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Overview of Pratt & Whitney Rocketdyne Modeling & Simulation Practices for Liquid Propellant Rocket Engines

New Horizon of Rocket Engine Modeling & Simulation

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Agenda

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- **Rocket Test Video**
- **Liquid Rocket Engine Characteristics**
- **Key Rocket Engine Components**
  - Function
  - Physics
  - Examples of Current Modeling & Simulations Practices
  - Engineering Needs & Technology Gaps
- **Challenges in Rocket Engine Development & Future Direction**

Liquid Rocket Engine Development is Challenging

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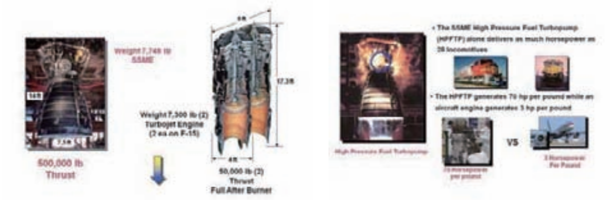
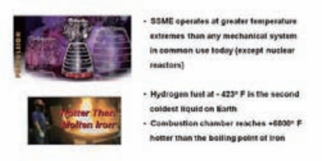
- **Tremendous Power Output**

3 Space Shuttle Main Engines (SSMEs) produce as much power as 23 Hoover Dams

- **High Power Density**

Thrust produced by a single SSME is more than 20 F-15 turbofan engines





- **Extreme Environment**

SSME operates at greater temperature extremes than any mechanical system known to man
(from 6000° F in the combustion chamber to fuel at -423° F just a few inches away)

Attention to Every Detail is Essential

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Typical Liquid-Propellant Rocket Engine Components

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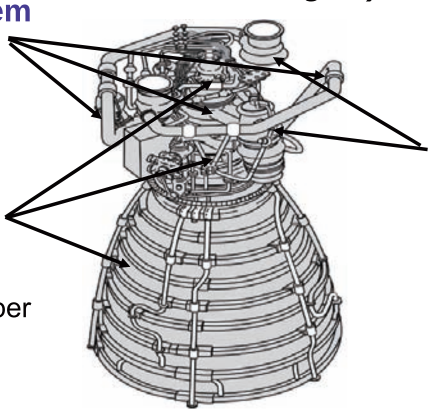
Staged Combustion Engine Cycle (e.g. Space Shuttle Main Engine)

Externals & Feed System

- Manifolds
- Ducts
- Valves

Thrust Chamber

- Preburners
- Main injector
- Combustion chamber
- Nozzle



Rotating Machinery

- Turbopumps
  (high & low pressure)

New Engine Development Cycle
Conceptual Design ~ 2-4 months
Preliminary Design ~ 6-8 months
Detailed Design ~ 12-14 months

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Rotating Machinery

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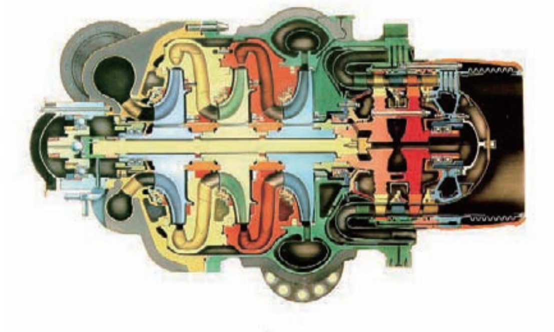
Typical Turbopump Cross-section (SSME HPFTP)



Rocket engine rotating machinery generally consist of pumps driven by turbines (turbopumps). The function of the turbopump is to receive the liquid propellants from the vehicle tanks at low pressure and deliver them to the combustion chamber at the required flow rate and injection pressure.

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Key Turbopump Sub-components

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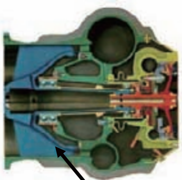
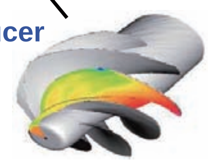


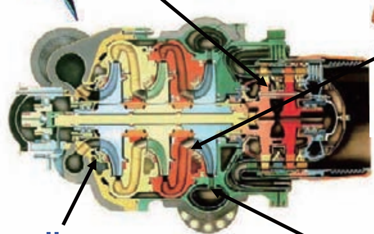


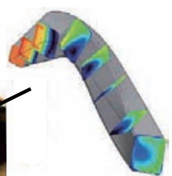
Inducer

The axial inlet portion of the turbopump rotor whose function is to raise the inlet head by a amount sufficient to preclude cavitation in the following stage

Turbine Blade Cascade

Blade cascade that provides the power to drive the pump

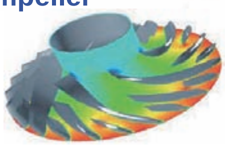




Crossover Duct

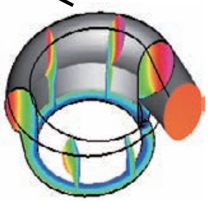
Stationary elements that convert kinetic energy imparted on the fluid by the rotating components to the static pressure as well as provide the correct flow angles to the downstream elements

Impeller



Centrifugal flow devices that change the flow direction from axial to radial and impart kinetic energy by doing work on the fluid

Volute



Scroll type devices required to capture the flow out of the turbopump stages and direct it into the downstream piping system

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Turbopump Physics

Rotating machinery flows are among the most complex internal flowpaths

- 3D, large regions of separation, strong flow non-uniformities
- May contain incompressible, subsonic, transonic and even supersonic flows within the same turbopump
- High speeds of rotation (e.g. 38,000 RPM for the SSME HPFTP) create a highly turbulent, and strongly anisotropic flow dominated by vortical motions, separated boundary layers and vortex shedding
- Multiphase flows (cavitation in inducers and liquid-gas mixtures around some types of bearings) are also observed
- Extremely high dynamic loads and thermal gradients (e.g. temperatures change by ~ 2000^{o} R within a few inches)

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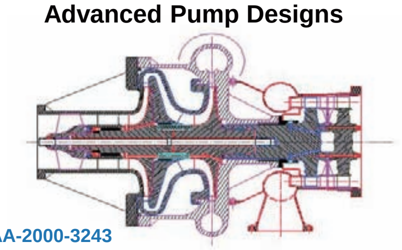
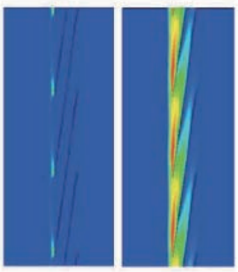
Centrifugal Pump Modeling and Simulation - Aerothermal

Advanced Pump Designs

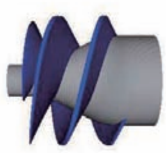


AIAA-2000-3243

Advanced Simulation Capability



Near Tip Vapor Distribution
High NPSH Low NPSH



AIAA-2004-2641

- **High efficiency single-stage and multi-stage centrifugal pumps for high power density applications**
  - SSME, RL-10, J-2X, RS-68
- **Excellent rotordynamic environments**
  - Hydrostatic bearings
  - Long life, high-speed turbopumps
- **Cavitation-free axial inducer research**
  - Active and passive tip-vortex suppression
- **Advanced pump design and simulation tools, DigitalTurbopump**
  - 1-Billion node flow simulation demonstration using commodity hardware, collaboration with Microsoft in 2007
  - Rotor-stator interaction
  - Cavitating flows
  - Coupled propellant tank and feedlines

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Turbine Modeling and Simulation – Aerothermal

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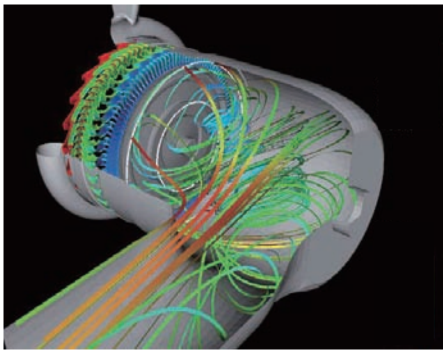
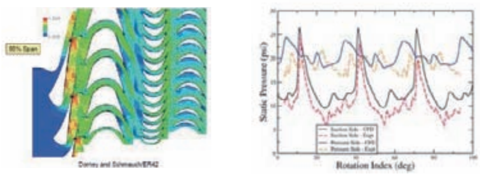
- **Applied to several booster and upper stage liquid rocket engines – validated with multiple data sets**
  - SSME, J-2S, J-2X, RS-68, RS-68A
- **Advanced turbine design and simulation tools provide advanced analysis capabilities**
  - Subsonic and supersonic turbines
  - Fully unsteady rotor-stator interaction
  - Single- and multi-stage analysis
  - Periodic sector and “full-wheel” analysis with large high-resolution computational grids ($\mathcal{O}$ 100 million grid cells)
  - Provides unsteady loading for complementary structural analysis

MB-XX Flange-to-Flange Simulation



NASA TPO Validation



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Turbopump Modeling and Simulation – Structures & Dynamics

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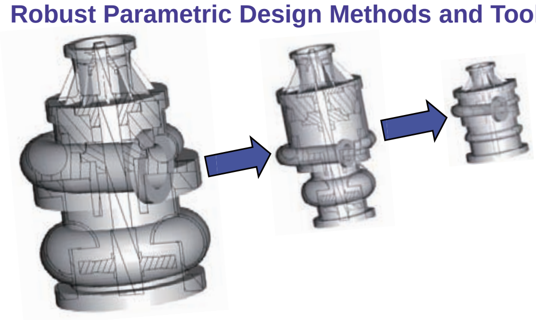
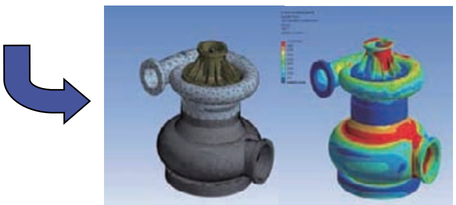
Robust Parametric Design Methods and Tools



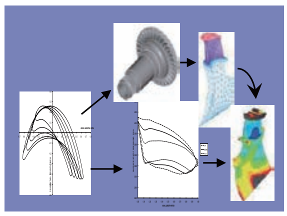
State of the Art Analytical Design Technologies

- Flight validated structural solutions over wide range of rocket engine turbopump pressure & temperature environments
- Unsteady dynamic pressure analysis linked to turbine life prediction for full wheel geometry
- Cavitation free inducer design & analysis
- Efficient turbine damper technologies
- Low leakage seal design & analysis
- Transient load prediction for journal bearings

Rapid 3D Meshing and Stress Analyses



Integrated Pump & Turbine Analysis & Optimization



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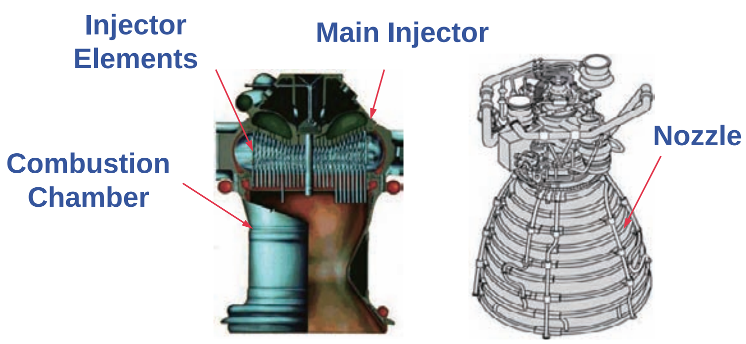
Turbopump Engineering Challenges & Technology Needs

- Ability to rapidly predict the flow and thermal environment in the entire turbopump (a CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
- Interfacing CFD predicted flow and thermal environments and loads with stress and structural dynamics codes and material databases to determine part thickness, yield and failure limits, and margins of safety (dual challenge – CFD has to provide what stress needs, stress has to understand CFD's limitations and areas of uncertainty)
- Understanding turbine disk instability mechanisms including acoustic excitation
- Developing a user-friendly methodology to include secondary (thermal) stresses in fracture mechanics analysis
- Acquiring quality test data and experiments to validate models and predictions

Thrust Chamber



Thrust chamber assemblies consist of three major components: the injector,the combustion chamber, the nozzle. The injector delivers the fuel and oxidizer to the combustion chamber through gas-gas, gas-liquid, or liquid-gas injector elements. In the combustion chamber, the fuel and oxidizer are injected, vaporized (if necessary), mixed, ignited, and burned. Once the propellants are combusted they can be expanded through a convergent-divergent nozzle producing thrust in the process.

Thrust Chamber Physics

Rocket engine thrust chamber design provides many challenges

- Spray combustion process encompasses many physical processes of different types, temporal and spatial scales, tightly coupled to each other (two-phase mixing, combustion, turbulence, kinetics, instabilities) making environment definition and modeling very difficult
- Extremely high heat loads require exotic materials and active cooling
- Transient phenomena can lead to severe instabilities in the combustor and nozzle
- Performance and durability issues require trade-offs and limit the design envelope
- Test data are difficult and very expensive to obtain

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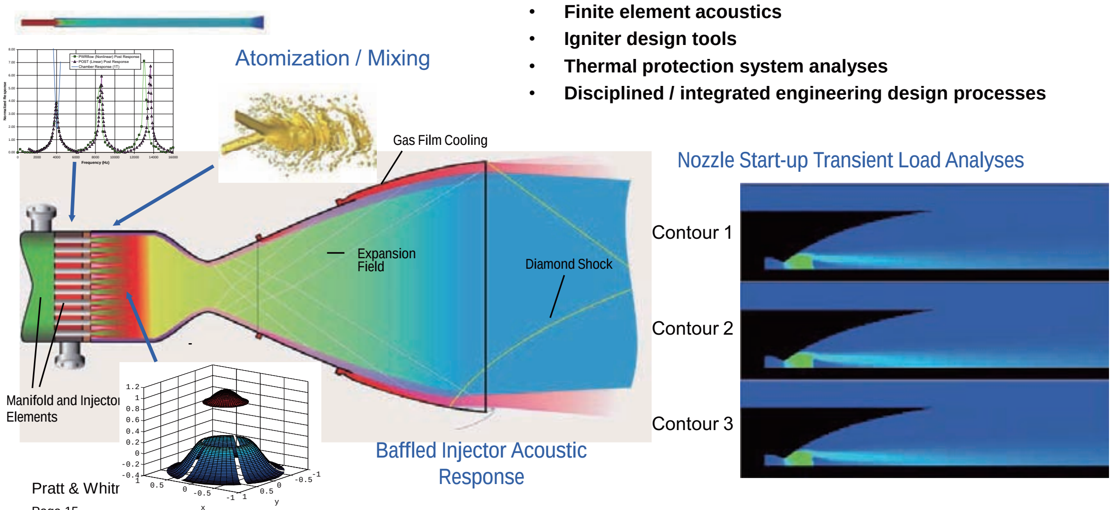
Thrust Chamber Modeling and Simulation - Aerothermal

State of the Art Analytical Design Technologies at PWR

- **Computational fluid dynamics (CFD) (mixing, vaporization, combustion & nozzle performance and loads)**
- **Boundary layer codes**
- **Gas and liquid film cooling**
- **Linear stability analyses (baffles, injector, cavities)**
- **Finite element acoustics**
- **Igniter design tools**
- **Thermal protection system analyses**
- **Disciplined / integrated engineering design processes**

Thrust Chamber Assembly Analysis - Selected Mechanistic Models

Injector Acoustics



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Thrust Chamber Modeling and Simulation – Structures & Dynamics

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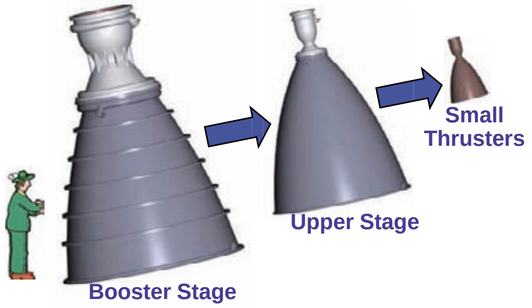
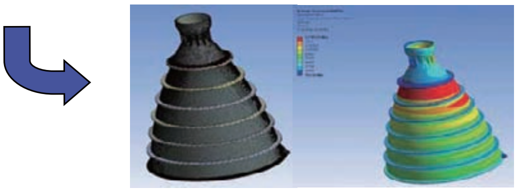
Robust Parametric Design Methods and Tools



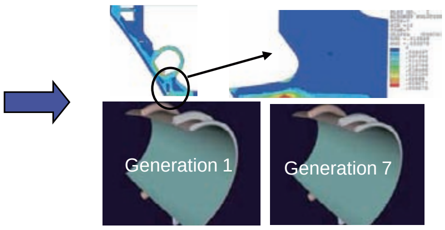
State of the Art Analytical Design Technologies

- Flight validated structural solutions over wide range of rocket engine thrust levels
- Expert structural analysis proficiency in strength, fatigue, fracture, dynamics, creep, plating, brazing & welding
- Large system dynamic interface load and environment prediction for random, sinusoidal, shock and acoustic loading sources
- High frequency accelerometer and strain gage data collection, analysis & storage
- Automated multi-disciplinary analysis and optimization system for nozzle and chamber design

Rapid 3D Meshing and Stress Analyses



Detailed Analyses & Optimization



Thrust Chamber Engineering Challenges & Technology Needs

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- Ability to rapidly predict the flow and thermal environment in the combustion chamber (another CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; mechanistic combustion models & correlations; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
- Interfacing CFD predicted flow and thermal environments and loads with stress and structural dynamics codes and material databases to select materials and coatings, yield and failure limits, active cooling requirements, and margins of safety (triple challenge – CFD has to provide what material scientists and stress engineers need, and they have to understand CFD's limitations and areas of uncertainty)
- Chamber durability and injector performance
- Combustion stability especially with hydrocarbon based fuels
- Acquiring quality test data and experiments to validate models and predictions

Externals & Feed System

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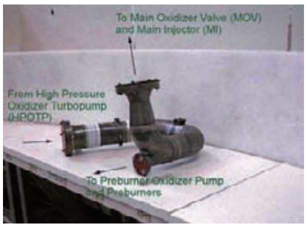
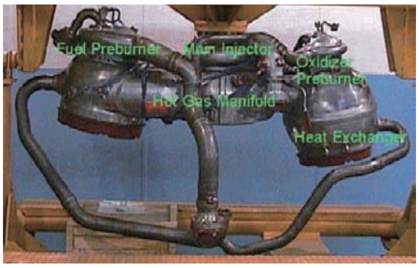
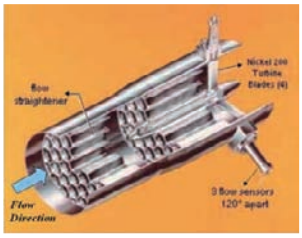
Typical Valves



SSME Hot Gas Manifold (HGM)



Fuel Flowmeter



Propellant Feed System is an assembly of ducts, valves, pipes, and manifolds that deliver the propellants to the turbopumps from the fuel and oxidizer tanks and then from the turbopumps to the combustion chamber.

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Externals & Feed System Physics

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These are largely incompressible internal flows in complex geometries

- 3D, large regions of separation, strong flow non-uniformities
- Strongly anisotropic flows dominated by vortical motions, separated boundary layers and vortex shedding
- Two phase (liquid/gas) flows may occur in some valves
- The challenge is to minimize the flow non-uniformities, total pressure drop, and the static & dynamic loads across the system
- The goal is to minimize weight

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Lines/Fuel Systems Controls System Modeling and Simulation

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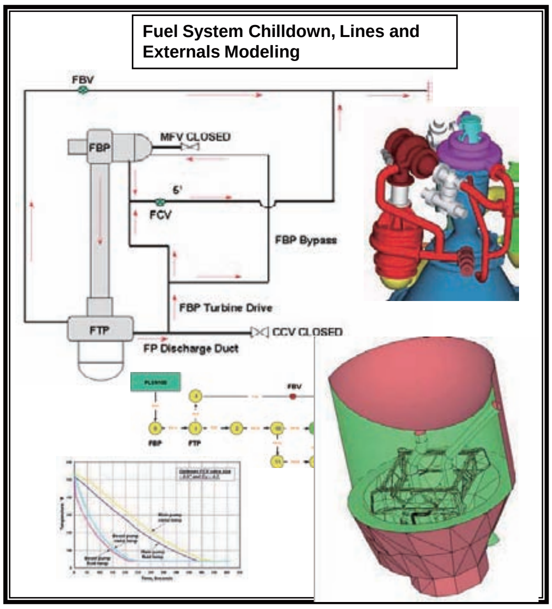
Active and Passive Thermal Control

- **Special purpose, custom programs**
- **General purpose tools- SINDA/FLUINT, Excel**
  - **Transient thermal & conjugate hydraulics**
  - **Built-in pressure drop and heat transfer correlations (SF)**
  - **Pump performance curves (SF)**
  - **Capillary devices**
  - **2-phase flow**
  - **Fluid mixtures**
- **SINDA/FLUINT enhancements**
  - **Process dynamics & control system algorithms**
  - **Advanced accumulator transient simulation methodology**
  - **Extended fluid property databases including cryogenic propellants**



Externals & Feed System Engineering Challenges & Technology Needs

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- Ability to rapidly predict the flow environment (a CFD challenge – dynamic grid adaptation; highly efficient solvers for 3D transient mixed flows; workable turbulence models; PC-based parallel computing capability (~ 1000 PCs); and large database management & postprocessing technologies)
- Interfacing CFD predicted flow environments and loads with stress and structural dynamics codes and material databases to determine part thickness, yield and failure limits, and margins of safety (dual challenge – CFD has to provide what stress needs, stress has to understand CFD's limitations and areas of uncertainty)
- Acquiring quality test data and experiments to validate models and predictions

New Rocket Engine Development Programs Face Many Challenges

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- New engine development is expensive and requires multi-year commitment
- Product integrity and performance can not be comprised in any way – especially in human flight
- However cost needs to be considered as an independent variable to establish the business case (go, no-go decision on the program)
- The design process is still a mix of engineering, science, experience, & art
- Since the SSMEs there has been no new flight engine development in the USA for a quarter of a century until the RS-68 engine (first flown in 2003)

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Critical Issues in Rocket Engine Development - *Technical*

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- System level design and analysis capability
  - Component level (e.g. turbopump) vs sub-component level design (e.g. impeller) considerations - entire engine being the ultimate goal
  - Fast enough to enable tradeoffs early in the design cycle
- Efficient and accurate simulation of dynamic flow phenomena and loads
  - Start-up and shut-down transients
  - Nozzle side loads, structural response to off-design loads
  - Instabilities (combustion and flow driven)
- Quantification of risk and uncertainty
  - Tool validation/verification/calibration issues
  - Scarcity of benchmark quality data
  - Limited success in modeling key phenomena (e.g. turbulence)

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Critical Issues in Rocket Engine Development - *Other*

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- **Experience base diminishing**
  - Current SOP blends experience, new tools, art and science
  - Experienced resident with key people retired or about to retire
  - Knowledge capture not progressing fast enough
- **Less testing, more modeling**
  - Cost considerations significantly reduce development testing
  - Programs assume first time success
  - No margin for error
- **Rocket propulsion industry is changing**
  - Driven more by the commercial market (fixed cost deals)
  - Global competition
  - Significant investment of Company resources required to stay competitive

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New Processes are Changing the Traditional Design & Analysis Practices

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- **Boundaries between design phases are shifting**
  - High fidelity analysis is being pushed earlier into the design cycle due to increased computer speeds and automation
  - Tools from detailed design (3-D CFD and FEM stress) are now being used in preliminary design
  - Preliminary design cycle times for some disciplines are approaching conceptual design cycle times
- **More demands are being placed on system level tools**
  - Operate in scalable heterogeneous computing environments
  - Control expensive analysis codes
  - Support optimization techniques utilizing more variables
  - Guide multiple disciplines

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New Processes Enhance Engine Reliability while Reducing Development Time and Cost

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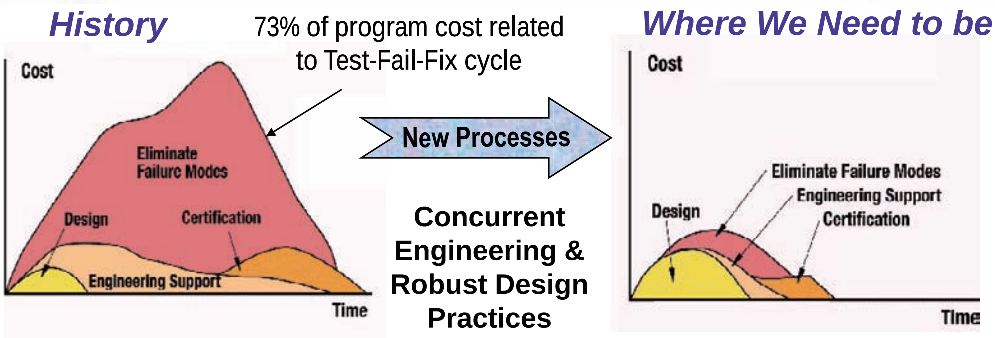

- Streamline design, analysis, & test processes
- Identify all possible failure modes early
- Fully explore the design space
- Account for variabilities
- Quantify risks, sensitivities, margins, system & component reliability

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PWR Robust Design Computational System (RDCS)

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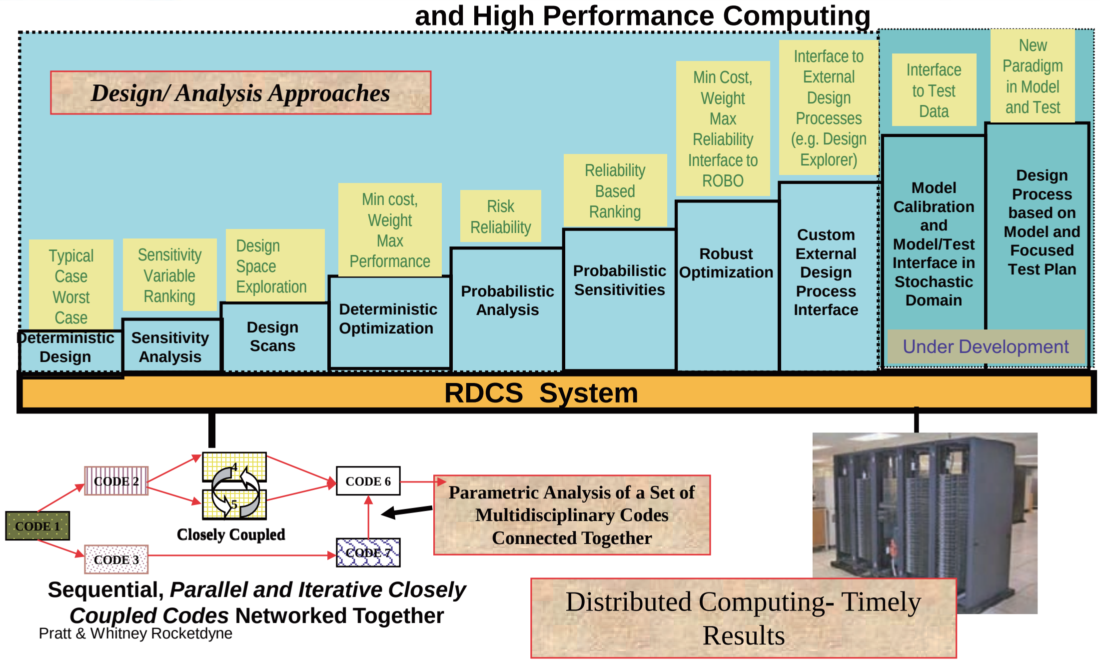
RDCS Strength Is *Equal* Parts Design Algorithms, Code Integration and High Performance Computing



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Major Components of Multi-Disciplinary Analysis, Optimization and Design Framework

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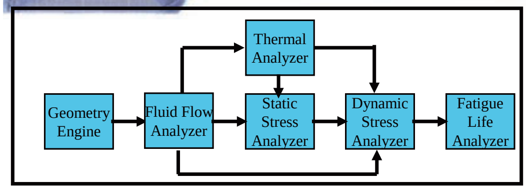
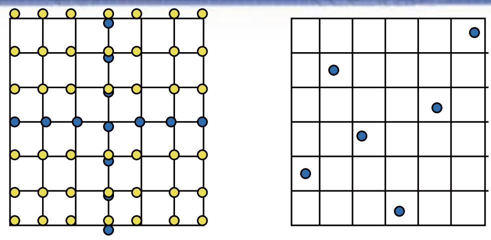
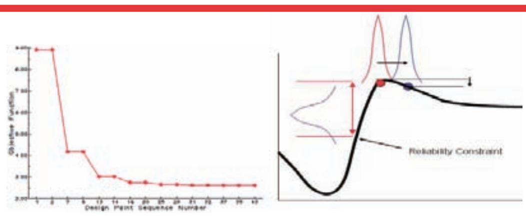


- **Automated Multidisciplinary Workflow Modeling**
  - Significantly reduces the design cycle time
  - Captures correlations and facilitates a consistent design



A) Partial and Full Factorial Designs B) Design of Experiments

- **Design Space Exploration**
  - Systematic evaluation of design alternatives and sensitivities
  - Efficient sampling in high dimensional space



- **Gradient, Genetic and Robust Design Optimization**
  - Weight minimization and performance maximization
  - Reliability based optimization of designs
  - Efficient optimization technologies in multi-dimensional Space

- **High Performance Computing**
  - Suite of Linux clusters
  - Use of high fidelity models
  - Parallel computation

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ISS Thermal Management System Modeling and Simulation

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Automated Thermal System for Space-Based Platforms

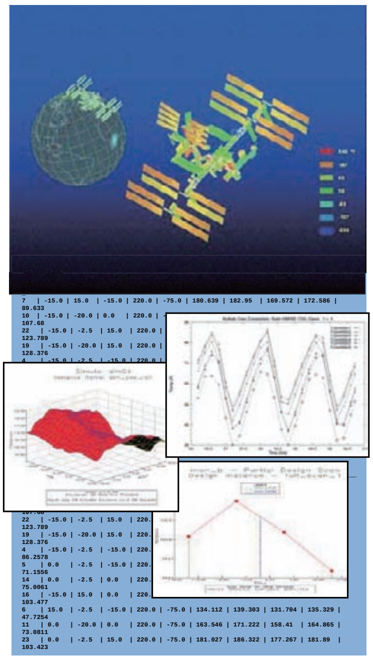
RDCS (Robust Design Computation System)

- *Automated screening parametrics:*
  - *orbit angle*
  - *altitude*
  - *ISS orientation angles*
- *Hundreds of cases with single submittal*
- *Massively parallel processing*

TSC (TRASYS-SINDA Cycle)

- *Automated analysis cycle*
- *Multiple orbit setup tools*
- *Orbital mechanics*
- *Environmental heating*
- *Radiation interchange*
- *Detailed temperature response*

ORBIT SETUP
↓
RADIATION ANALYSIS (TRASYS)
↓
RADIATION RESULTS INTERFACING
↓
THERMAL MODEL TEMPLATE UPDATE
↓
THERMAL SOLUTION (SINDA/FLUINT)



Total Productivity Increase ~ 20:1

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Some Closing Thoughts

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- The future of Space Transportation will be controlled by market forces in military, commercial, scientific applications
  - Safety and Reliability are essential but cost will be the discriminator (both non-recurring and recurring costs will be considered)
  - Upcoming decision on the direction of the US Space Program is critical
  - New NASA vision seems to favor more international collaboration
  - Global competition will however intensify especially in the commercial market
- Future development programs will rely heavily on system level thinking, robust design principles, multidisciplinary analysis and optimization, and on the use of high fidelity predictive tools even in the conceptual design cycle
- Development testing will be significantly reduced in favor of large scale, high fidelity simulations and virtual engineering practices

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