GE RESEARCH

Richard Arthur

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Computational Methods Research

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RichardBArthur

richardarthur.medium.com

GE COLLABORATIONS WITH DOE AT THE EXASCALE

GE Research… an innovation engine

connecting to GE businesses, government agencies & strategic partners

Generating
1/3 of world's electricity

Powering
Takeoff every 2 seconds

Curing
16,000+ scans every minute

Drivers of needed Confidence & Reliability

Fielded Product Characteristics

Gas Turbines	CT scanners	Engines	Wind turbines	Oil & Gas	Additive
12,000	**13,000** 400,000+ for all imaging + medical	**70,000**	**40,000**	**150,000+**	**1,400**

Critical Infrastructure

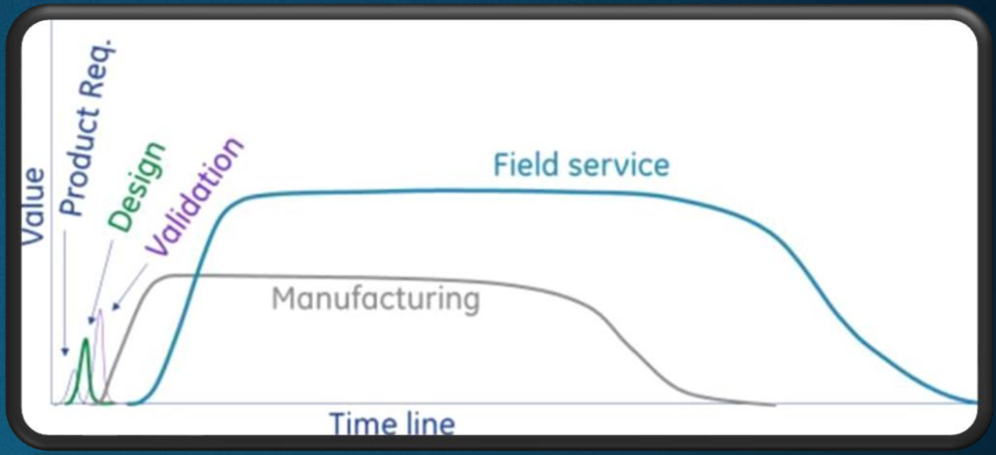
safety / failure consequence
surface for cyberattack

Long field life

durable to extended use &
changes to environment / mission

Capital intensive

maintenance contracts for uptime
cost-effective sensor monitoring



Modeling & Simulation well-established at GE / GE Research

Gas Turbines | CT scanners | Engines | Wind turbines | Oil & Gas | Additive

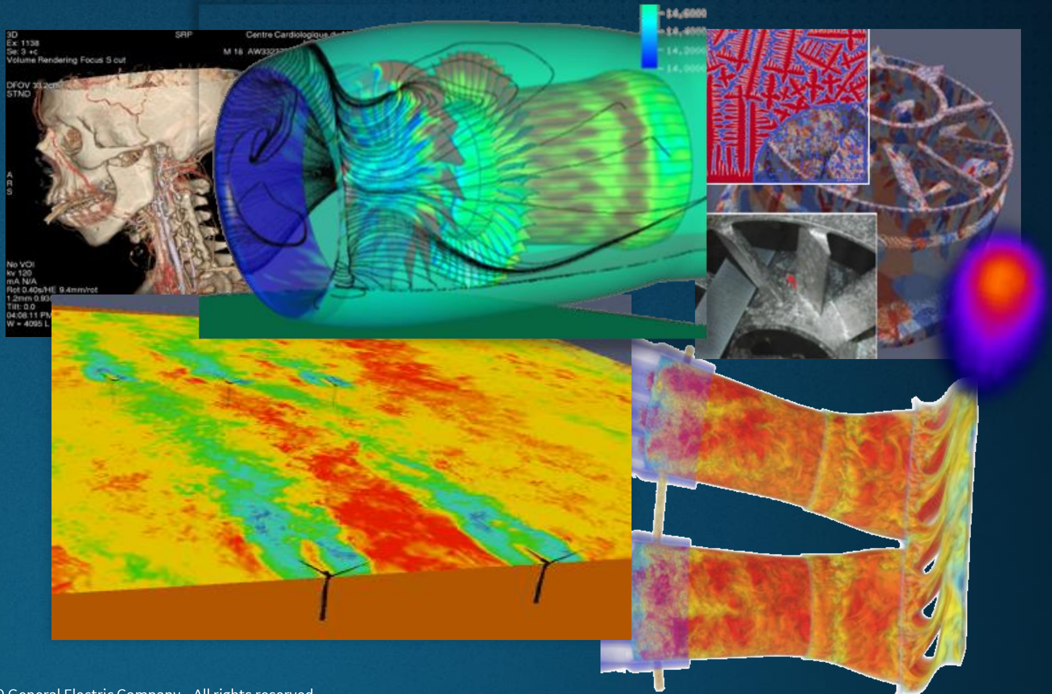
Computational Science & Engineering

Modeling (Form & Function)
&
Simulation (Credibility & Confidence)

TO SEE

TO UNDERSTAND

TO PREDICT



TO SEE

Computational model as scientific instrument

MICROSCOPE

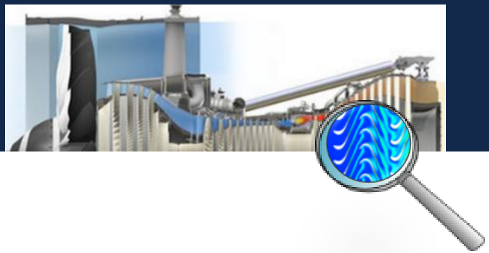
Interrogate extreme detail

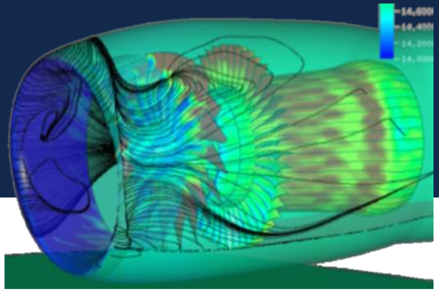
MACROSCOPE

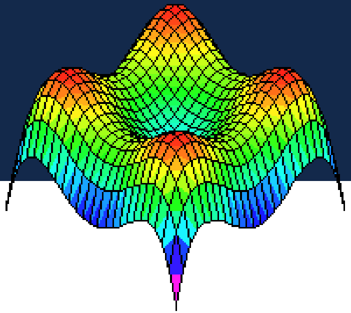
Perceive system-wide interactions

HYPERSCOPE

Explore vast dimensionality







Used throughout today's GE products

Widely Applicable

- Aerodynamics, heat transfer, aero-mechanics, aero-acoustics, combustion
- Aviation, Energy, Renewables

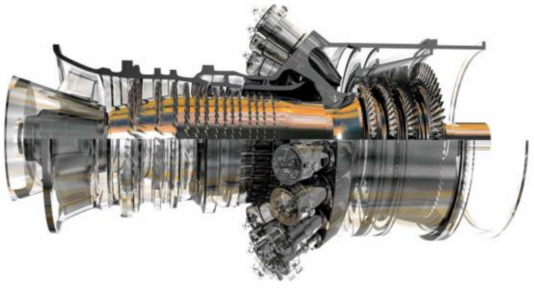
Long term investment in **Software**

- Solvers, meshing, post-processing
- ~50 years of investment

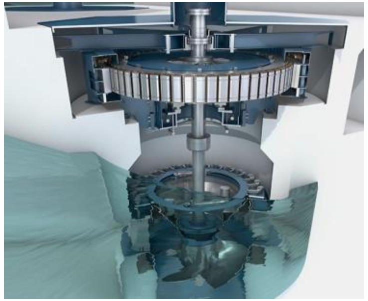
Sustained investment in **HPC Infrastructure**

- Significant in-house capabilities
- Compete for peer-reviewed grants to access Leadership Compute facilities

Aviation



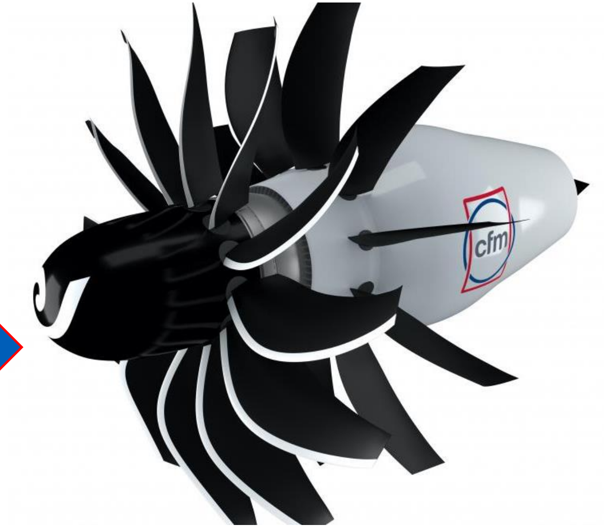
Power



Hydro

Wind

Aircraft Engines — Pushing the state of the art to reduce fuel burn and CO_2 emissions



GE / Safran CFM56

First flew in 1979 and
continuously improved

GE / Safran LEAP

Next generation single aisle (2016) … B737, A320
Architecture, material, advanced components
15% reduction in fuel burn

GE / Safran RISE Demonstrator

20% reduction in fuel burn
SAF and Hydrogen Capable
20% -100% reduction in CO2 emissions

THE CHALLENGE — Design engine with sufficient propulsive efficiency to enable use of hydrogen as zero CO_2 emission fuel

Airbus Video (LinkedIn)

Sustainable Propulsion

- Path to **zero CO_2** emissions requires **hydrogen** as a fuel.
- But economic factors impose barriers such as:
  1. Price of fuel source **per km** traveled.
  2. Reduced **passenger load** (4x fuel volume per joule)
  3. Reduced **aircraft range** (onboard fuel capacity)
- **Must improve propulsive efficiency**.

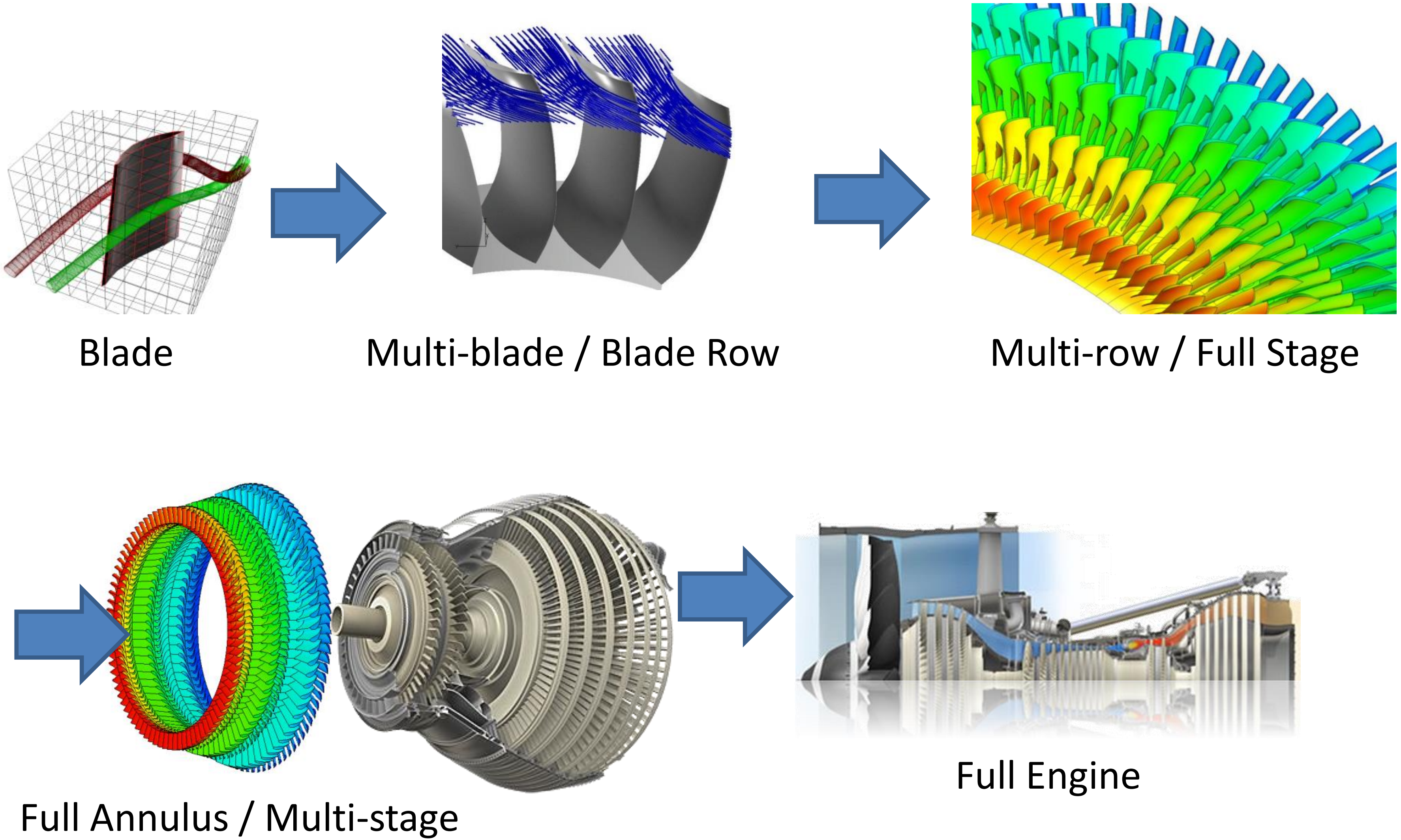
RISE™: Revolutionary Innovation for Sustainable Engines

cfm = SAFRAN + GE

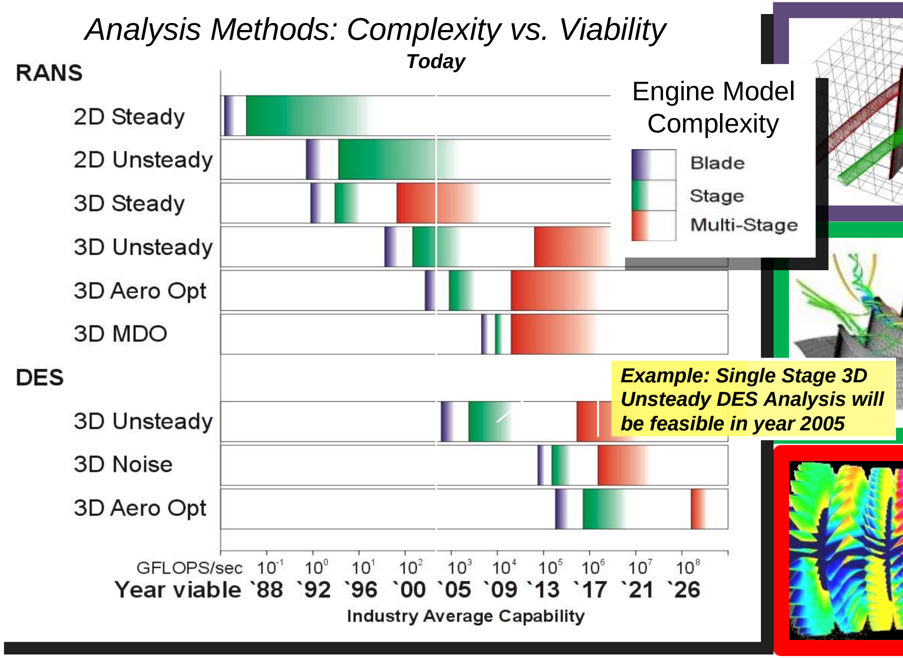
* RISE is a registered trademark of CFM International, a 50-50 joint company between GE and Safran Aircraft Engines

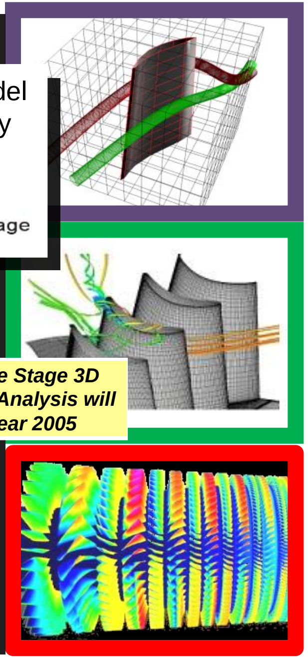
[infographic]

- RISE program: **Open fan** design is key.


Blade
Multi-blade / Blade Row
Multi-row / Full Stage
Full Annulus / Multi-stage
Full Engine

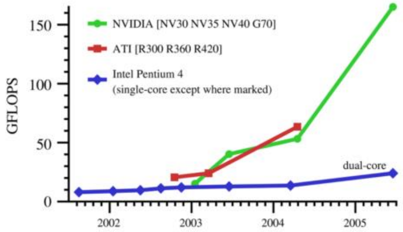
Computational View from mid 2000’s





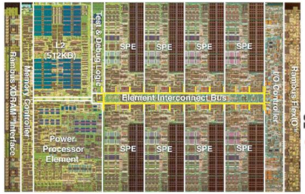
?

GPUs ~2005



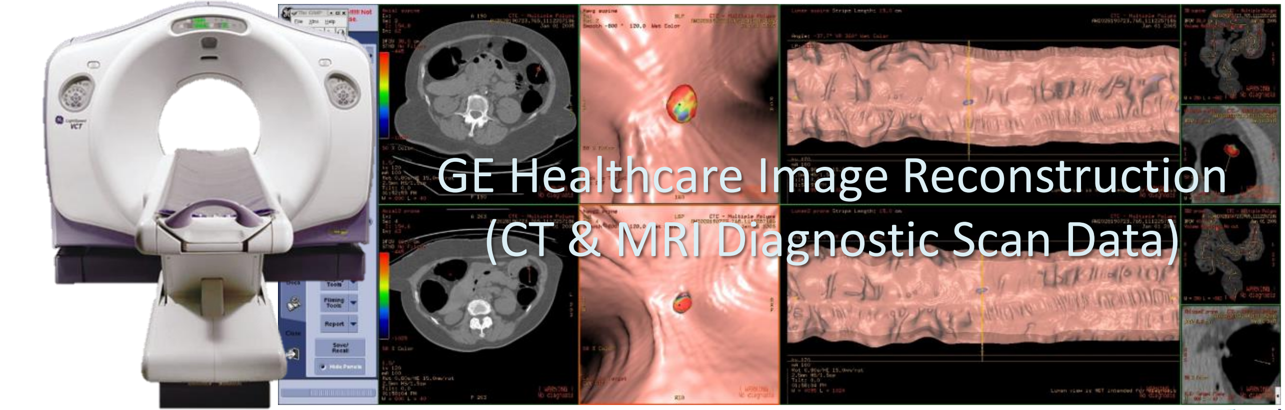
FPGAs ~2002

STI Cell ~2007

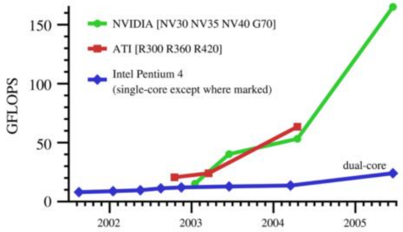


SONY
TOSHIBA
IBM

Heart of PlayStation3



GPUs ~2005



FPGAs ~2002

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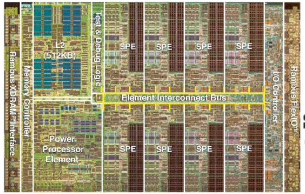
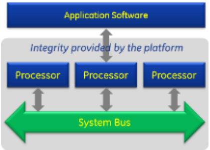


SONY
TOSHIBA
IBM

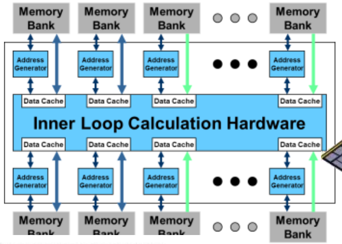
Heart of PlayStation3

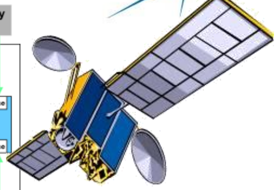
High Integrity Embedded Computing

787 Core Compute System



LOCKHEED MARTIN





Breakthrough multi-core architecture and ultra high-speed communications capabilities for high-performance workloads

IBM

Revolutionizing medical and molecular imaging systems with Cell Broadband Engine technology

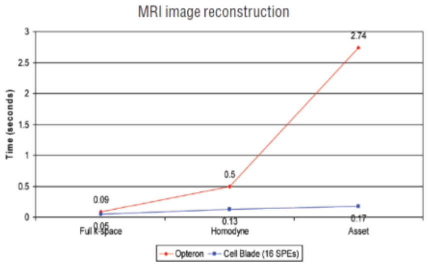
The role of imaging will change from a test, ordered by the physician and performed by a specialist, to a fully integrated clinical decision-support function. Benefits will be dramatic in efficiency, productivity and quality of patient care. In future healthcare workflows, patient information will be accessible at all levels of care, from neighborhood clinics to general practitioners; from regional hospitals to highly specialized academic

Image reconstruction

The problem of reconstructing medical images from measurements of the electromagnetic radiation around the body of a patient belong to the class of mathematical problems called inverse problems. These tomographic image reconstruction methods are central to many of the new applications in medical imaging and they are very computationally demanding. In the past, Digital Signal Processors (DSPs) and the implementation of specific architectures, connecting Application Specific Integrated Circuits (ASICs) or Field Programmable Gate Arrays (FPGAs) to the memory through dedicated high-speed busses were used to solve these problems. However, these hardware architectures are expensive, take a long time to develop, and can be quite difficult to program/modify.

GE Research gains a 16x improvement on MRI image reconstruction

Recently, a team at GE Global Research implemented three MRI image reconstruction algorithms on the IBM BladeServer QS20 with Cell/B.E. processors. Each algorithm was implemented and compared



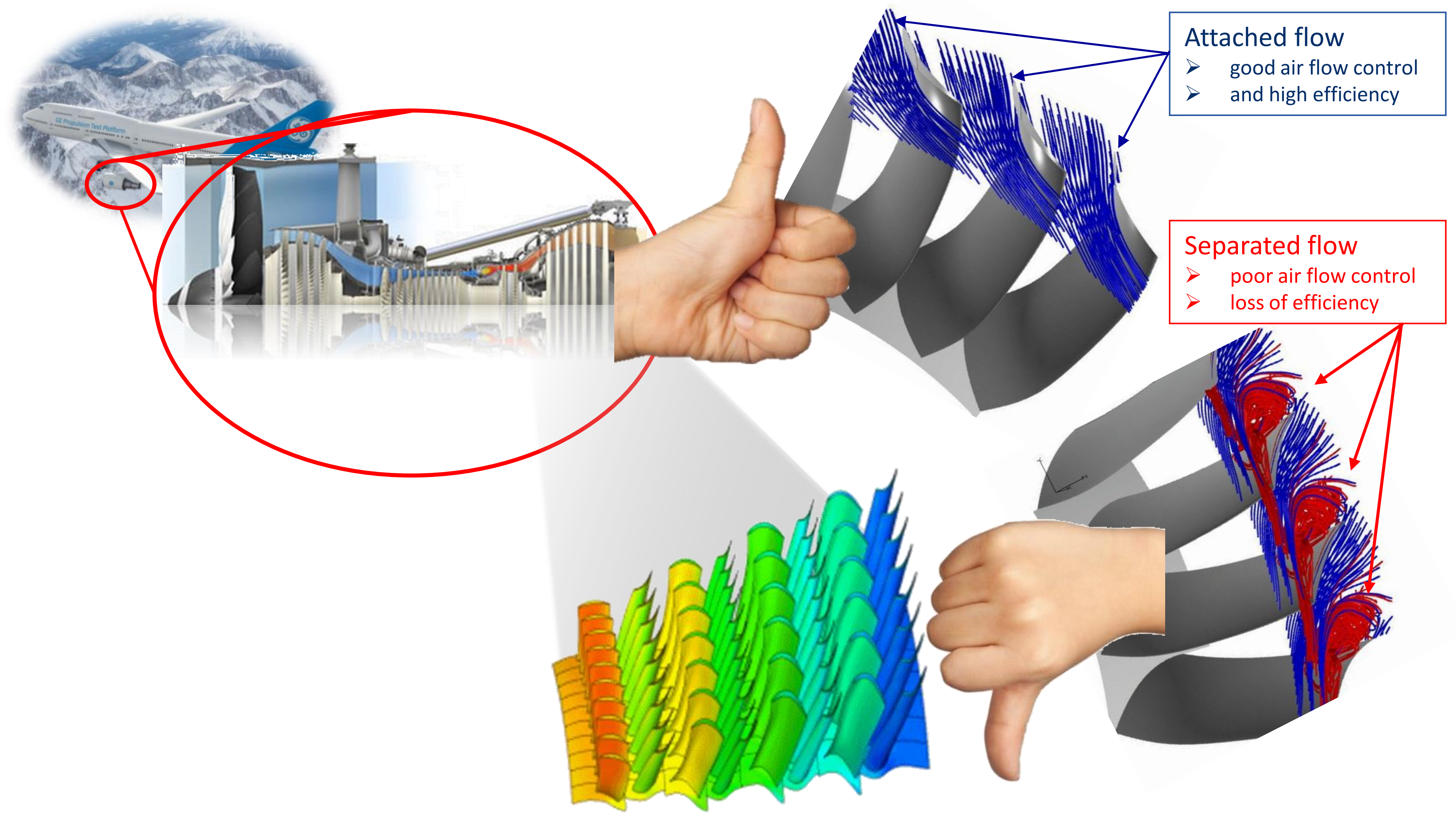
GE ready pre-2010 for
hardware-software co-design
& use of accelerators
for **performance**…

but limited in massively parallel (**scalability**).

Assistance from IBM TJW (Jim Sexton & team)
to port GE CFD solver (Tacoma) to BlueGene/L

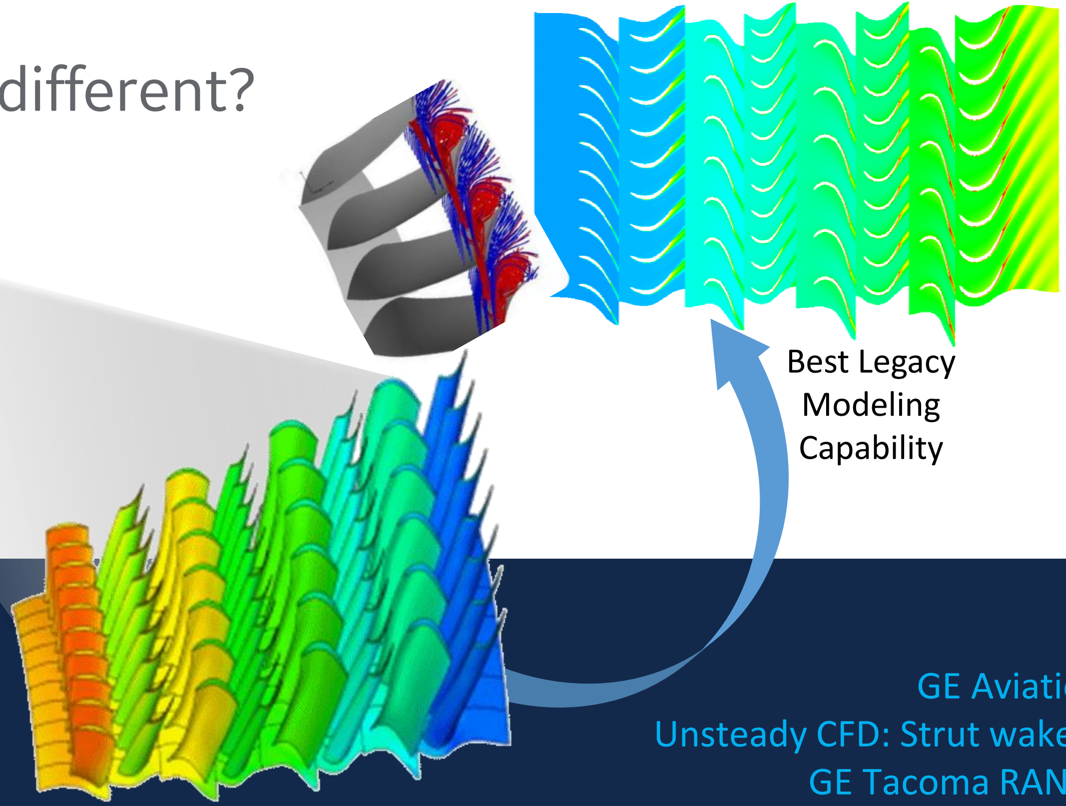

GE Propulsion Test Platform


GE Propulsion Test Platform



Attached flow
good air flow control
and high efficiency
Separated flow
poor air flow control
loss of efficiency

Will we SEE something different?

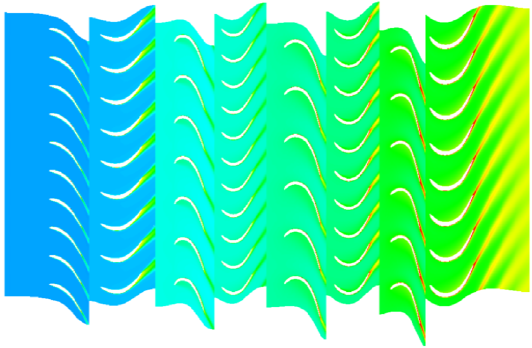


GE Aviation LEAP
Unsteady CFD: Strut wake effects
GE Tacoma RANS solver

Will it be useful?

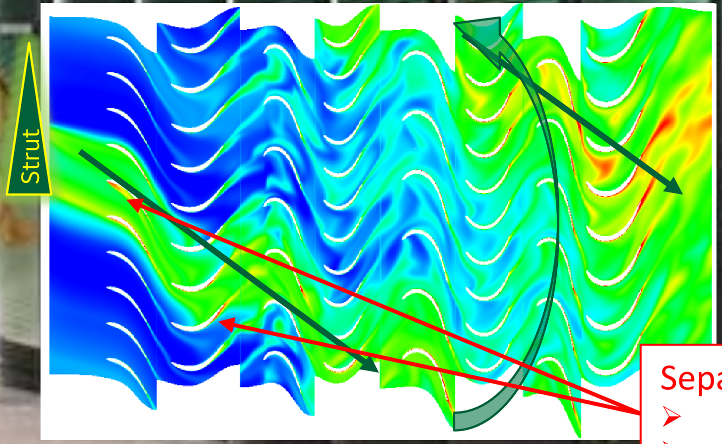
Never Before Seen

Prior State of the Art:
Steady Analysis
(GE Internal HPC)



- Unobservable physically
- Relevant to engineering design
- 2012 IDC award:

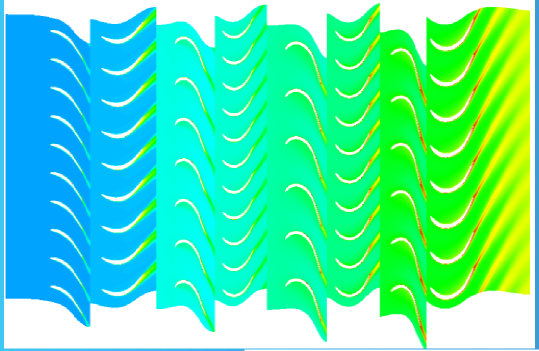
Result on **OLCF Jaguar Cray XT5** (2010): **Unsteady** analysis with **wake from strut**

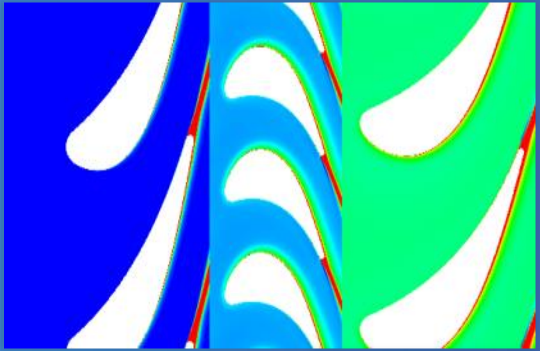


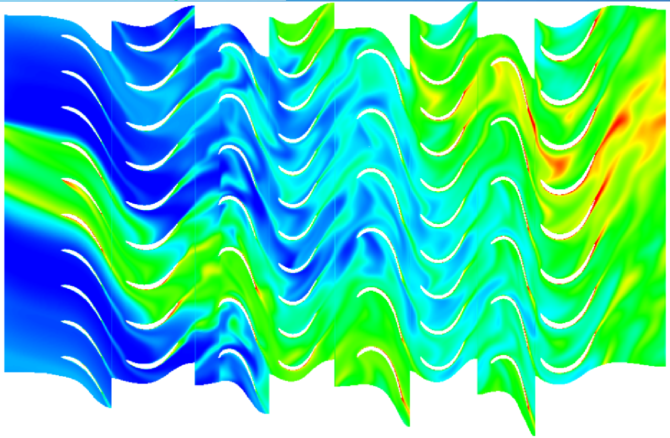
Separated flow
- ➢ poor air flow control
- ➢ loss of efficiency

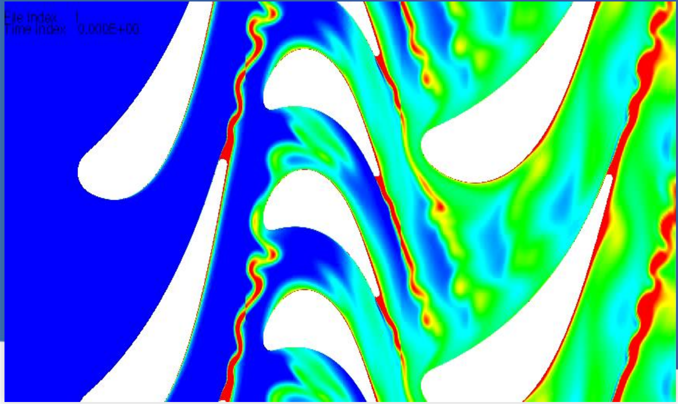
OAK RIDGE
National Laboratory

TO SEE

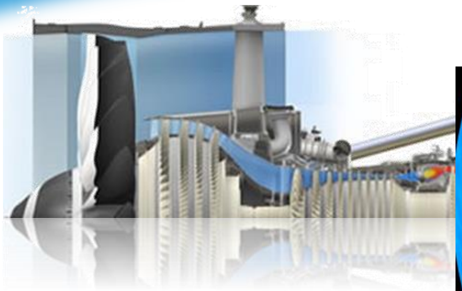








TO SEE



GE Global Research acquires a Cray Supercomputer

Recommend | Tweet | Email | Print

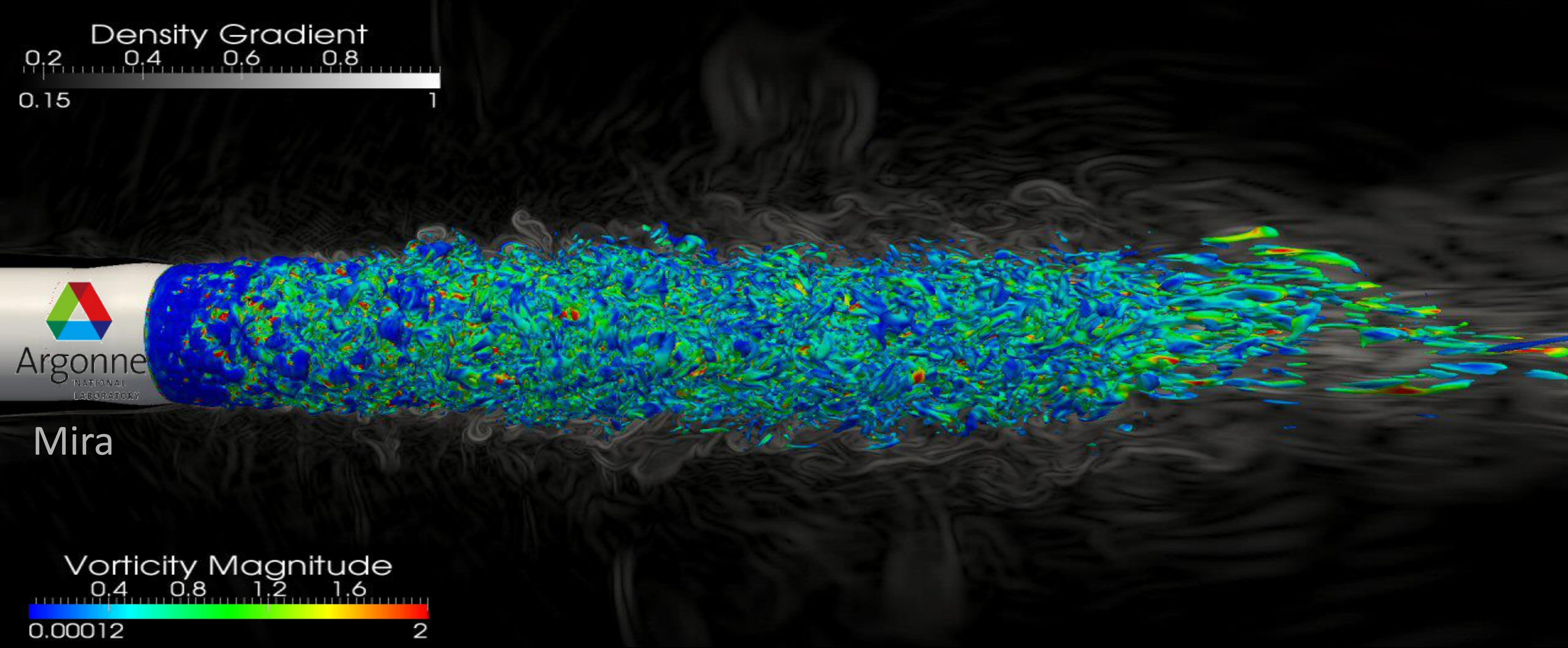
Companies: Cray Inc. | General Electric Co.

Related Quotes

Symbol	Price	Change
CRAY	6.39	+0.13

On Tuesday June 21, 2011, 5:59 am EDT

Cray Inc. (NasdaqGS:CRAY) announced the company has sold a ... to GE Global Research, the technology ... that could not be simulated using standard commodity clusters.

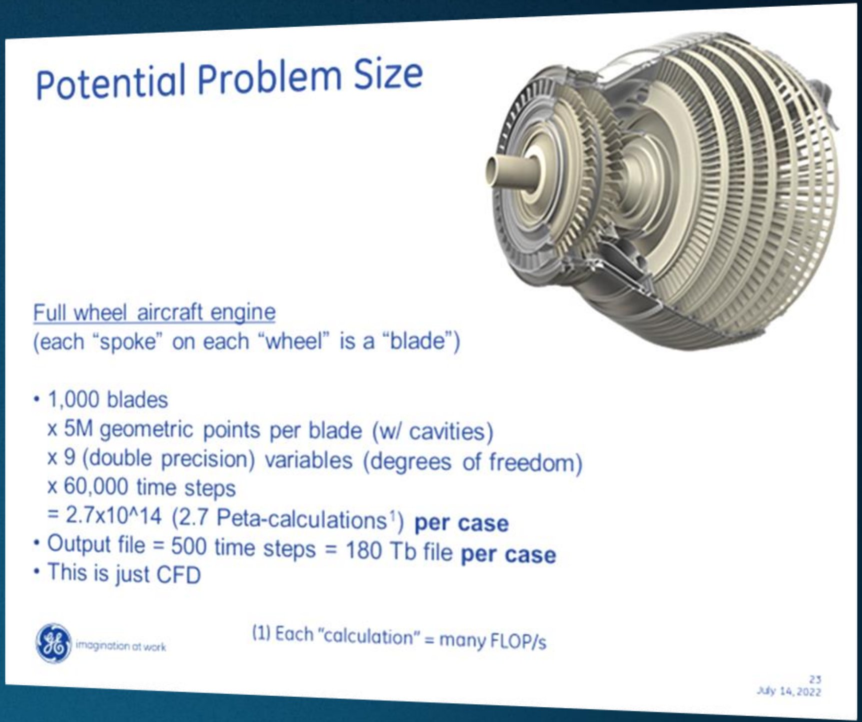


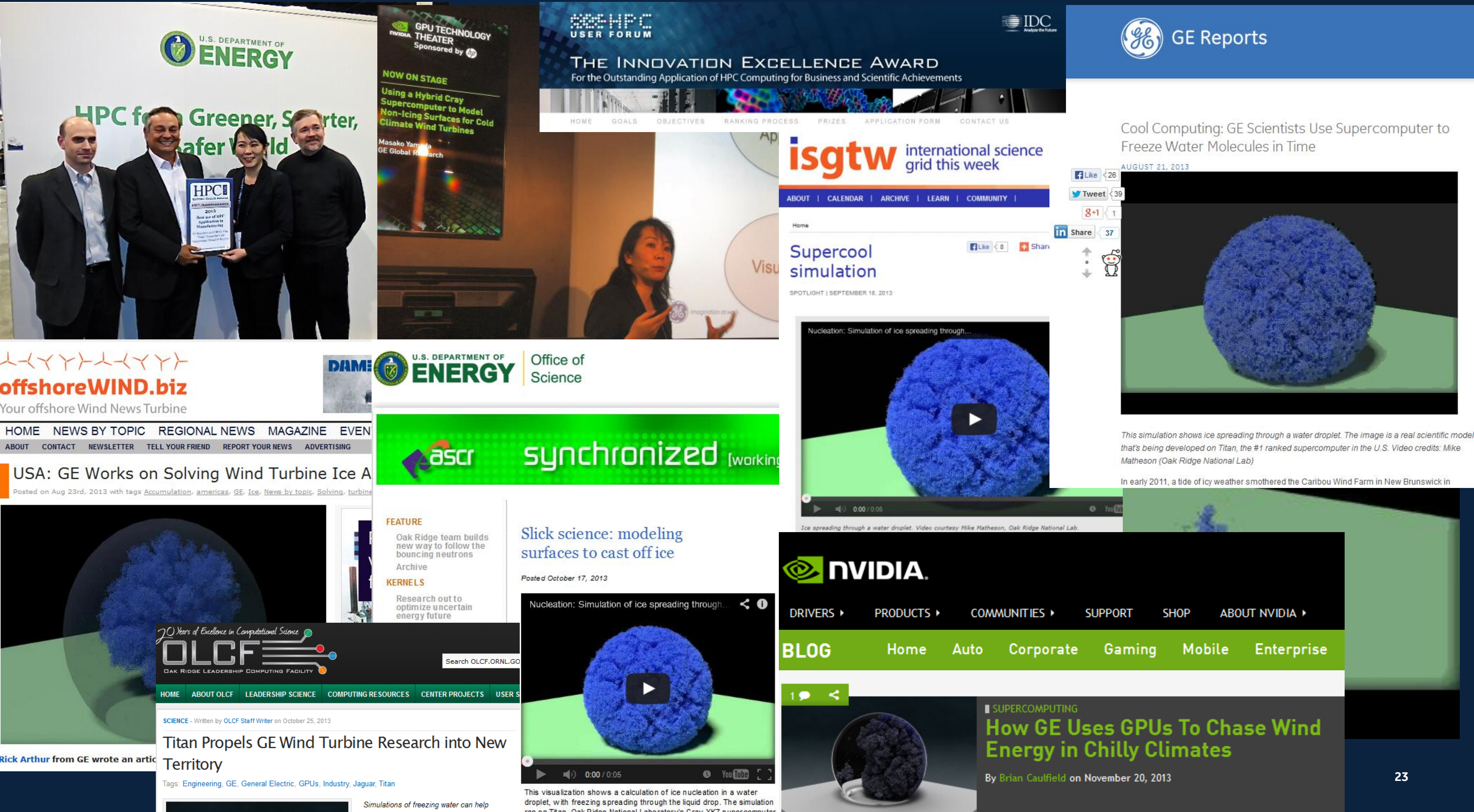
Early promise to predict performance vs. physical test (Aeroacoustics)

2011 Exascale Panel @Capitol

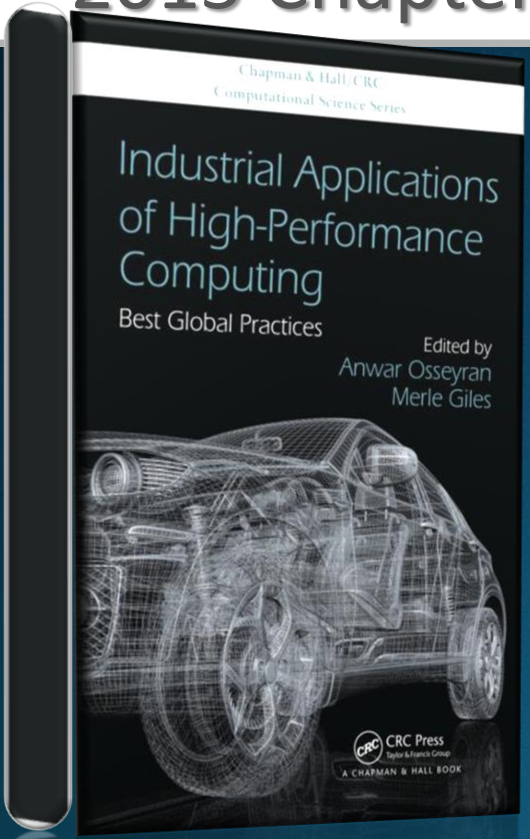
Supercomputing for Science & Competitiveness

American Chemical Society
March 17th, 2011




U.S. DEPARTMENT OF ENERGY
HPC for Greener, Smarter, Safer World
GPU TECHNOLOGY THEATER
Sponsored by
NOW ON STAGE
Using a Hybrid Cray Supercomputer to Model Non-Icing Surfaces for Cold Climate Wind Turbines
Masako Yamada
GE Global Research
HPC USER FORUM
IDC
THE INNOVATION EXCELLENCE AWARD
For the Outstanding Application of HPC Computing for Business and Scientific Achievements
HOME GOALS OBJECTIVES RANKING PROCESS PRIZES APPLICATION FORM CONTACT US
GE Reports
Cool Computing: GE Scientists Use Supercomputer to Freeze Water Molecules in Time
AUGUST 21, 2013
This simulation shows ice spreading through a water droplet. The image is a real scientific model that's being developed on Titan, the #1 ranked supercomputer in the U.S. Video credits: Mike Matheson (Oak Ridge National Lab)
In early 2011, a tide of icy weather smothered the Caribou Wind Farm in New Brunswick in
isgtw international science grid this week
ABOUT | CALENDAR | ARCHIVE | LEARN | COMMUNITY |
Supercool simulation
SPOTLIGHT | SEPTEMBER 18, 2013
Nucleation: Simulation of ice spreading through...
Ice spreading through a water droplet. Video courtesy Mike Matheson, Oak Ridge National Lab.
offshoreWIND.biz
Your offshore Wind News Turbine
HOME NEWS BY TOPIC REGIONAL NEWS MAGAZINE EVEN
ABOUT CONTACT NEWSLETTER TELL YOUR FRIEND REPORT YOUR NEWS ADVERTISING
USA: GE Works on Solving Wind Turbine Ice A
Posted on Aug 23rd, 2013 with tags Accumulation, americas, GE, Ice, News by topic, Solving, turbine
Rick Arthur from GE wrote an artic
U.S. DEPARTMENT OF ENERGY Office of Science
ascr synchronized [working
FEATURE
Oak Ridge team builds new way to follow the bouncing neutrons
Archive
KERNELS
Research out to optimize uncertain energy future
Slick science: modeling surfaces to cast off ice
Posted October 17, 2013
Nucleation: Simulation of ice spreading through...
This visualization shows a calculation of ice nucleation in a water droplet, with freezing spreading through the liquid drop. The simulation
20 Years of Excellence in Computational Science
OLCF
OAK RIDGE LEADERSHIP COMPUTING FACILITY
HOME ABOUT OLCF LEADERSHIP SCIENCE COMPUTING RESOURCES CENTER PROJECTS
SCIENCE - Written by OLCF Staff Writer on October 25, 2013
Titan Propels GE Wind Turbine Research into New Territory
Tags: Engineering, GE, General Electric, GPUs, Industry, Jaguar, Titan
Simulations of freezing water can help
NVIDIA
DRIVERS PRODUCTS COMMUNITIES SUPPORT SHOP ABOUT NVIDIA
BLOG Home Auto Corporate Gaming Mobile Enterprise
SUPERCOMPUTING
How GE Uses GPUs To Chase Wind Energy in Chilly Climates
By Brian Caulfield on November 20, 2013

2015 Chapter: GE's Journey to Supercomputing

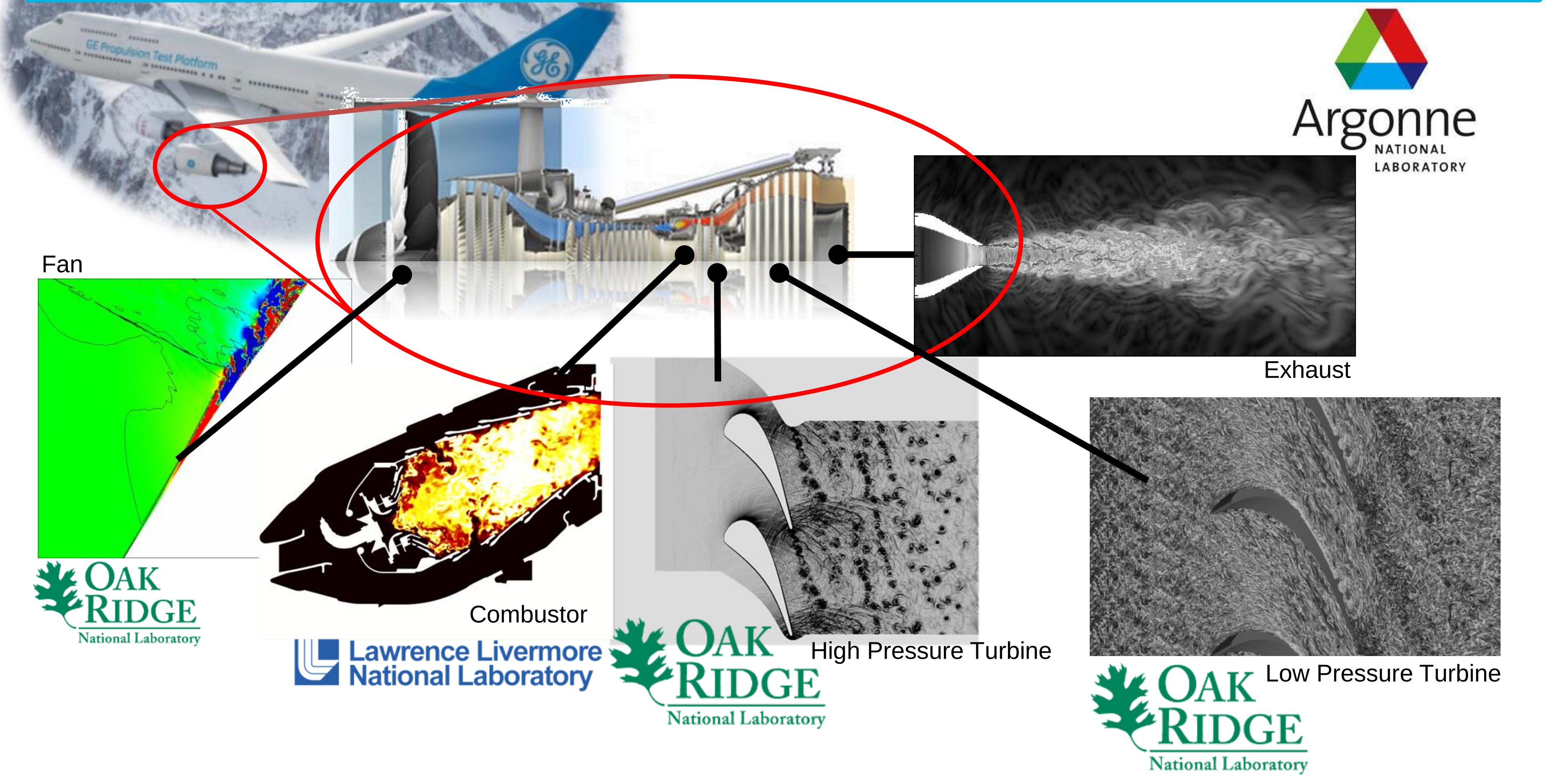


A. Osseyran & M. Giles,
Industrial Applications of High-Performance Computing: Best Global Practices, (pp. 253-277).
London, England: Chapman & Hall/CRC Press (2015)

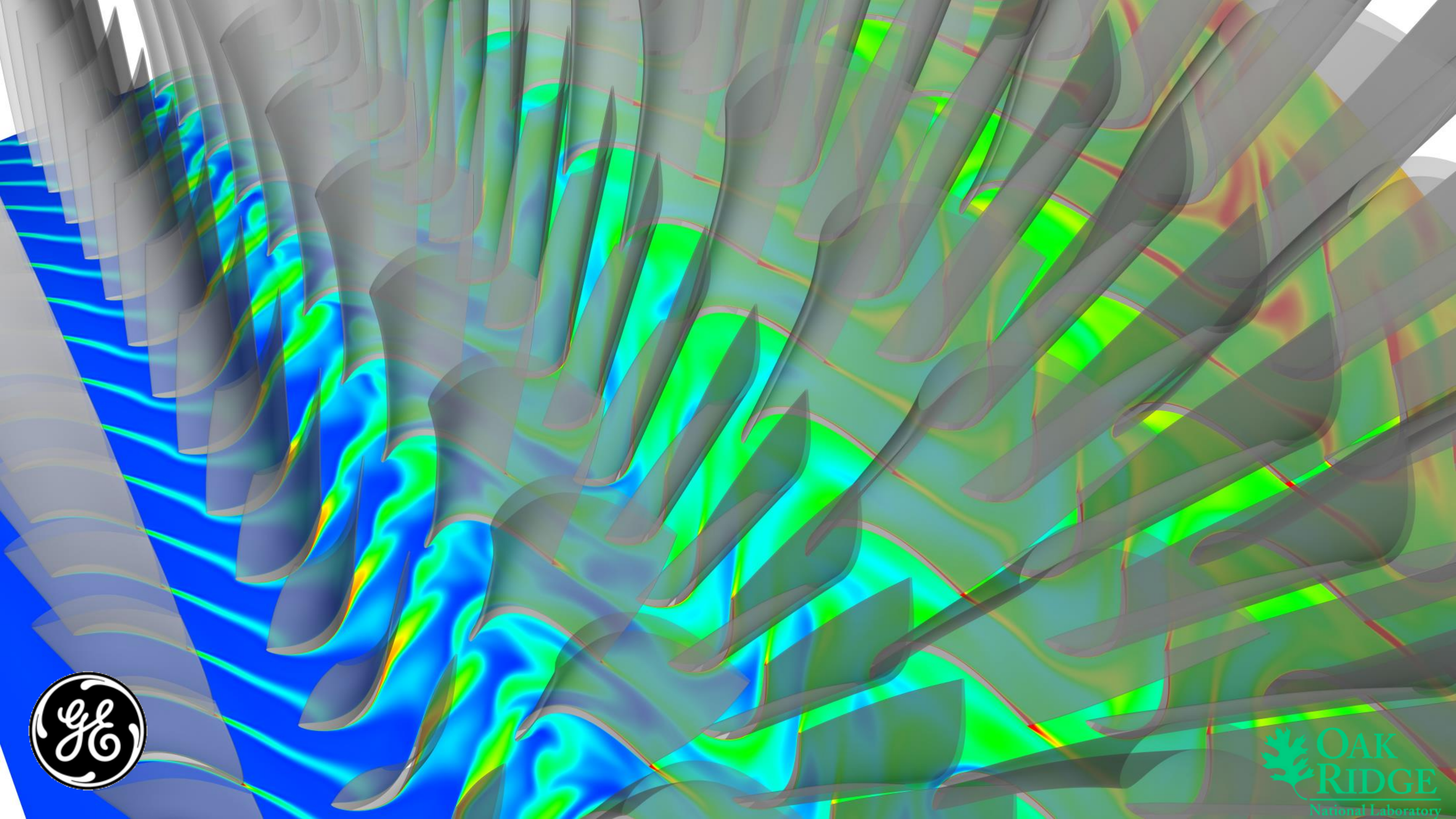
Chapter by Richard Arthur, GE Research
Case study in full chapter by Masako Yamada, GE Research

© CRC Press

April 2016 National Lab Day Poster (2022 Update)



TO UNDERSTAND


OAK RIDGE
National Laboratory

GE Energy Executive Joe Citeno

2018 Smoky Mountains Conference Keynote

Oak Ridge National Laboratory | Argonne National Laboratory

Super Collaboration

Smoky Mountains Computational Sciences and Engineering Conference

Joe Citeno,
GE Power
August 28, 2018

Acknowledging computational support from Dept of Energy Office of Science, Oak Ridge National Laboratory, Argonne National Laboratory

Issue: Combustion Turbulence
Thermo-acoustic Instability on
GE's Next-Generation Gas Turbine

Combustion in gas turbines

12 Combustors in a 7HA Gas Turbine, **each one** consumes **in just 1 minute....**

3 tons of fuel/air mixture ... like **21** tractor trailers of combustible mixture

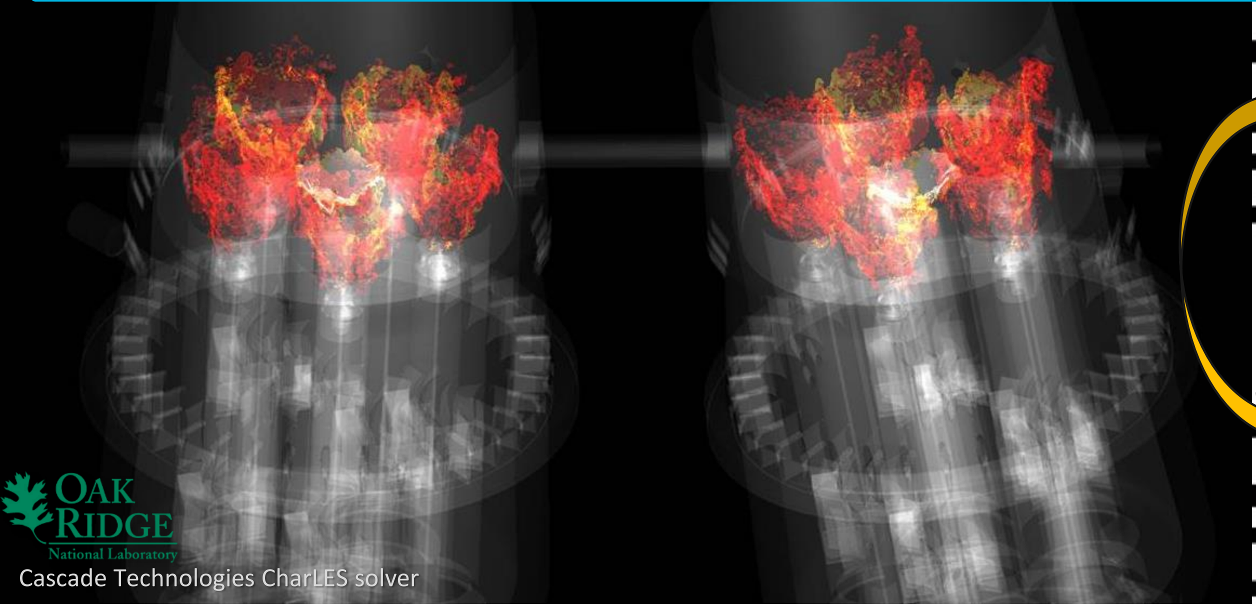
The energy equivalent of **9** propane tanks per minute .... Like 6,500 backyard gas grills

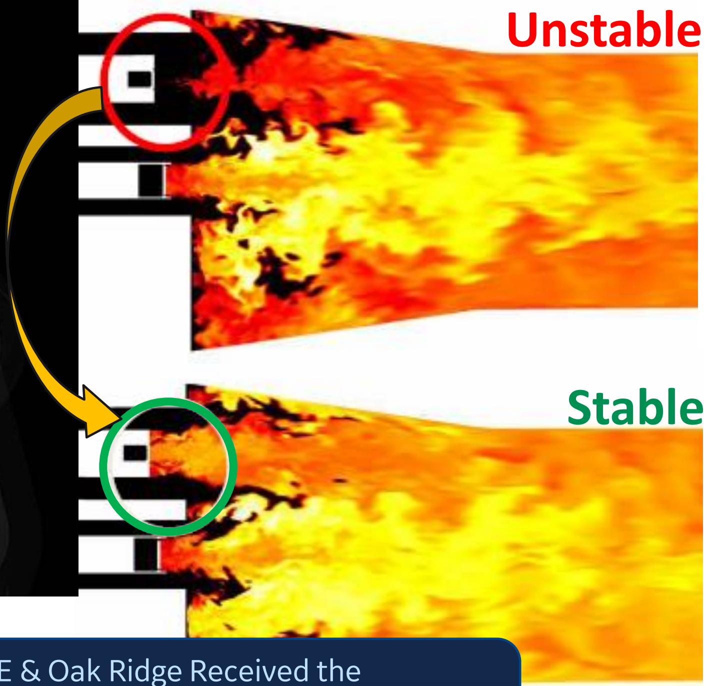
Produces just **7** ounces of NOx pollutant

GE 7HA: World's Most Efficient 60Hz Gas Turbine

THE CHALLENGE

Understand observed thermo-acoustic instability;
beyond-state-of-the-art (single combustor) simulation capability





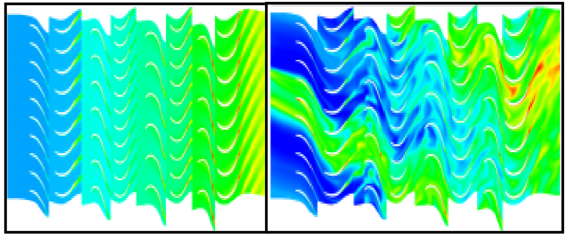
Never seen before simulation:
Multi-combustor dynamics interactions

GE & Oak Ridge Received the
2016 HPCwire Reader's Choice Award for
Best HPC Application in the Energy Industry

GE Breakthrough Scale & Fidelity with DOE Leadership Computing

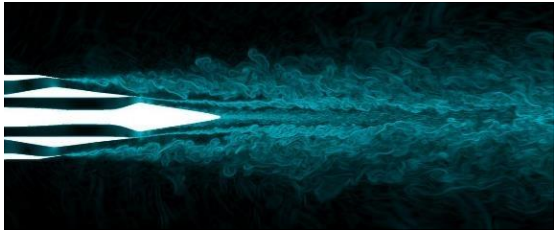
UNSTEADY WAKE ANALYSIS

Jaguar Cray XK7
GE In-house RANS Solver
Brian Mitchell, GE



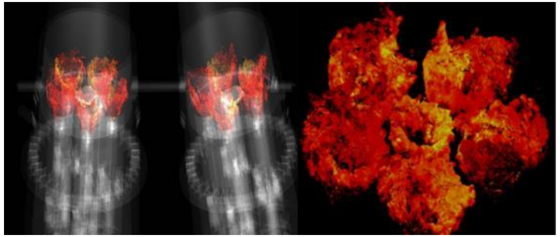
AEROACOUSTIC ANALYSIS

Mira IBM BlueGene/Q
AFRL LES Solver
Umesh Paliath, GE



COMBUSTION ANALYSIS

Titan Cray XT4
Cascade LES Solver
Joe Citeno, GE

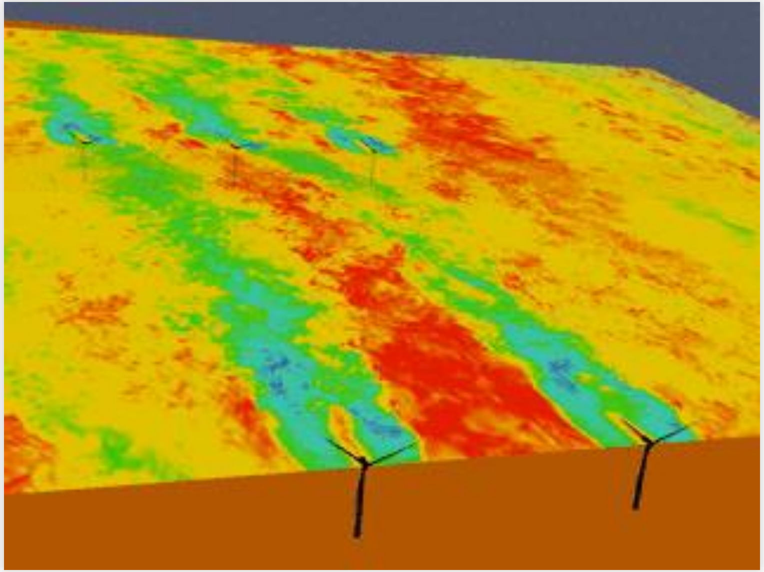


LEAP AVIATION ENGINE | **9X AVIATION ENGINE** | **7HA2 GAS TURBINE**

THE CHALLENGE

Understand wind turbine wake impact on wind farm performance

GE Research received the 2018 HPCwire Editor's Choice Award for Best Use of HPC in Manufacturing



Goal: Optimize wind farm design to improve energy generation efficiency of turbines

CHALLENGE | Understand sources of manufacturing defects in materials and processes to improve first-time yields

GE Additive Manufacturing

New Business for Novel Capabilities

Leveraged **HPC4EnergyInnovation** program

HPC4MANUFACTURING

Highly complex and relatively new manufacturing process

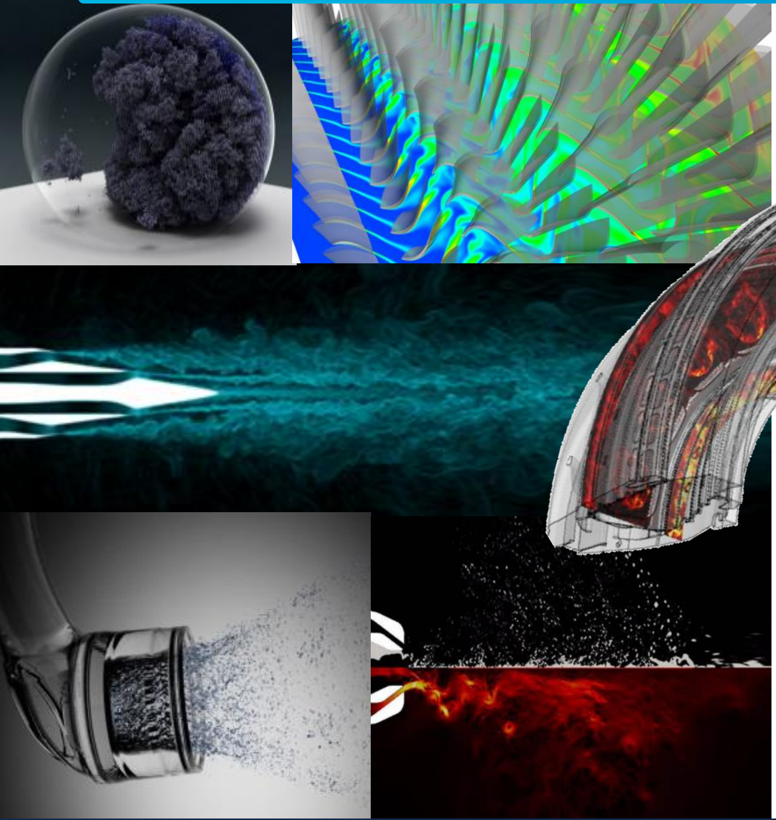
- Wide spectrum of length scales (from powder grains to solid parts)
- Very long process times (kilometres of scanning)
- Complex physics from the melt pool to the final workpiece
- Complex parts and supports structures (lattice-type e.g.)

CONCEPTLASER

Arcam EBM
a GE Additive company

24 hours

2009-2017 OVER 1 BILLION CORE-HOURS AWARDED TO GE IN PEER-REVIEWED COMPETITIVE GRANTS



- ~14 INCITE + ~22 ALCC + ~6 HPC4Manufacturing
- Multiple pan-lab engagements

Argonne NATIONAL LABORATORY

OAK RIDGE National Laborator

Sandia National Laboratories

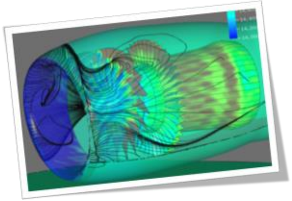
Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY

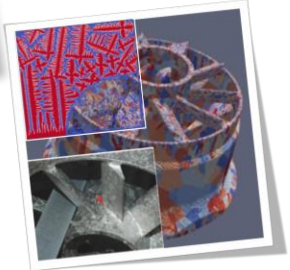
- Gas Turbine, Wind Turbine & Aviation
  - Combustion (Atomization, Interactions)
  - Unsteady Aerothermal & Aeroacoustics
- Ice Formation (nucleation) & Adhesion
- Alloy Solidification (part castings)
- Additive Manufacturing (metal powder)

2019 ECP Annual Meeting Poster

Wind Turbine Blade Acoustics

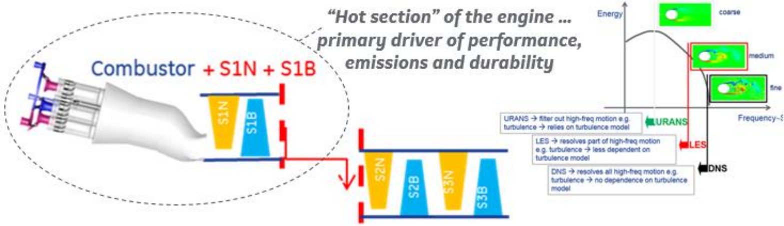


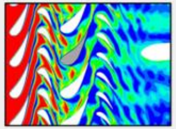
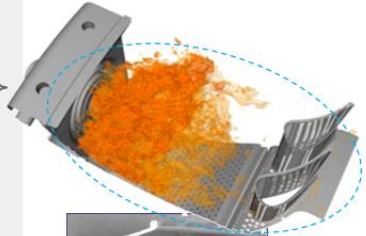
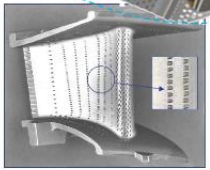
Inlet Distortion Flow Impact On Engine Fan



Multiscale Modeling of Manufacturing & Materials to Improve Performance

Example: Combustor + High-Pressure Turbine



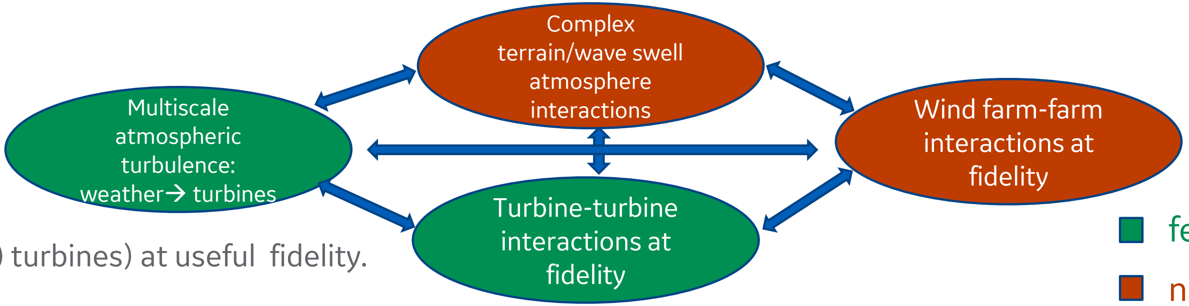
	State of the Art	Exascale
Computational Models	 Combustor-only LES  HPT stage URANS  Flat plate film cooling LES	  LES of Combustor + HPT stage + cooling holes
Insight	• Improved combustion physics • Turbine wake propagation	• Combustor acoustic effects • Wake migration / turbulence evolution through Stage-1 • Film cooling efficacy in 3D flow
Impact	• Increase fuel efficiency through higher temperature operation • Decrease CO2/NOX emissions	• Further increase in fuel efficiency & decrease in CO2/NOX • Reduce / improve expensive tests • Novel design practices employing multi-scale multi-physics flow

Understand impact of coastal low-level wind-jets on offshore wind farm performance and reliability

ALCC awards (2020-22)

Leveraging ExaWind applications

Allows study of small wind farms (O(10) turbines) at useful fidelity.



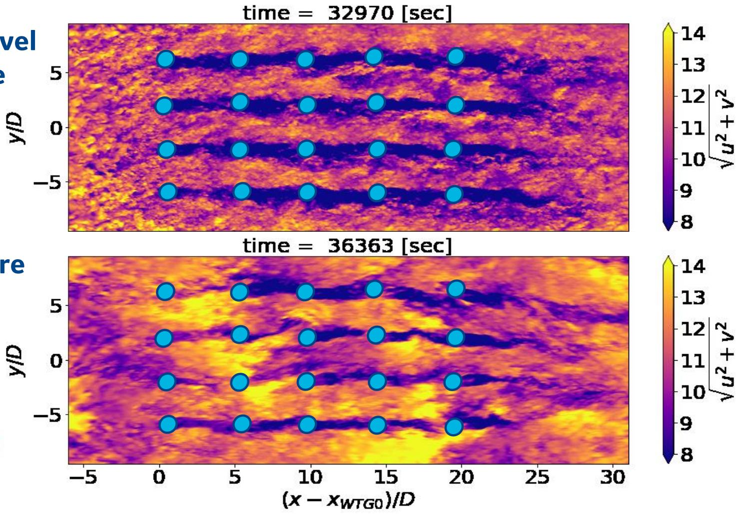
feasible

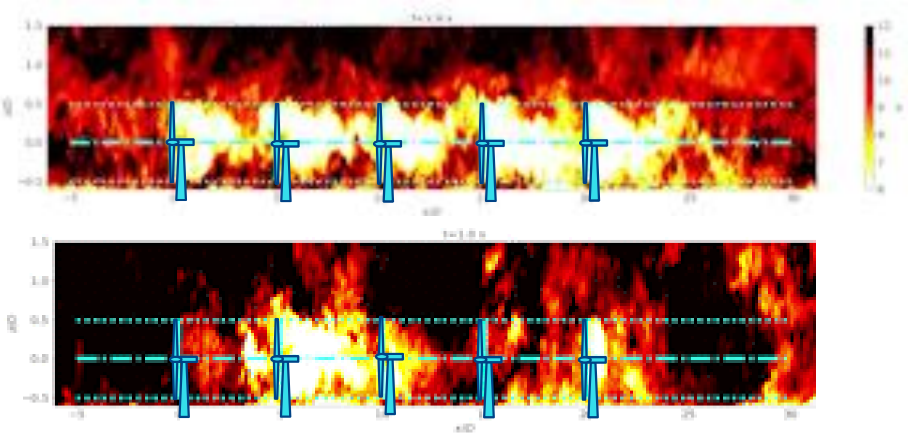
not feasible

(at **Petascale**)

Offshore low-level jet turbulence

Daytime onshore turbulence





Side view of axial velocity within a row of the wind farm

(Press: <The Verve> <GE> <DOE> <InsideHPC> <HPCwire>)

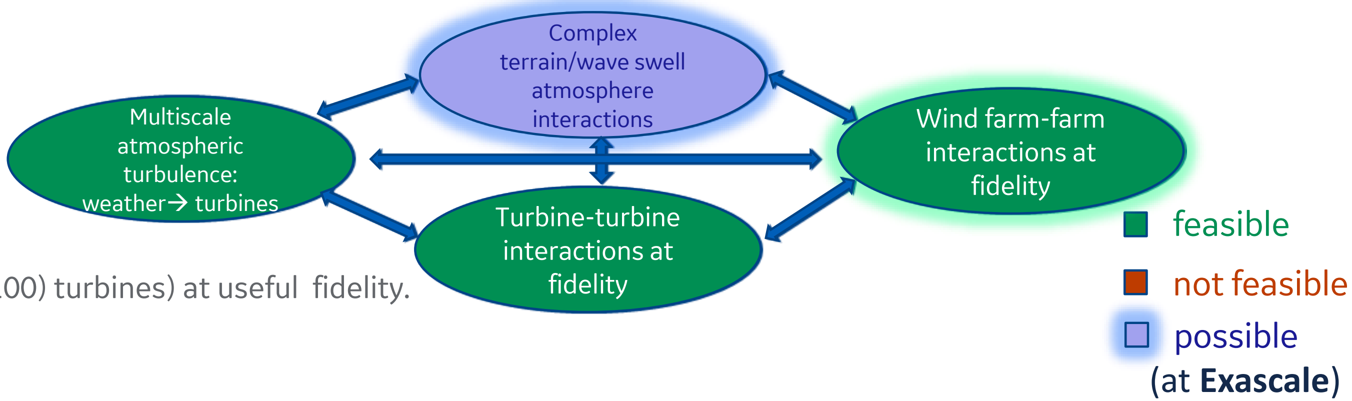
TO PREDICT

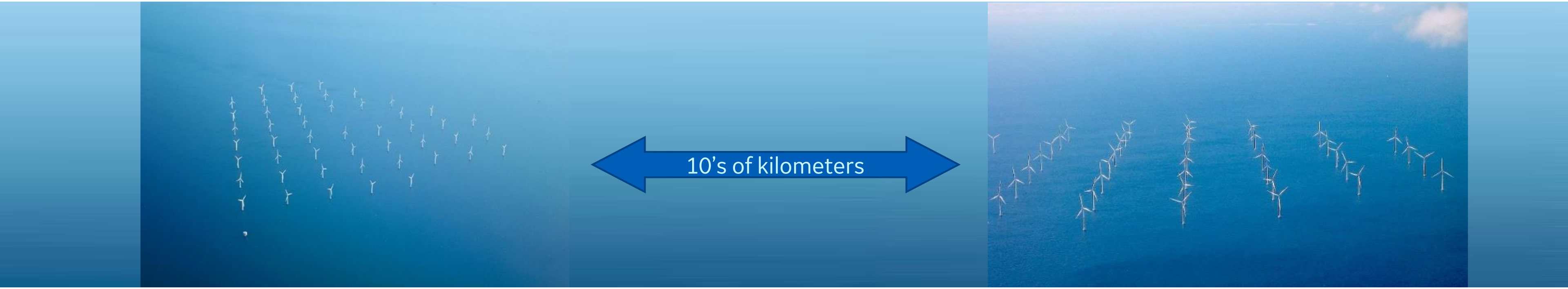
CHALLENGE – Predict impact of farm-scale wakes on down-flow wind farms

EXASCALE COMPUTING PROJECT

Looking Forward

Exascale computing + improvements to Exawind tools will allow studying multiple large wind farms (O(100) turbines) at useful fidelity.

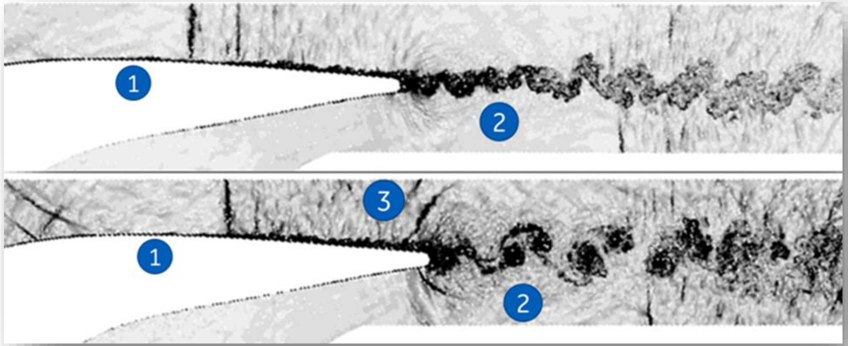




Øresund wind farm (Baltic sea)

Liligrund wind farm (Sweden)

Design objectives: Efficiency and Durability over various operating conditions



ALCC 2021-2022 Project CFD153 (Osusky)

Applying Machine Learning to Reynolds Number Impact on HPT Flow

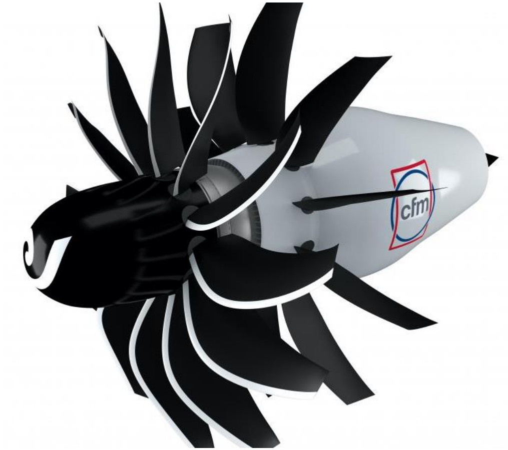
Understand flow behavior changes due to selection of Reynolds number:

1. Laminar-to-turbulent transitions (***reduced energy capture***)
2. Flow structures in wake (***reduced performance***)
3. Acoustic wave propagation from trailing edge (***reduced stability***)

High-fidelity datasets as training repository to create surrogate models able to substitute for complex effects in lower-fidelity simulations.

Design engine with sufficient propulsive efficiency to enable use of hydrogen as zero CO_2 emission fuel

RISE™: **R**evolutionary **I**nnovation for **S**ustainable **E**ngines



GE / Safran RISE Demonstrator

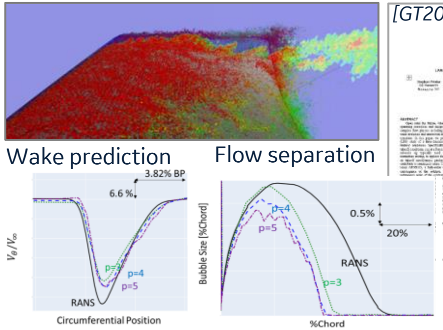
20% reduction in fuel burn
SAF and Hydrogen Capable
20% -100% reduction in CO2 emissions

CFM RISE™* industry program to enable sustainable aviation

RISE™: **R**evolutionary **I**nnovation for **S**ustainable **E**ngines

* RISE is a registered trademark of CFM International, a 50-50 joint company between GE and Safran Aircraft Engines

THE CHALLENGE – Predict flight test performance from models validated on TRL4 rig tests

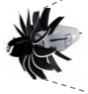


Rig Test Scale

INCITE 2021 (Summit)
Early Science (Perlmutter)

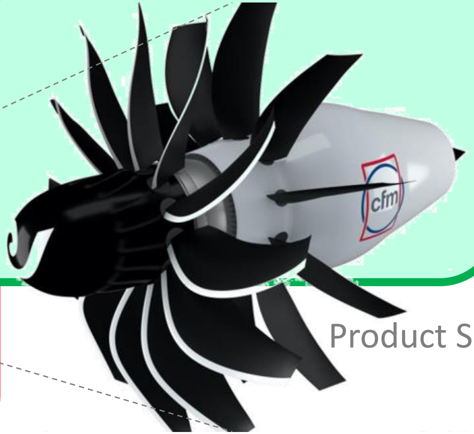
Takeoff ~100x Rig to Flight Scale

Cruise ~ 10x Rig-to-Flight



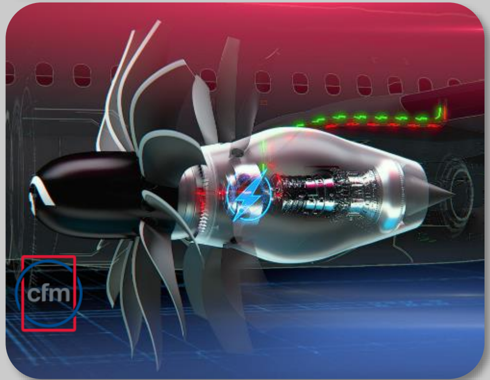
ALCC 2022-23
(Frontier, Summit, Perlmutter)

Flight Scale



Product Scale

cfm = SAFRAN + GE



CFM RISE™* industry program to enable sustainable aviation

RISE™: **R**evolutionary **I**nnovation for **S**ustainable **E**ngines

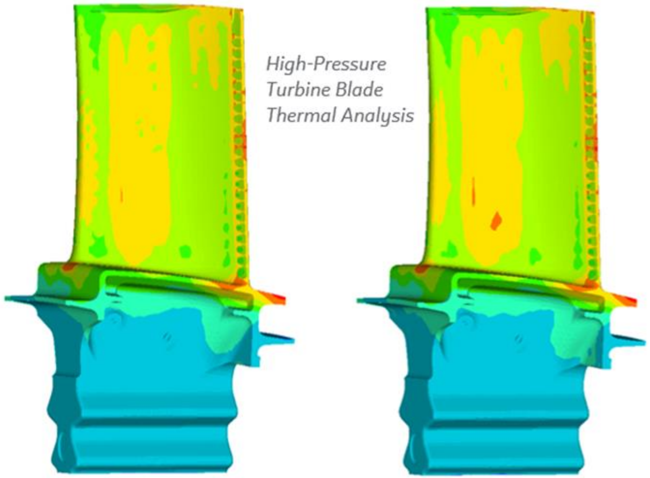
* RISE is a registered trademark of CFM International, a 50-50 joint company between GE and Safran Aircraft Engines

Discovering new ways to control the **challenging flow physics** that limit improvements in **noise and efficiency**
Product-scale flight Reynolds number: **only possible via Frontier**

Novel *ScientificML* Workflow: Bespoke Surrogate Model Factory

Finite Element Model Results (~1 Hour)

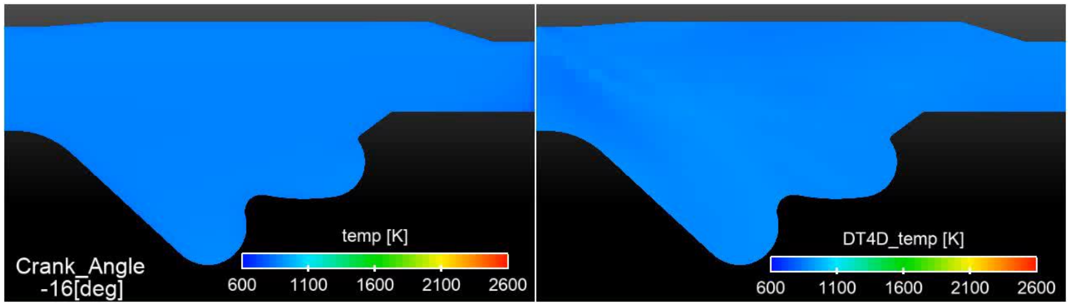
M.L. Surrogate Model Results (~1 Second)



High-Pressure Turbine Blade Thermal Analysis

TRANSIENT CFD
1 Solution = ~2 Days

FULL-ORDER SURROGATE
1 Million Solutions = ~15 Minutes



Tallman, ORNL AIRES Worship '20

Post-Grant Publications

Application of Cascade model towards development of DLN2.6e technology ◆ Numerical methods behind Cascade ◆ Premixed Combustion Model & acoustics prediction ◆ Application Paper for prediction of thermoacoustics & other quantaties and comparison with lab and engine ◆ LES & thermoacoustic prediction of combustion process in lean premixed gas turbine with Staged Fuel Injection ◆ Using a New Entropy Loss Analysis to Assess the Accuracy of RANS Predictions of an HPT Vane ◆ The Current State of High-Fidelity Simulations for Main Gas Path Turbomachinery Components and Their Industrial Impact ◆ High-Fidelity Simulations of Low-Pressure Turbines: Effect of Flow Coefficient and Reduced Frequency on Losses ◆ High-Fidelity Simulations of a Linear HPT Vane Cascade Subject to Varying Inlet Turbulence ◆ Machine learning for turbulence model development using a high-fidelity HPT cascade simulation ◆ Transition investigations based on large eddy simulation of high-pressure turbines vane at realistic Reynolds and Mach numbers ◆ Highly Resolved LES of a Linear HPT Vane Cascade Using Structured and Unstructured Codes ◆ Multiple invited seminars given based on this work - Can pull that list together ◆ Application of High Performance Computing for Simulating Cycle-to-Cycle Variation in Dual-Fuel Combustion Engines ◆ Unsteady adjoint of pressure loss for a fundamental transonic turbine vane ◆ Fluid Dynamics Effects on Microstructure Prediction in the Laser Additive Manufacturing Process ◆ Fluid Dynamics Effects on Microstructure Prediction for the Single-track Laser Additive Manufacturing Process ◆ Effect of Particle Spreading Dynamics on Powder Bed Quality ◆ Fluid Dynamics Effects on Microstructure Prediction in Single-Laser Tracks for Additive Manufacturing of IN625 ◆ Effect of Particle Spreading Dynamics on Powder Bed Quality in Metal Additive Manufacturing ◆ Quantification of Powder Bed Structure for Metal Powder Bed Additive Manufacturing Using Discrete Element Method ◆ Wall-modeled LES study of surface roughness effects from additive manufacturing for gas turbines ◆ Near Wall resolution Requirements for High-Order FR/CPR Method for Wall-Resolved Large Eddy Simulations ◆ GPU accelerated Turbomachinery LES using DG methods ◆ Large Eddy Simulation for Jet Installation Effects ◆ Investigation of Noise Generated by a DU96 Airfoil ◆ Large eddy simulation of a wind turbine airfoil at high angle of attack ◆ Large eddy simulation of airfoil self-noise ◆ Report for Workshop: Trailing-Edge noise ◆ Towards Identifying Contribution of Wake Turbulence on Inflow Turbulence Noise from Wind Turbines ◆ Large Eddy Simulation of a Wind-Turbine Airfoil at High Freestream Flow Angle ◆ Effect of Installation Geometry on Turbulent Mixing Noise from Jet Engine Exhaust ◆ Large Eddy Simulation for jets from chevron & dual flow nozzle ◆ Turbulent Mixing Noise from Jet Exhaust Nozzles ◆ Aerodynamic Noise Prediction for a Rod-Airfoil Configuration using Large Eddy Simulations

(Recent)
2020-2022 ALCC / INCITE Project Publications

B. Jayaraman, E. Quon, J. Li, and T. Chatterjee,
"**Structure of Offshore Low-Level Jet Turbulence and Implications to Meso-micro Coupling**",
TORQUE2022 paper 651, J. Phys.: Conf. Ser. 2265 022064.

T. Chatterjee, J. Li, S. Yellapantula, B. Jayaraman, B. and E. Quon,
"**Wind Farm Response to Mesoscale-driven Offshore Low Level Jets: A Multiscale Large Eddy Simulation Study**",
TORQUE2022 paper 536, J. Phys.: Conf. Ser. 2265 022004.

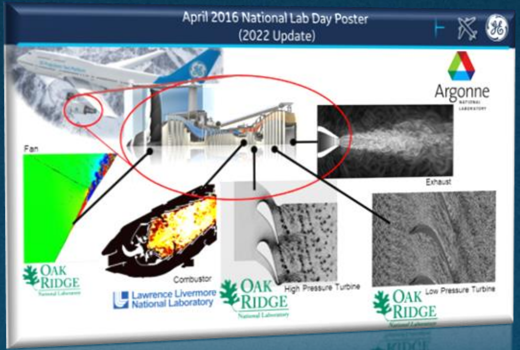
S. Priebe, D. Wilkin, A. Breeze-Stringfellow, A. Mousavi, R. Bhaskaran, L. d'Aquila,
"**Large Eddy Simulations of a Transonic Airfoil Cascade**",
GT2022-80683, ASME Turbo Expo 2022, Rotterdam, The Netherlands, June 13-17, 2022.

R. Bhaskaran, R. Kannan, B. Barr and S. Priebe,
"**Science-Guided Machine Learning for Wall-Modeled Large Eddy Simulation**,"
2021 IEEE International Conference on Big Data (Big Data), 2021, pp. 1809-1816, doi: 10.1109/BigData52589.2021.9671436.

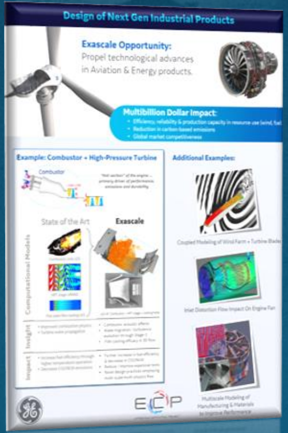
S. Priebe, T. Wood, J. Yi and A. Mousavi,
"**Large Eddy Simulation of an Open Rotor Fan Blade**",
Paper GT2022-80538, ASME Turbo Expo 2022, Rotterdam, The Netherlands, June 13-17, 2022.

(Presentation) B. Mitchell, KAUST Conference: ***Flow Simulation at the Exascale****, March 28-30, 2022*

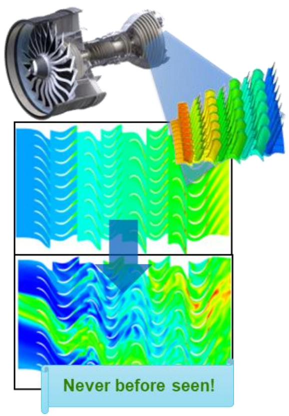
GE Support for Leadership Computing & Exascale



[2014 House Briefing on Value of Supercomputers for Science & Industry]
[2017 Senate Panel: U.S. Science Facilities: Unlocking Innovation]
[2018: House Panel: Big Data Challenges and Advanced Computing Solutions]



HPC: Computational Science & Engineering Partnerships – THANK YOU!



Leadership-class Supercomputers → Inspire & Guide → GE Internal Supercomputers

- State of the Art Hardware
- Feasibility Study @Scale
- Scalable Software Design & Benchmarking
- Peer-reviewed Credibility & Communications
- Lower TRL problems (Science)

- Hardware Tuned to GE's Needs
- Validation @Scale
- Software Innovation and Adoption
- GE Proprietary cases aimed at NPI
- Higher TRL problems (Applied Science & Engineering)

Building a world that works

@arthurrge

RichardBArthur

richardarthur.medium.com

Background materials follow…

DAVE KEPCZYNSKI

Chair, ECP Industry Council

Exascale Computing Project (ECP) Industry Council Chair Brunon (Dave) Kepczynski serves as Chief Information Officer, General Electric (GE) Global Research Centers and the Engineering Product Leader for GE's Digital Technologies. His missions are the scaling and maturing of digital thread technologies and engineering horizontal products across the enterprise to deliver outcomes in technical velocity, cost, and quality. In a previous role at GE, he was Engineering Chief Information Officer for GE Oil & Gas where his teams drove digital transformation.

Before GE, he spent more than 25 years with General Motors, leading teams in Global Systems Development & Business/IT Transformation, Global Design Execution & Operations, Vehicle & Powertrain Product Development, Assembly Operations, and Manufacturing Engineering. His teams developed and deployed solutions enabling the design, validation, and manufacture of world-class automotive products.

Dave has been an active member of the ECP Industry Council since its inception and became chair in April 2018.

Simulate Predict Insight Learn Validate

2020 Computational Methods Workshop
2022 GE Simulation Symposium

Whitney Symposium 2015

Physics & Big Data for Customer Outcomes

Whitney Symposium 2012

Analytics, Modeling and Simulation
in the Age of the Industrial Internet

Whitney Symposium 2016

AI: The Promise of Limitless Industrial Opportunity

2022 GE Simulation Symposium

2020 Computational Methods Workshop


Steve Arnold — Discipline Lead – Materials and Structures
Transformational Tools and Technology Program
NASA Glenn Research Center


Mike Heroux — Director – Exascale Computing Project (ECP) Software Pillar
Senior Scientist – Advanced Simulation & Computing (ASC)
Sandia National Laboratories, U.S. Department of Energy


Greg Laskowski — Director of Fluid Mechanics
Alumnus of Sandia, GE Aviation (Lynn) & GE Research
Dassault Systèmes


Dan Seal — Sr. Manager – Product Lifecycle Management
Lead - Immersive Development (ImDev) Initiative leveraging Digital Thread / Twin
Boeing Defense, Space & Security

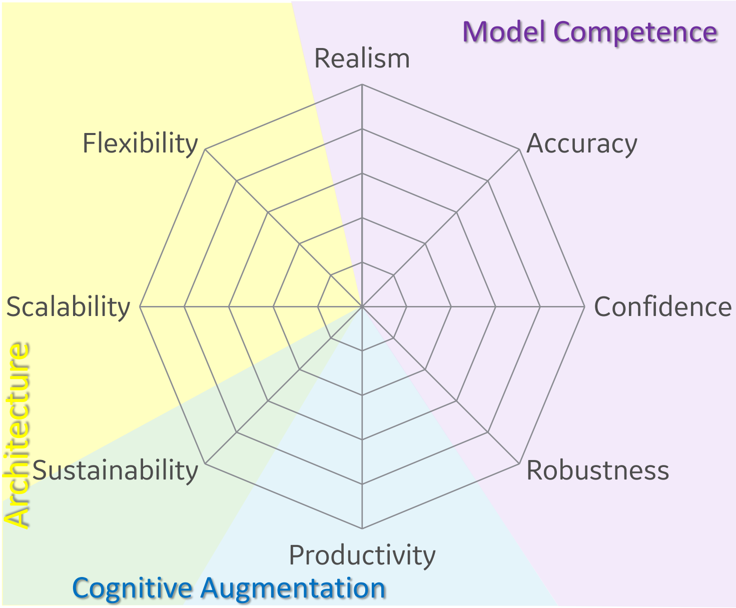

Ed Kraft — Retired – Chief Technologist for Ground Testing
One of Principal Architects for Air Force Digital Thread/Digital Twin initiative
Air Force Test Center, Arnold Air Force Base

- Steven Levine, Sr. Dir. Virtual Human Modeling, Dassault Systèmes
- Eric Stahlberg, Dir. Cancer Data Science, Frederick National Lab
- Laurence Sampson, Sr. Dir., Siemens Digital Industries Software
- Amanda Randles, Biomedical Engineering, Duke University
- Marc Horner, Distinguished Engineer, Ansys, Inc.
- Eric Bogatin, University of Colorado, Boulder

General Electric (Internal)

- Patrick Harrington, Sr. Mechanical Engineer
- Kyle Reiser, Mechanical Architect
- Emma Cusack, Mechanical Engineer
- Gunaseelan Murugan, Sr. Systems Engineer, GE Healthcare
- Rick Arthur, Sr. Director, Computational Methods, GE Research
- Ann Buneo, Product Leader, HPC, GE Research
- Doug Grant, Sr. Mechanical Engineer, GE Healthcare
- Jonathan Bruss, Sr. Engineer, Mechanical Engineering, GE Healthcare

Modeling Maturity Rubric



Realism — *Completeness of …*

Accuracy — *Validity within…*

Confidence — *Error bounding within…*

Robustness — *Stability & Assertability of…*

… Model's *Region of Competence*

Productivity — *& Waste Reduction*

Sustainability — *& Architecture Quality*

Cognitive Augmentation

Scalability — *Capable & High Performance*

Flexibility — *Modular, Extensible, Interoperable*

Architecture

Framework to Assess MODEL MATURITY

Assert a ***Region of Model Competence***

where its use is numerically stable (**ROBUSTNESS**)
with minimal simplifying constraints (**REALISM**) and
quantifiably bounds uncertainties (**CONFIDENCE**)
of results with validated predictive **ACCURACY**

Implemented with an ***Architecture*** that

performs capably (**SCALABILITY**)
and is interoperable and **FLEXIBILE**

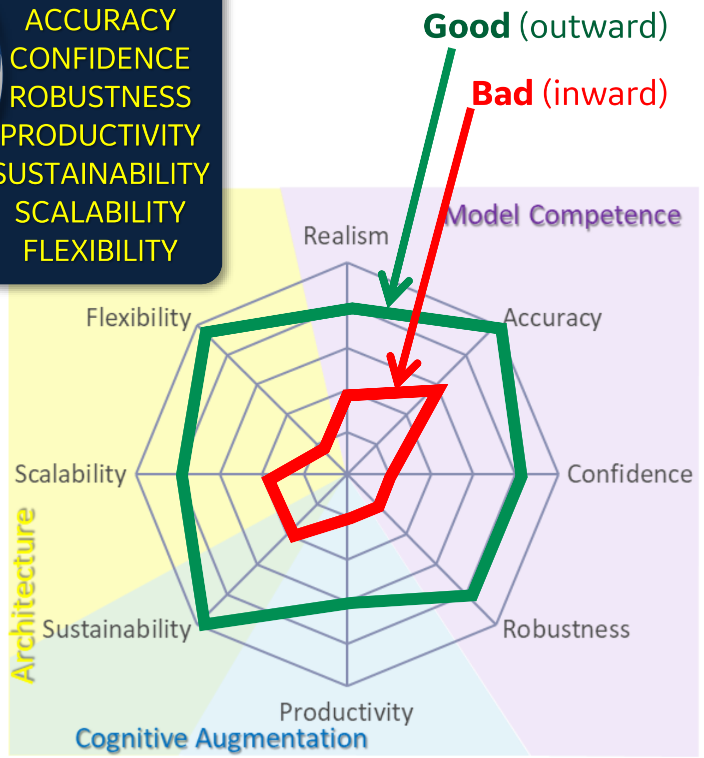
Employing modern ***Software Engineering & Computational Methods*** (including AI/ML) discipline and tools to

promote efficient workflows (**PRODUCTIVITY**),
reduce waste and improve quality (**SUSTAINABILITY**)

See also
richardarthur.medium.com/co-design-web

MODEL

REALISM
ACCURACY
CONFIDENCE
ROBUSTNESS
PRODUCTIVITY
SUSTAINABILITY
SCALABILITY
FLEXIBILITY



Additional Reference: PCMM Adaptation by GE Digital Twin Model Maturity Team:

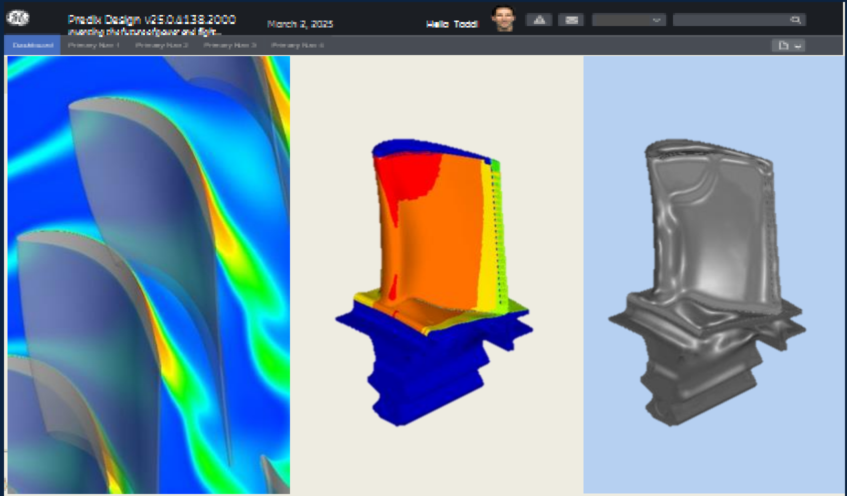
Sandia National Laboratories

PCMM

Per Asset Based Models	L0: Empirical Trial & Error	L1: Expertise-driven	L2: Model-assisted	L3: Model-driven
Model Representation *What features are neglected because of simplifications or stylizations?*	Little or no representational fidelity requirements established for the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))	Significant assumptions of the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))	Limited assumptions of the model geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's))	Real time process and quality assurance data used to refine model assumptions and develop physics based and data driven reduced order models
Process Physics Fidelity *How fundamental are physics & material models + degree of model calibration?*	Empirical data-driven models and/or judgment used to define important parameters of the asset of interest	Some physics based models exist for key parameters of the asset of interest	(Suite of) physics based models exist for the key parameters of the asset of interest	Real time predictions of physics based process performance enable enterprise decisions made within process takt time
Code/Algorithm/Model Integration *Do algorithm deficiencies, software errors, and poor SQE practices corrupt results?*	Minimal or no testing of any commercial off the shelf (COTS) or custom software elements with little of no configuration management procedures specified or followed	Source code and algorithms are either COTS software or managed by configuration management procedures with limited comparisons to established algorithm benchmarks	Customized and/or modified algorithms are tested and compared to benchmark data and/or solutions to determine impact on numerical convergence and physics	Integration of algorithms with machine controls and multi-physics data fusion
Solution Verification *Are numerical solution errors and procedural human errors corrupting the simulation results?*	Modeling assumptions have an unknown effect on the accuracy and/or precision of the numerical model predictions	Alternative model builds considered; Numerical, discretization, and model assumption induced errors qualitatively estimated based on model input/output for each use case; Qualitative assessment of model limitations and weaknesses provided.	Alternative model builds have been considered; Numerical, discretization, and model assumption induced errors quantitatively estimated across validation envelope and used to establish best practices; Quantitative assessment of model limitations and weaknesses provided.	Real time comparison of predictions with process data
Model Validation *How is accuracy of simulation & experimental data assessed over the validation hierarchy?*	Judgment and/or limited experimental data exists to validate model predictions	Industry standard use cases and benchmark experimental data sets exist and used to calibrate models at one or more distinct validation points	Data from actual enterprise and/or customer/supplier processes used to calibrate model predictions and establish validation envelopes	Model predictions are used to adapt process parameters for real time control
Uncertainty Quantification *How thoroughly are uncertainties and sensitivities characterized and propagated?*	Model prediction uncertainties and sensitivities to key input parameters are not assessed as part of the simulation	Prediction uncertainties inferred from benchmark experimental use case validation data with limited sensitivity studies conducted for key parameters	Prediction uncertainties segregated and propagated by source (geometry, material properties, and process conditions (parameters, initial conditions (IC's), and/or boundary conditions (BC's)) etc.) with detailed sensitivity analyses conducted	Uncertainty and confidence estimates made for all predictions using physics based data-driven reduced order models
Peer review	Absent	Informal / ad-hoc peer review	Peer review conducted as process	Formal independent peer review process

GE Research

Physical system models with predictive REALISM



Fluid Dynamics   Heat Transfer   Structural

COLLABORATIVE MULTI-DISCIPLINARY MODEL INTEGRATION

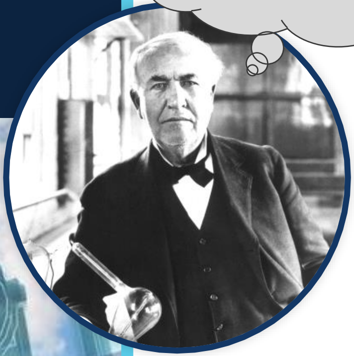
GEOMETRIC DIMENSIONING & TOLERANCING PRECISION

MULTI-SCALE MATERIALS MODELS

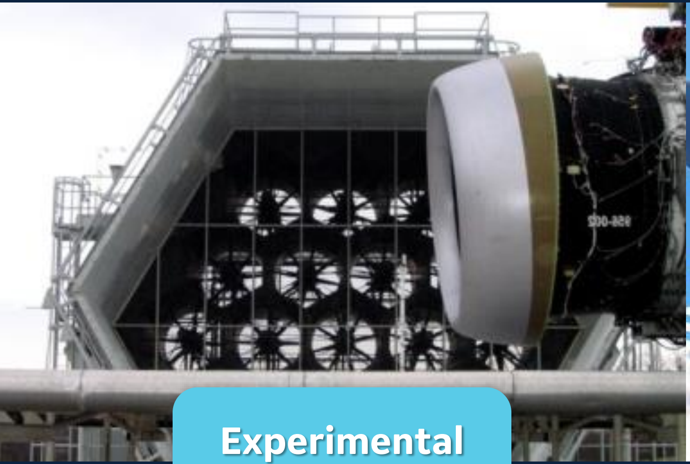
COUPLED MULTI-PHYSICS& CO-SIMULATION

Physically validate predictive ACCURACY

Garbage In
Garbage Out



“RIG” TEST



Experimental Measurement

DIGITAL TWIN

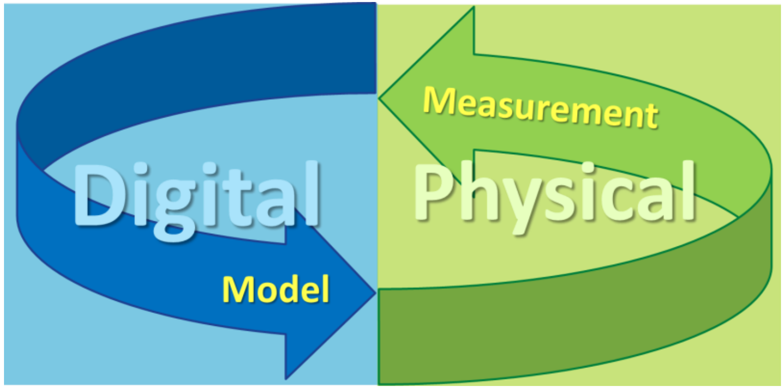
Targeted Field Sampling

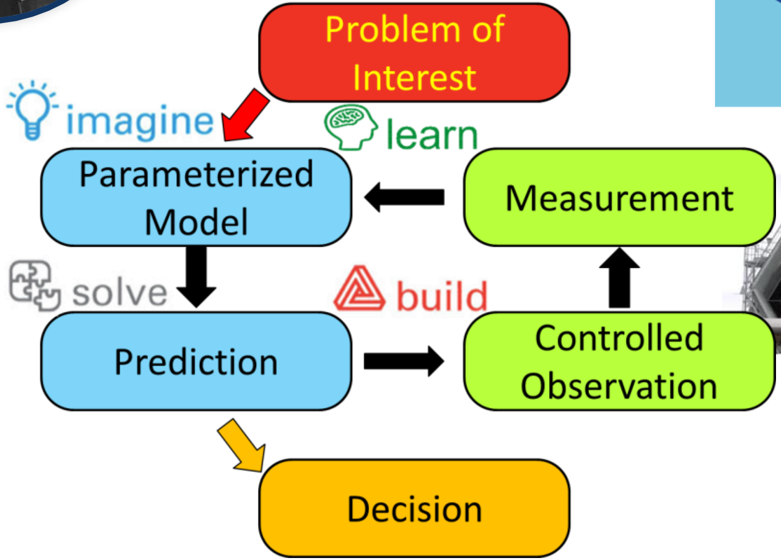
to trust critical model results
& bound assertable CONFIDENCE

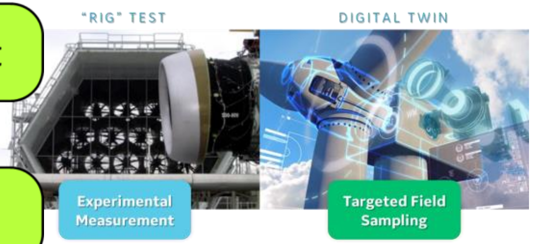
VERIFICATION & VALIDATION

CALIBRATION & UNCERTAINTY QUANTIFICATION

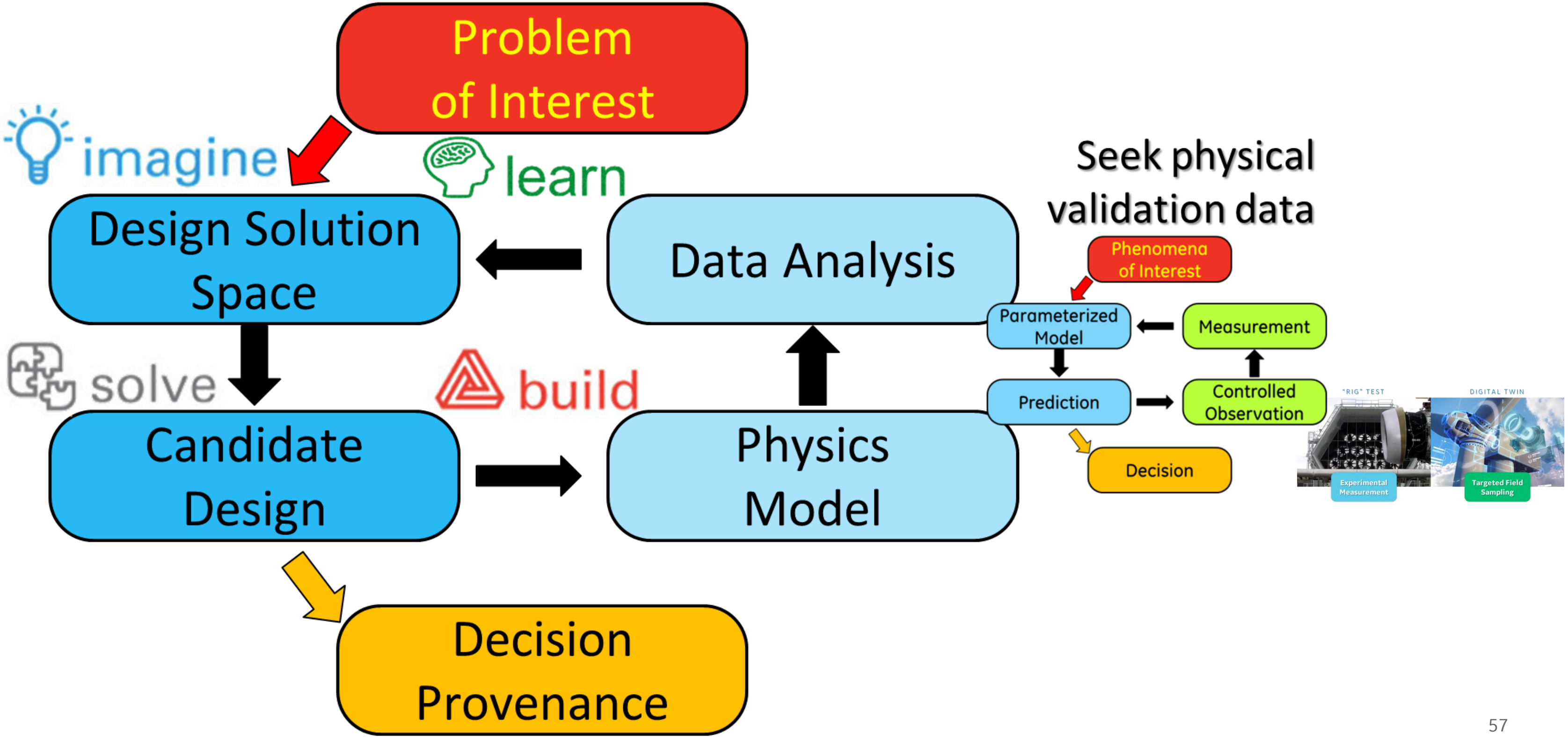
Systemic Reduction of Uncertainty







Decision Space Mapping: *Guided Validation & Calibration*



Geometry Ecosystem: Gaps & Failure Modes

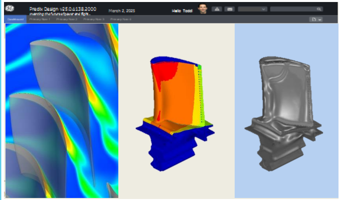
1. Labor-intensive complex mesh generation and validation
   ("are we sufficiently confident with the geometry spec to take the next step?" – the step being to send to manufacturing or even simply to use to instantiate CFD/FEM analyses ~ flow, thermal, stress/strain, etc.")
2. Elegantly and robustly handle tolerances
   (including consistency & coherence/feasibility in design tolerances vs. manufacturing tolerances)
3. Handling imperfect or formulaic geometry *(gaps/overlaps/shards)*
4. Geometric change propagation across adjacent parts
5. Mapping / calibration with point cloud measurement
   (including evaluating tolerance deviation/acceptance)
6. Load-balancing/adaptive refinement/scalability in highly complex *(especially evolving/sliding and dynamic physics)* meshes

CAD
vs.
Meshed
vs.
Voxel
vs.
Meshless / Particle
vs.
Systems Model
vs.
??? ...

Geometry Ecosystem: EMERGING Gaps

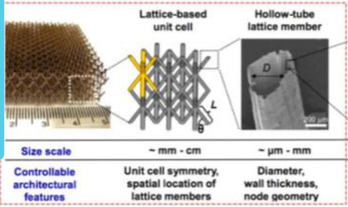
7. Sufficiently authoritative and comprehensive specification of a single source reference for deriving geometries for all potential uses (i.e., end-use context-driven)

   a. *automated mesh generation guided by embedded domain knowledge*
   b. *(e.g., performance flow vs. cooling flow vs. conjugate heat transfer vs. solid thermal flow vs. stress/strain thermal cycling and crack propagation vs. tensile strength / etc.)*
   c. *(or manufacturing GTD@room temperature vs. performing GTD@operational temperature / etc.)*
   d. *(and systems modeling inclusion of kinematics / articulation information),*
   e. *with sufficient fidelity to reduce physical testing-for-certification with virtualized certification-by-analysis*
   f. *as well as geometry simplification (including high-order analyses),*
   g. *(with in-situ reflective/introspective learning (of principles, simplification opportunities, etc.) during meshing.)*

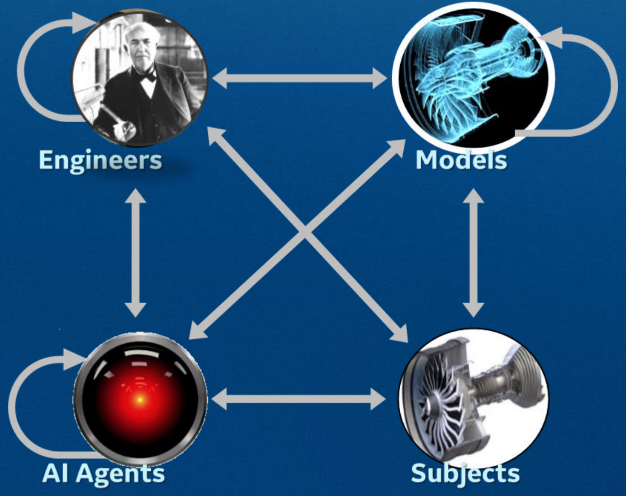


8. Sufficiently support capabilities for advanced manufacturing use cases including

   a. *nonuniform materials (gradient composition, designed microstructures, etc.),*
   b. *surface tagging in complex internal geometries (such as micro-trifurcating core structures in heat exchangers) and geometries resulting from generative design (fully exploiting additive degrees of freedom & biomorphic shapes),*
   c. *specification for geometric fit by functional intent rather than explicit shape (generatively/programmatically derived),*
   d. *assessment of opportunities for multi-part consolidation,*
   e. *auto-propagate novel manufacturing capability up the toolchain to design decisions (e.g., via design assistants),*
   f. *inclusion of intermediate geometries for manufacturing (such as mid-process geometries or temporary bit holds) and process guidance (such as surface roughness, crystal orientations, measurement & inspection features)*



Strategy: Actions & Assets



Modernization of Science & Engineering: Data as Strategic Asset

- Gap Assessment: legacy tools & practices (e.g., physical testing, certification)
- Modeling Maturity: identify opportunities to pilot feasibility study, reduction to practice
- Continuous Improvement/Exploit ML: automation, virtualization, standardization, FAIR data/workflows, …

Modeling Infrastructure: Systemic Mindfulness & Knowledge Stewardship

- In-silico Infrastructure: HPC, cloud, software & methods ecosystem (capacity + capability)
- Modeling Literacy/Fluency: executive competency/confidence + workforce development
- Human-Machine Collaboration: data & decision provenance, continuum mindset