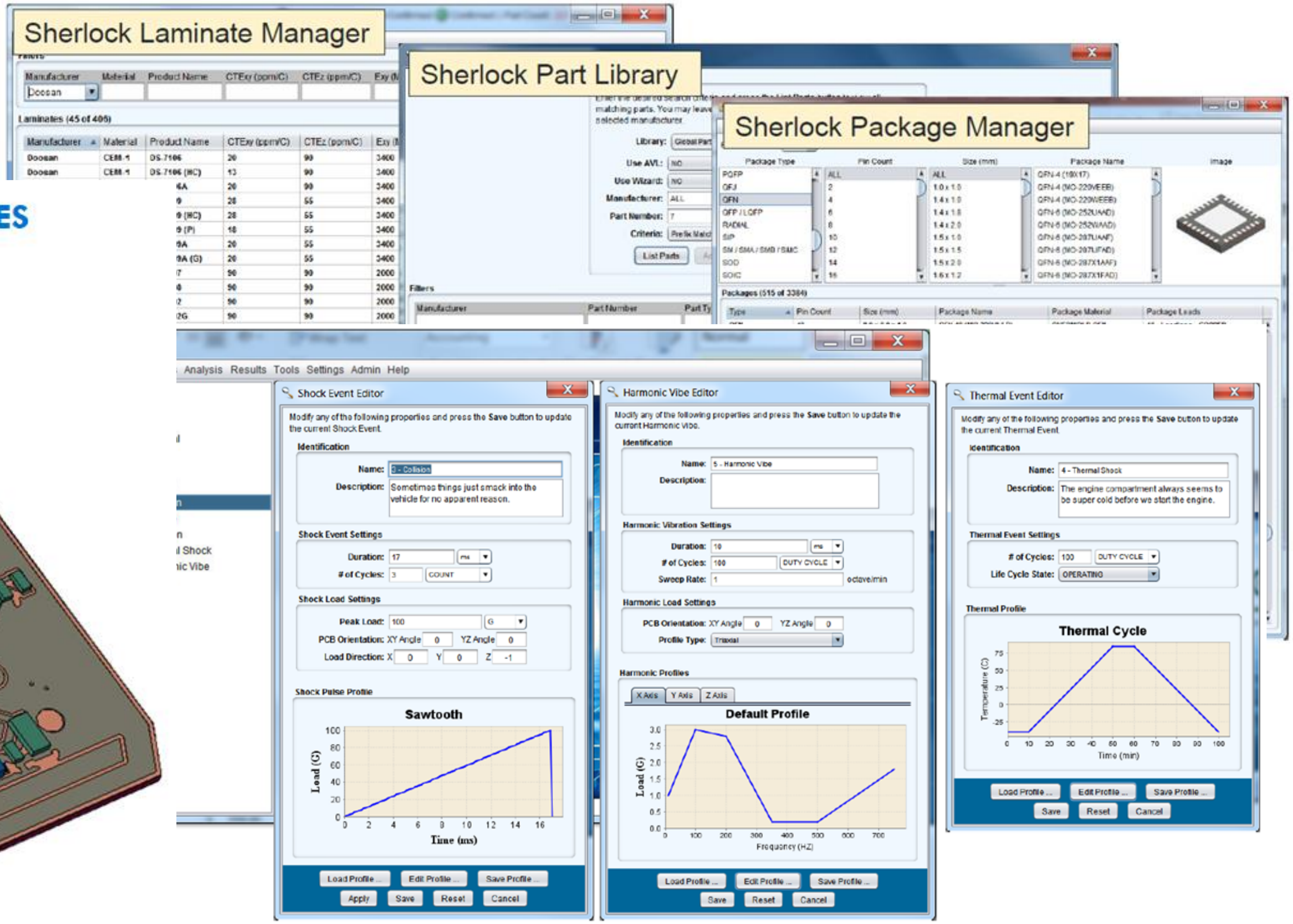
4

Sherlock – Electronics Reliability

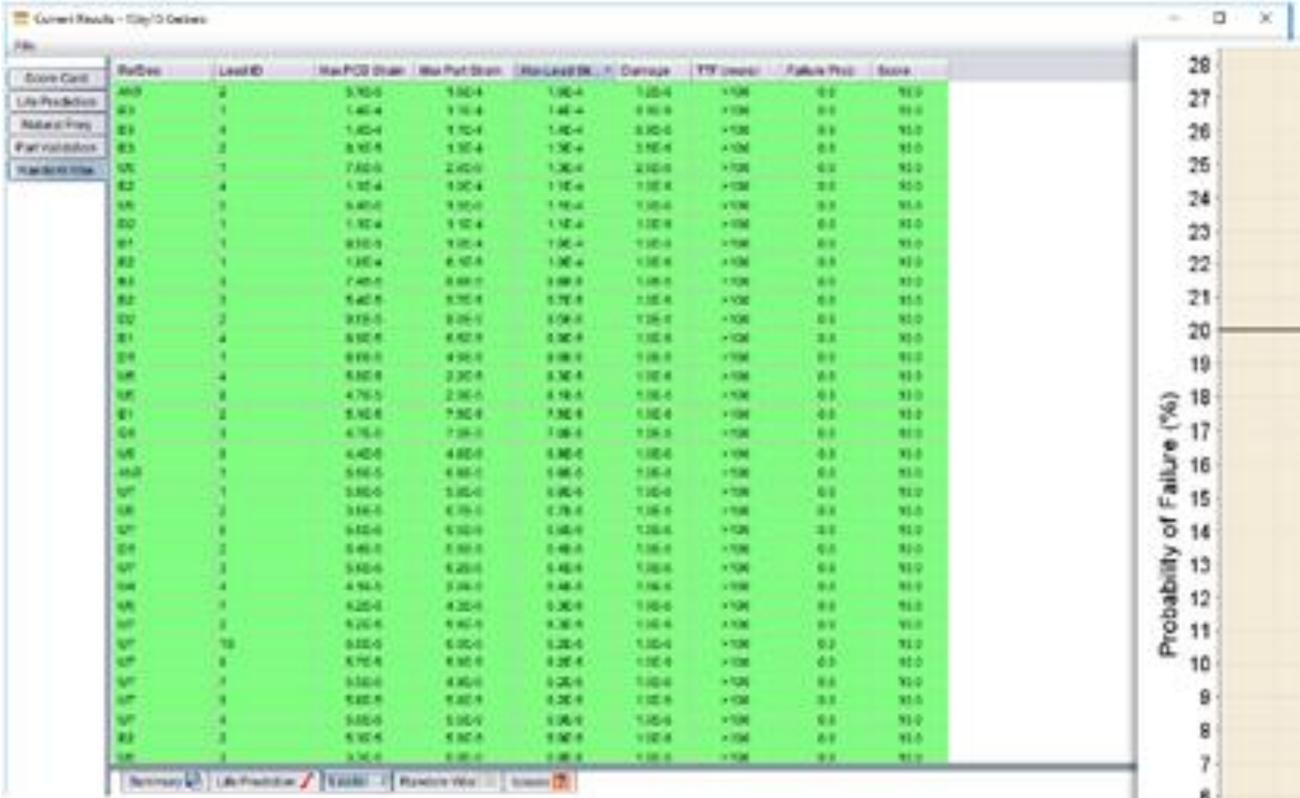


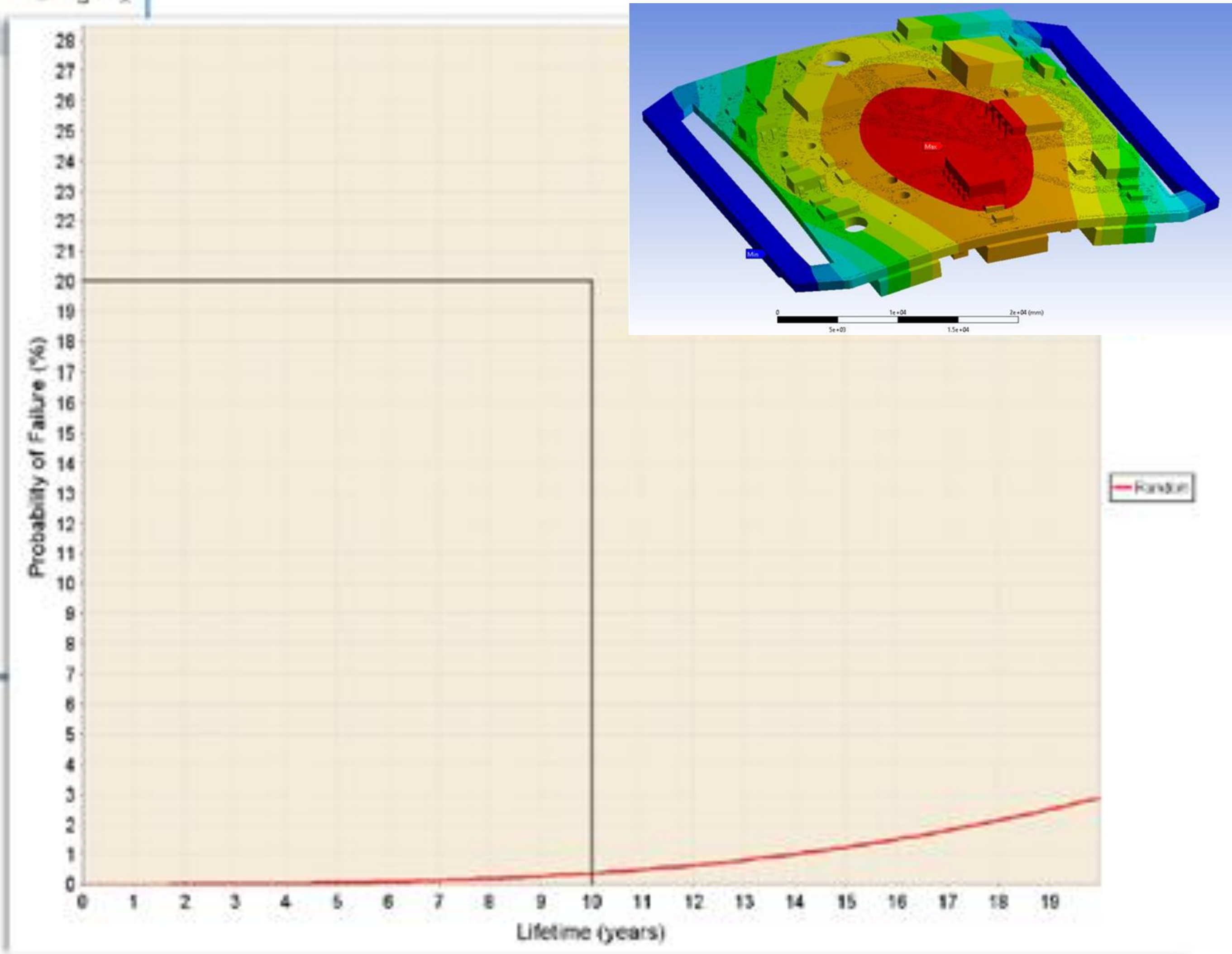
Sherlock – Electronics Reliability





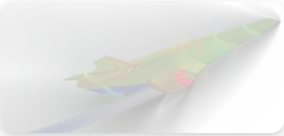
Sherlock – Electronics Reliability



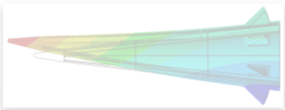


- Cumulative Damage Index (CDI)
- Time to failure
- Life Curve

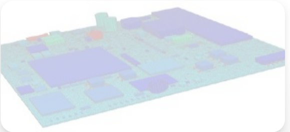
Outline



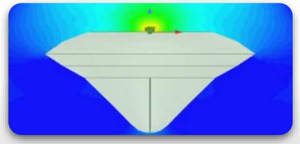
Aerothermodynamic environment



Structural integrity and deformation for a hypersonic vehicle



Sensor reliability in high heat-flux environment



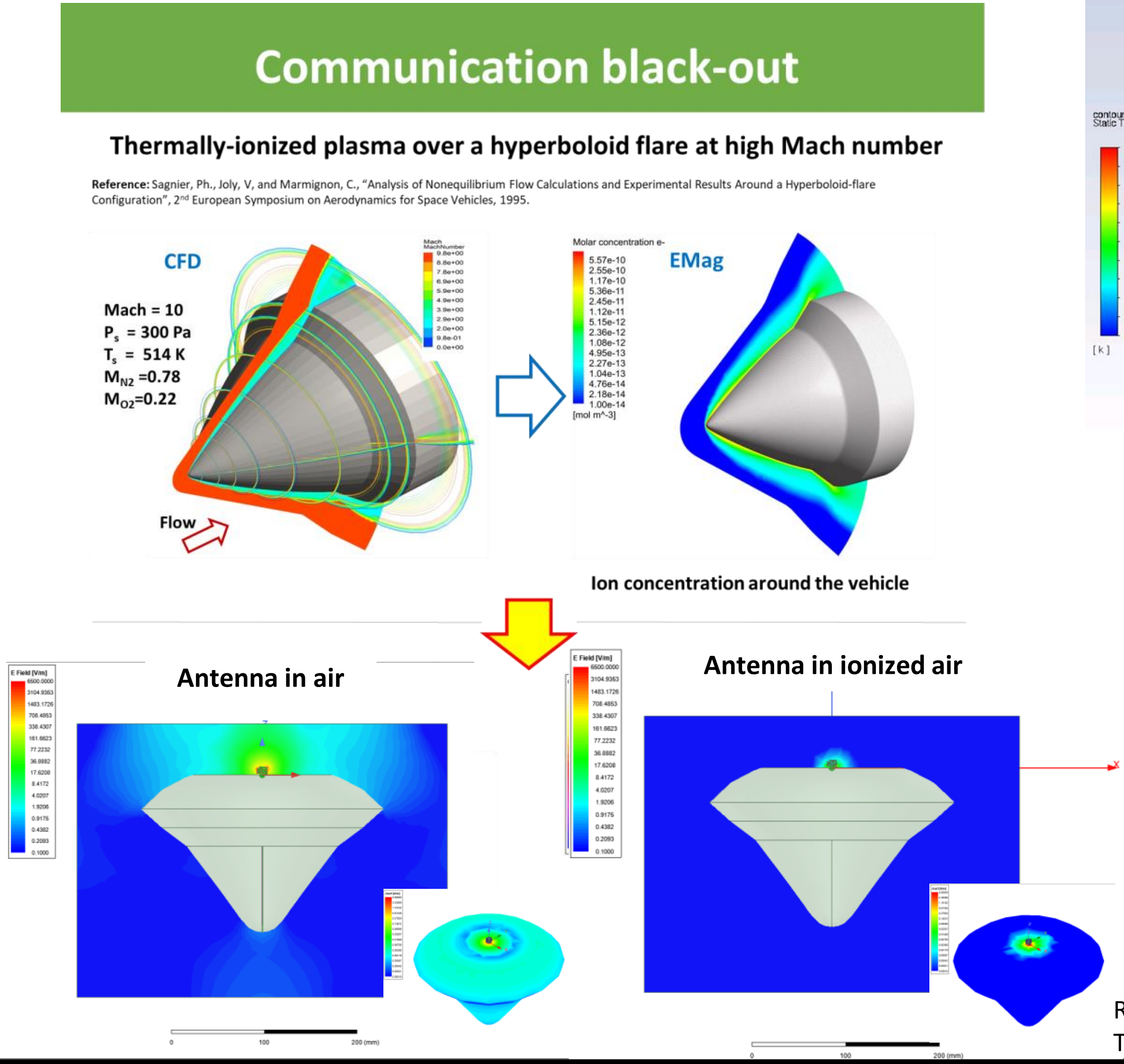
Predicting communication degradation and blackout

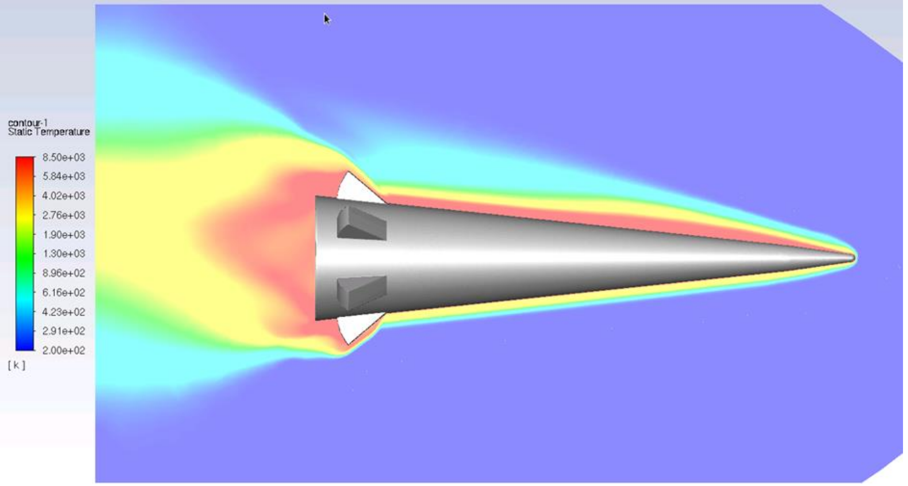
Tool-chaining and workflow assembly for hypersonics

Jeff Tharp

Ansys

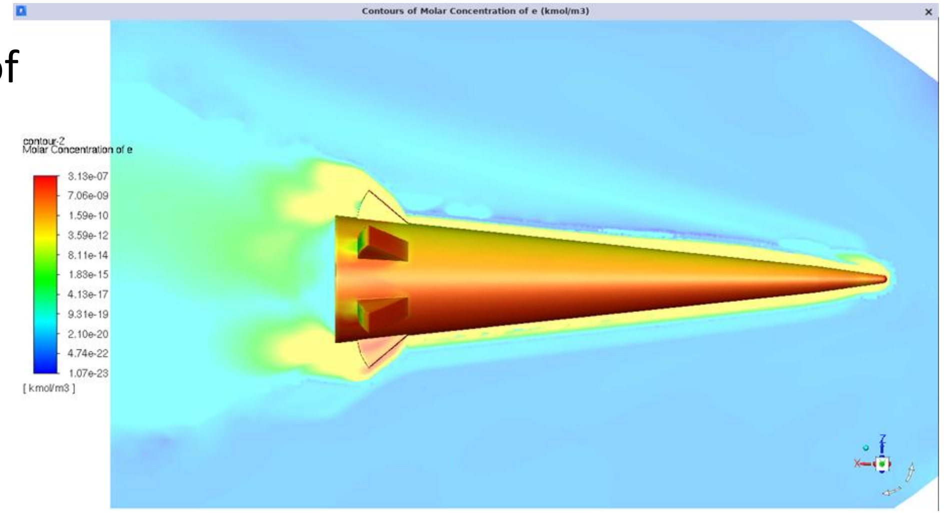
Bringing Ionization Physics into Electrical Analysis





Spatial Variation of Temperature

Spatial Variation of Thermally Induced Electron Concentration



Ref: "*Development and validation the ANSYS hypersonic prototype*", Viti et al., Hypersonic Technology and Systems Conference, Alexandria, VA, 26-29 August, 2019.

Extracting Electrical Material Properties of Plasma from Fluent

- HFSS includes the ability to import 3D Spatially Varying datasets for the definition of material properties To create a complex conductivity model, the following is utilized from Fluent for each spatial location
- Number Density of Electrons (1/m^3)
- Number Density of Non-electrons (positive ions and neutral species) (1/m^3)
- Temperature (K)
- With these values one can use the below, based upon the Drude Model for Free Plasma,

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

$$\nu_c = 6.3\times10^{-15} n_m \sqrt{\frac{T}{300}}$$

$$\sigma(\omega) = \frac{\sigma_o}{1+j\omega\tau} = \left(\underbrace{\frac{\sigma_o}{1+\omega^2\tau^2}}_{\sigma'(\omega)}\right) - j\left(\underbrace{\frac{\sigma_o\omega\tau}{1+\omega^2\tau^2}}_{\sigma''(\omega)}\right)$$

DC Conductivity = $\sigma_0 = \omega_p{}^2\epsilon_0\frac{1}{v}$

$$\varepsilon_r(\omega,x,y,z) = 1 - \frac{\sigma''}{\omega\epsilon_0}$$

$$\sigma'(\omega,x,y,z) = \frac{\sigma_0}{1+\omega^2\tau^2}$$

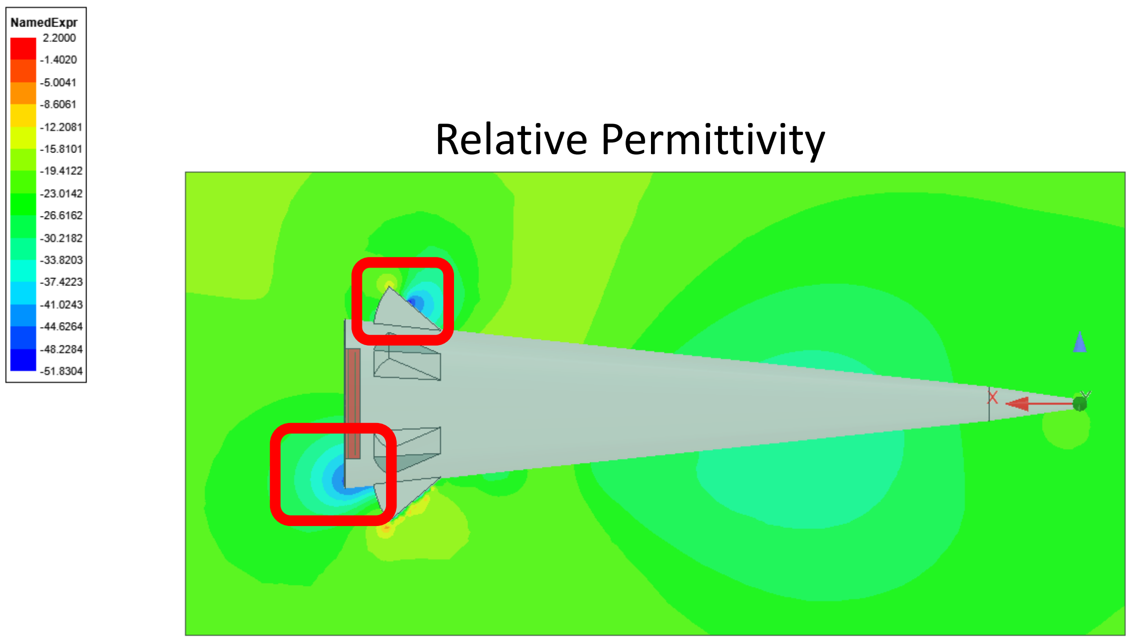
- ω_p is the plasma frequency, n_e is the number density of electrons, n_m is the number density of non-electrons
- ν_c is the damping frequency associated with loss = $1/\tau$

Extracting Electrical Material Properties of Plasma from Fluent

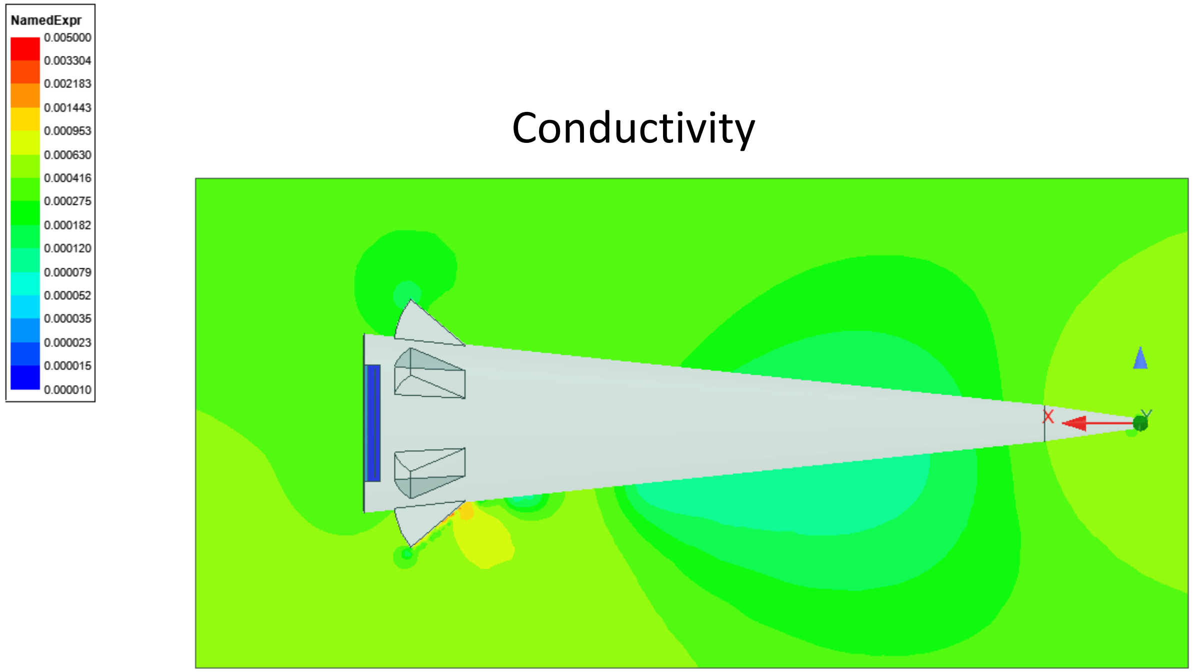
Spatially Varying Permittivity and Conductivity (Mach 20)

- Once the datasets are created for permittivity and conductivity, they can be imported
- Regions of high electron concentration display large negative permittivity
  - Negative permittivities induce evanescent field propagation with a decay length related to the magnitude. If the negative permittivity becomes large, it can decay all signal preventing communication to a receiving antenna

Relative Permittivity

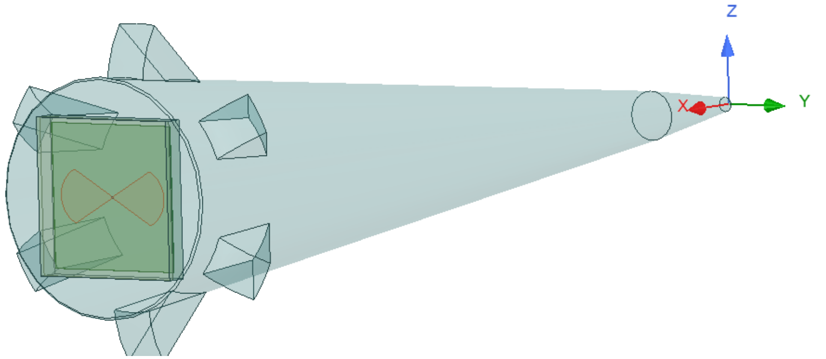


Conductivity

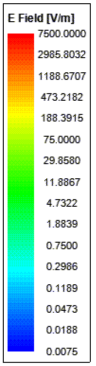


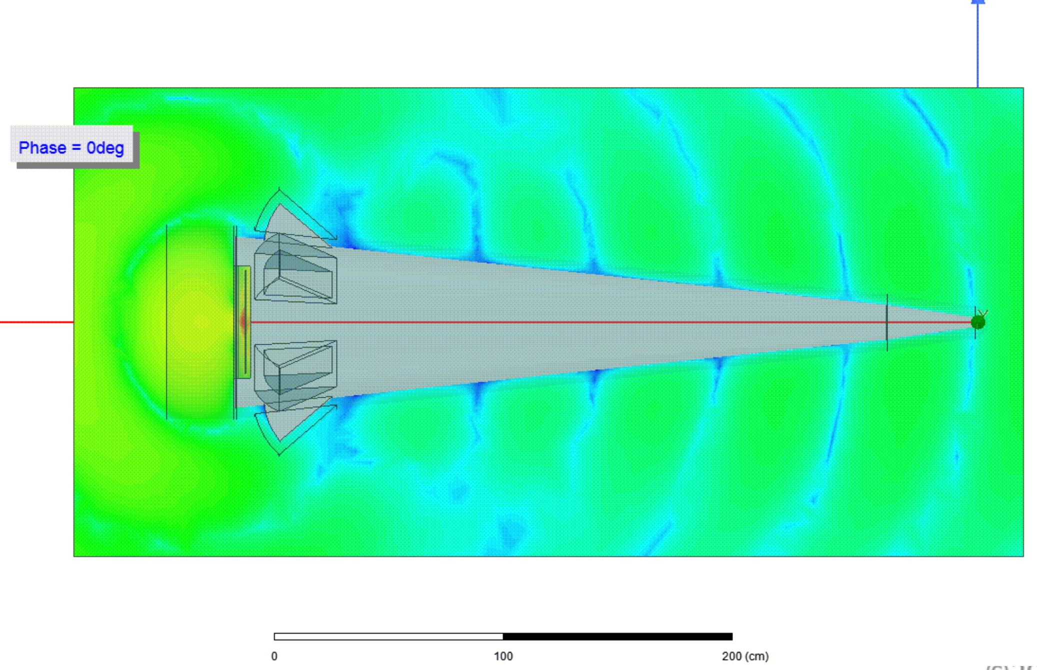
Plasma effects on Antenna Field Generation

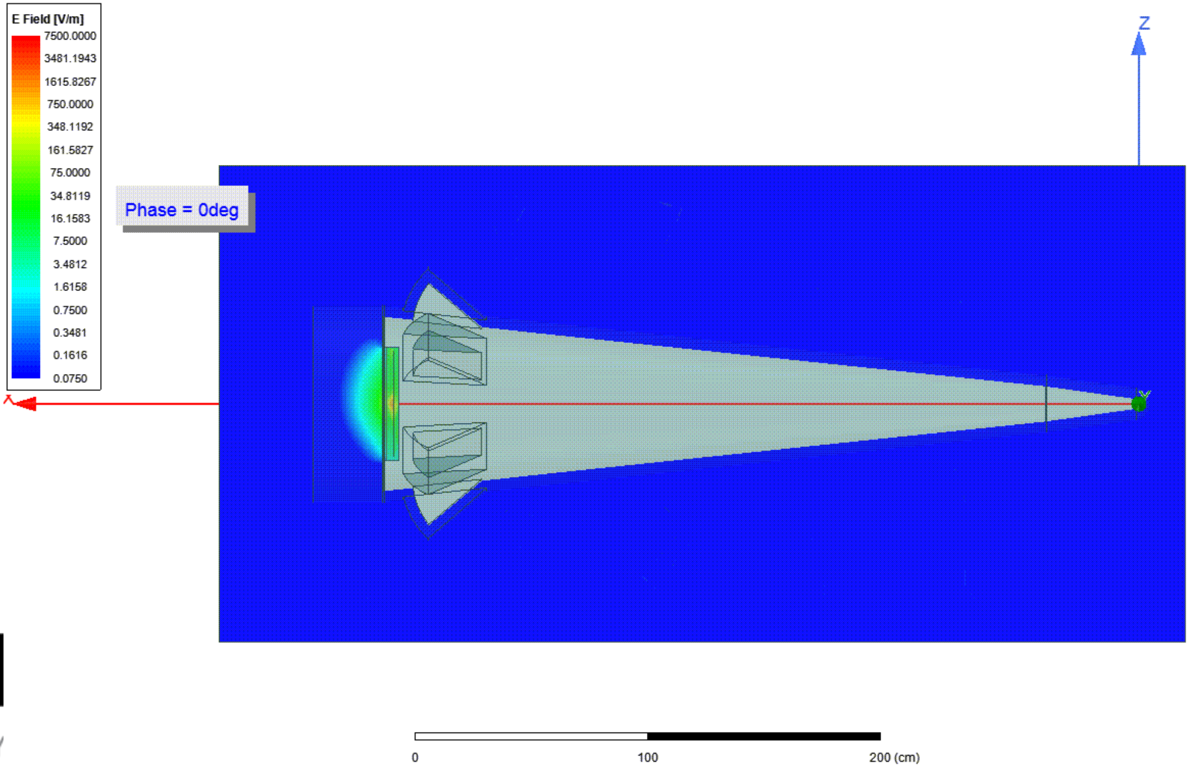
Simulated Results and Comparisons (Mach 20)



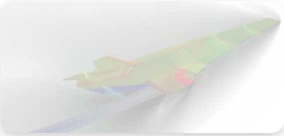
- A simple bowtie antenna with a dielectric radome was installed in the rear of the projectile
  - Operating Frequency of 300MHz
  - Notice marked degradation of Electric Field propagating into region
    - ➢ Same scale for both field plots







Outline



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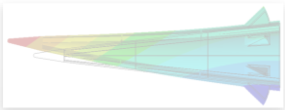

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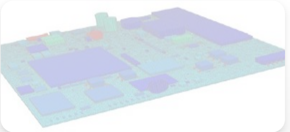

Sensor reliability in high heat-flux environment

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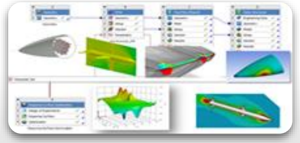


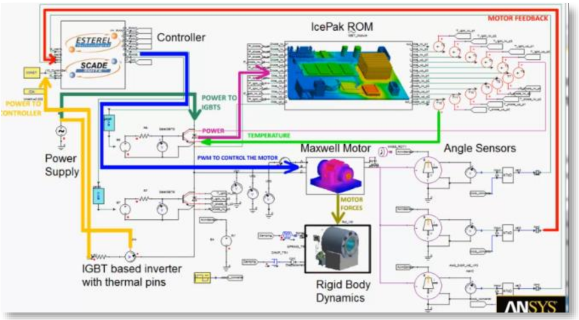
Tool-chaining and workflow assembly for hypersonics

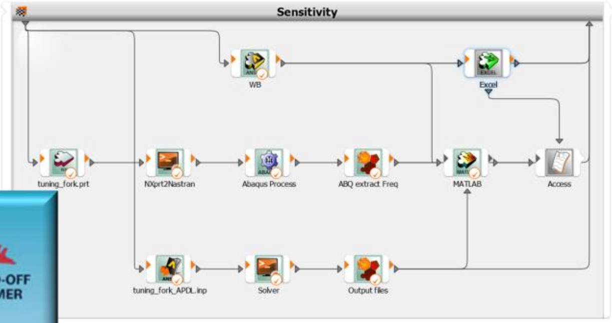
Craig Miller

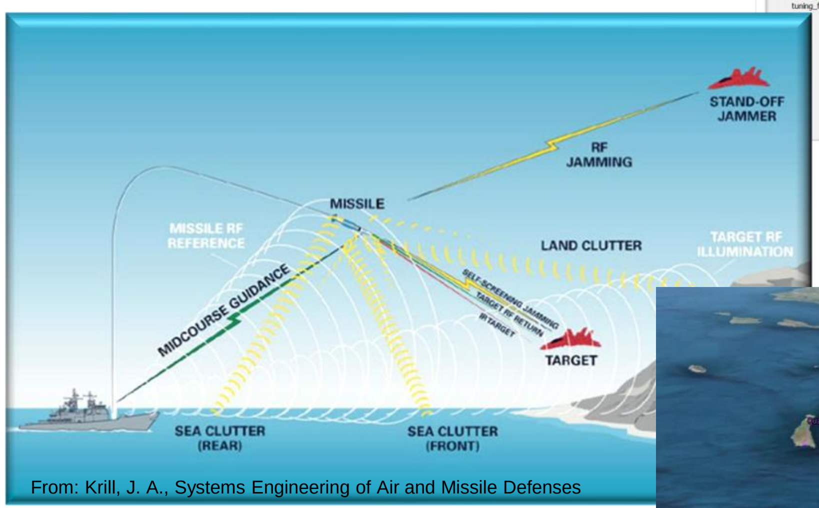
Ansys

Simulation Process Assembly

- Hypersonics is an inherently multi-domain challenge. Simulating physics models will require connecting different tools & codes at various levels of abstraction
- Control System
  - Simulate flight controls using physical behavior of vehicle
  - Aeroservoelasticity
- Navigation and guidance
  - MBSE for controls development
  - Virtual environment for testing
- Open System Platform
  - Connect Ansys simulations using APIs to in-house codes and 3rd party tools
- Wargaming
  - Integrate realistic 3D physical models in simulated interconnected environment
  - Partnership with AGI to develop realistic physics-based system behavior

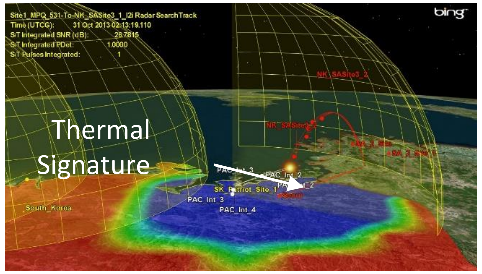


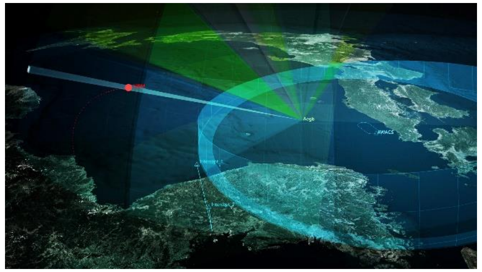


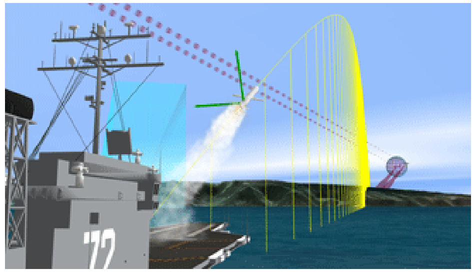


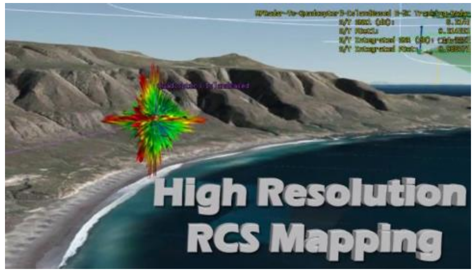
From: Krill, J. A., Systems Engineering of Air and Missile Defenses

AGI-Ansys Hypersonic Example









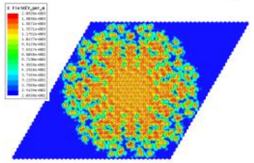
AGI

Trajectory Data

- **Time**
- **Altitude**
- **Mach Number**
- **Angle of Attack**

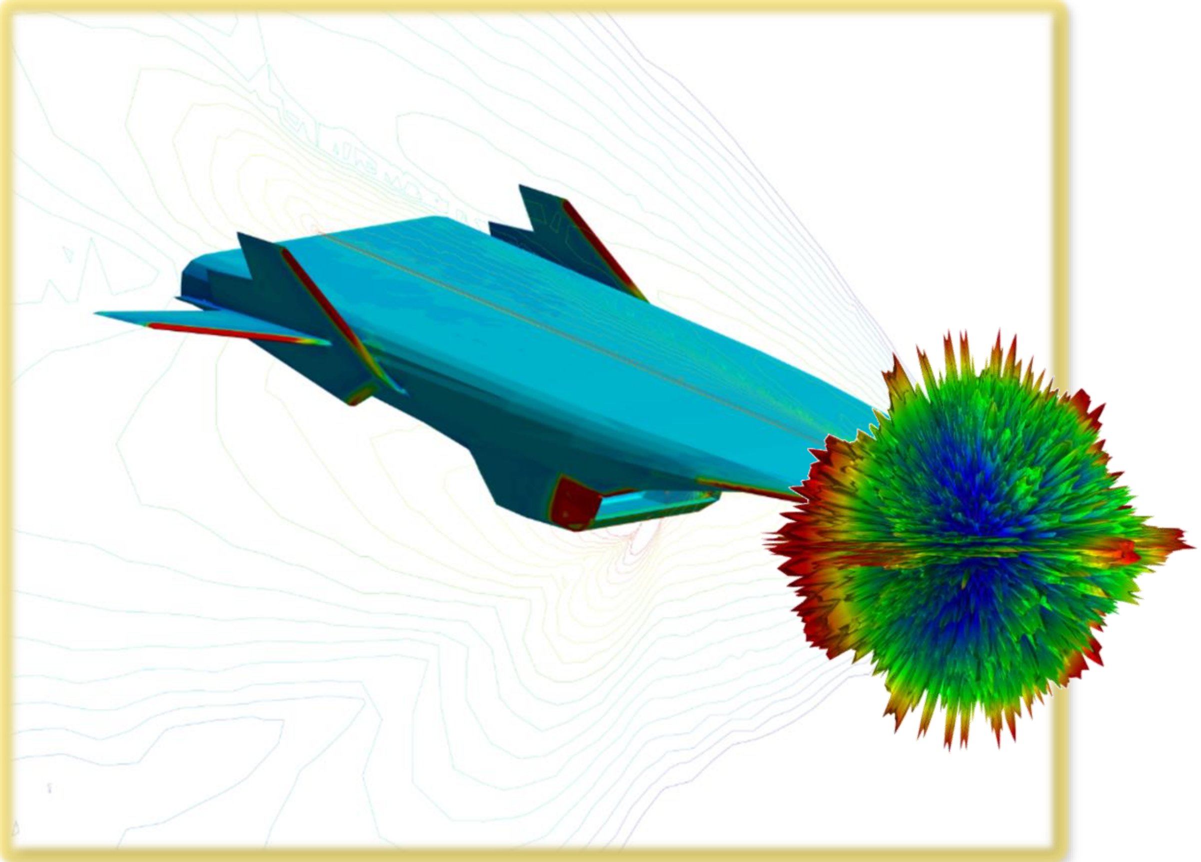
Aviator Performance Model
EO/IR Target Signature

Dynamic pointing geometries



RCS / Antenna Gain

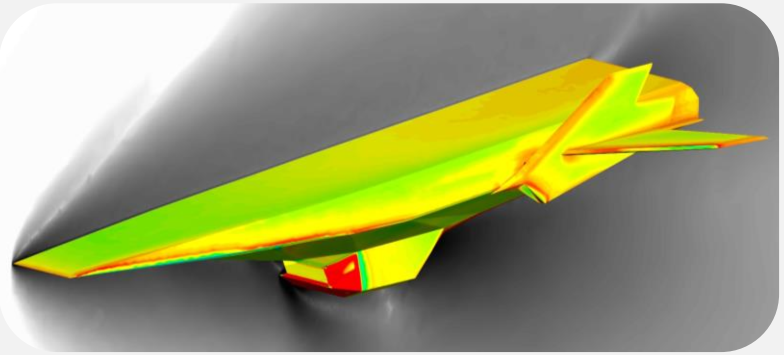
ANSYS



High-fidelity models of hypersonic vehicle

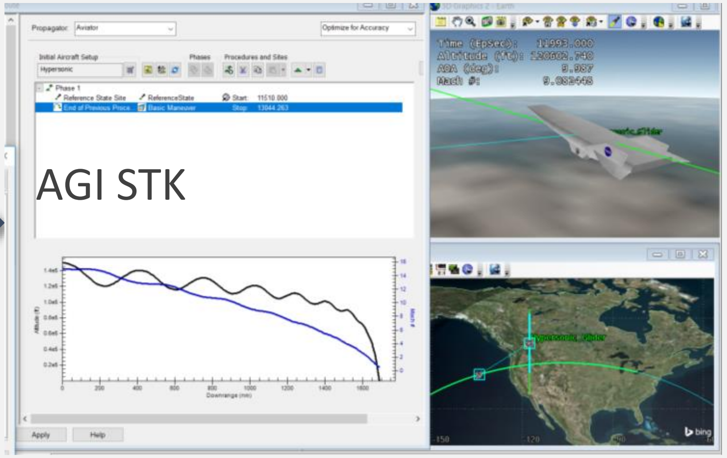
Digital Mission Engineering fueled by Ansys high-fidelity CFD physics

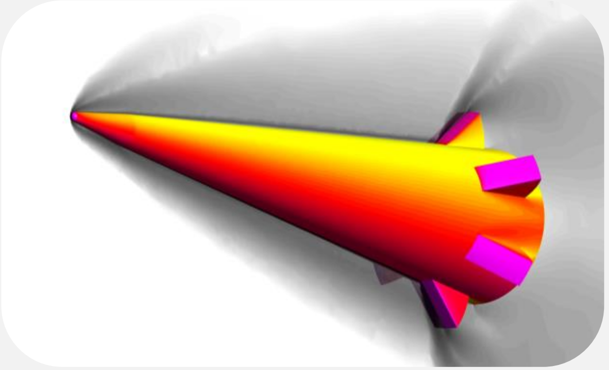
High-Fidelity Physics | Digital Mission Sim



High-fidelity CFD analysis of vehicle (Ansys CFD)

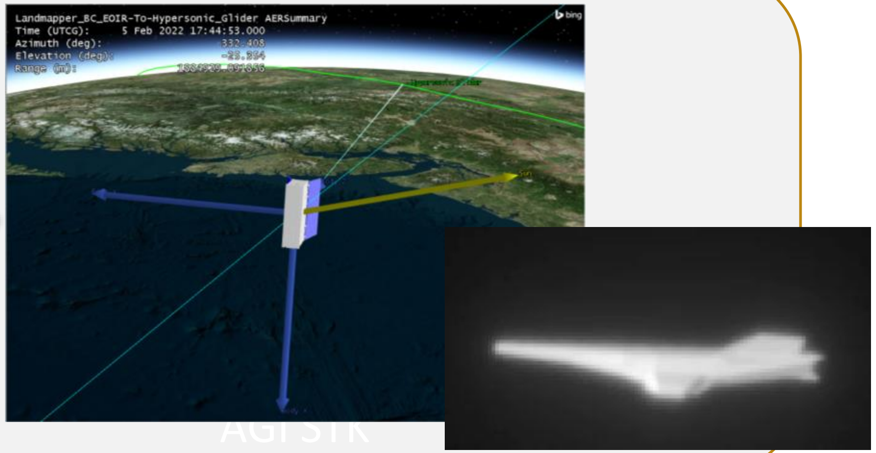
High-fidelity aerodynamic data





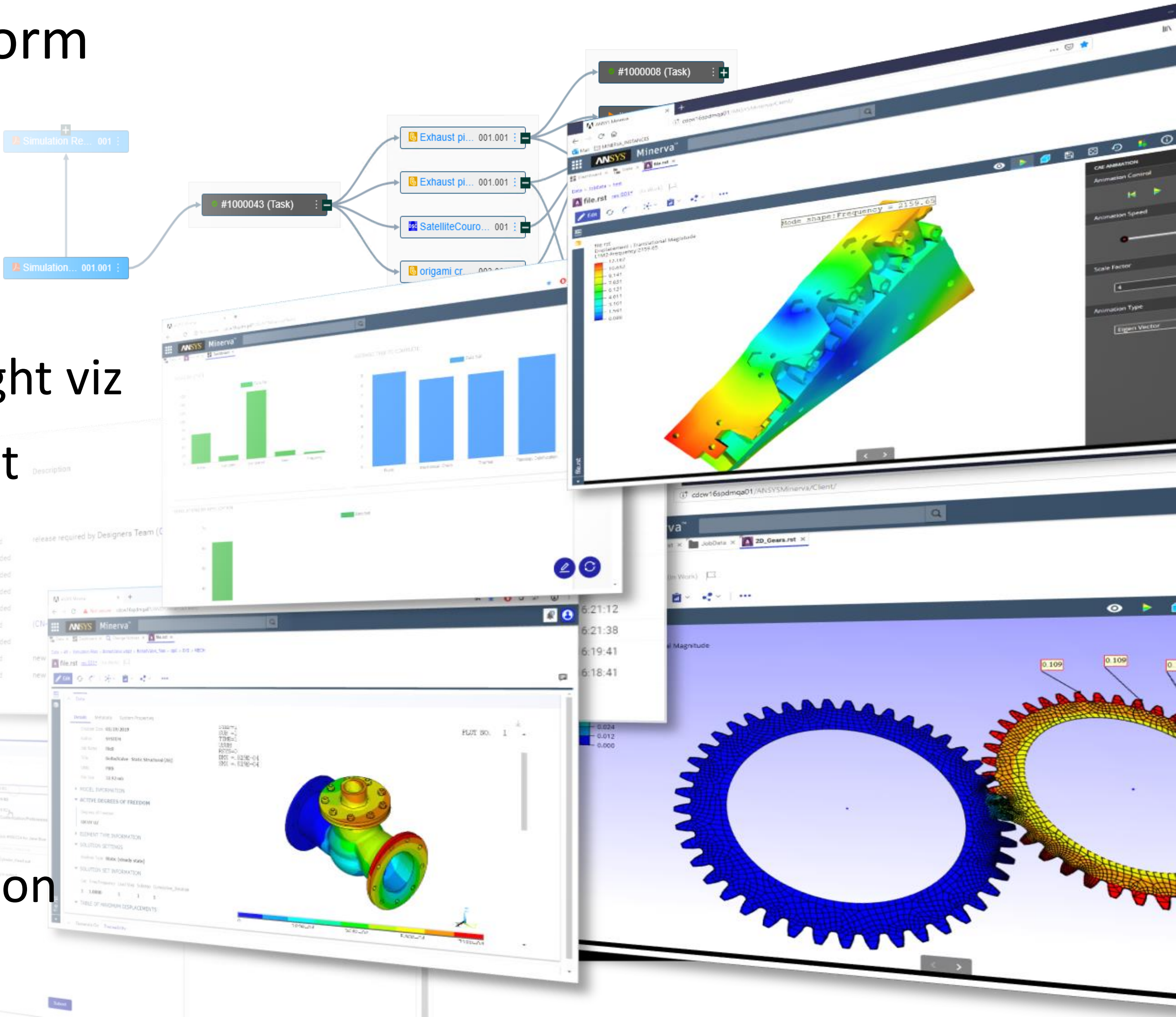
Vehicle and surface and engine plume temperature

Thermal radiation information



Ansys Simulation Platform

- Dashboards/reporting
- Data section
- Metadata/report/lightweight viz
- Configuration Management
- Local app Launcher
- Job Submission
- Collaboration
- Tasks/Work Requests
- Ansys Workbench integration



Thank you