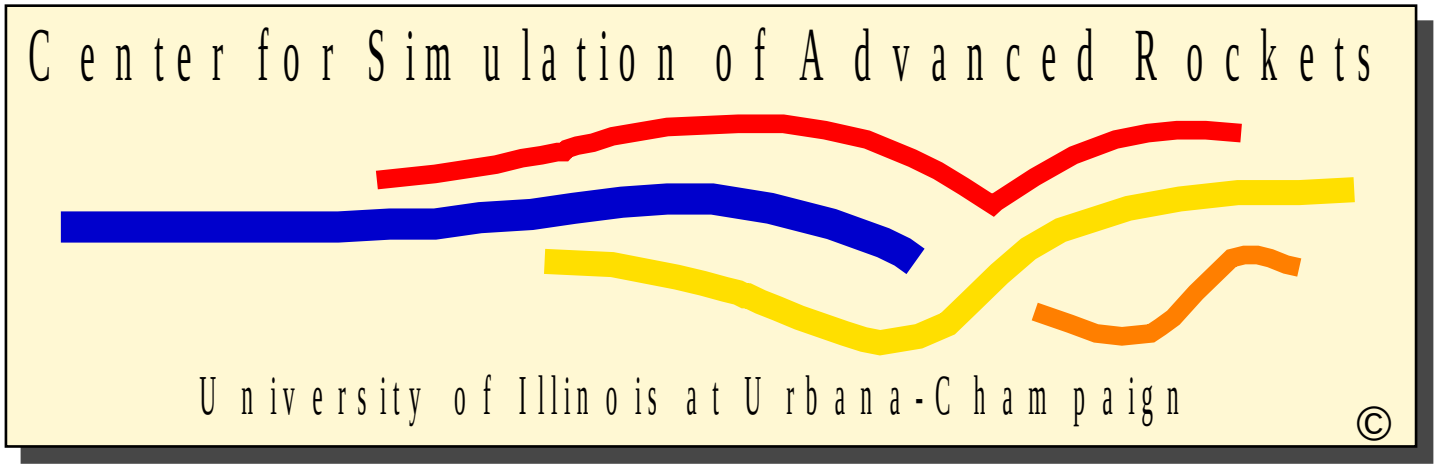


Integrated Simulation of Solid Propellant Rockets

William A. Dick

Managing Director

4 April 2001

Overview

- Center program goals
- US DOE ASCI Program
- Research plan and Roadmap
- Organization
- Progress to date — mostly non-CFD
- Future development

Computational Science and Engineering

Education Program

Computational Science & Engineering Option

12 departments
130 faculty associates
60 students enrolled
10 graduate fellows

Research Program

Center for Simulation of Advanced Rockets

DOE funded
$20 million over 5 years
42 faculty
45 graduate students
25 professional staff

Center for Process Simulation and Design

NSF & DARPA funded
$2.5 million over 3 years
12 faculty
13 students & staff

US DOE Accelerated Strategic Computing Initiative

- Response to Comprehensive Test Ban Treaty, 1996
- Simulation only — no testing of "strategic stockpile"
- Huge computational capability
  - Sandia — 8000 processor, Intel Pentium
  - Los Alamos — 4000 processor, SGI Origin2000
  - Lawrence Livermore — 1500 x 4 processor, IBM SP2
- Full 3-D simulation science development

US Department of Energy ASCI/ASAP Centers

- Focus on single application that requires an integrated, multidisciplinary approach
- Tackle technical and organizational challenges analogous to those in stockpile stewardship
- Maintain balance among disciplines, especially between science and computation
- Validate!

Accelerated Strategic Computing Initiative
Academic Strategic Alliances Program

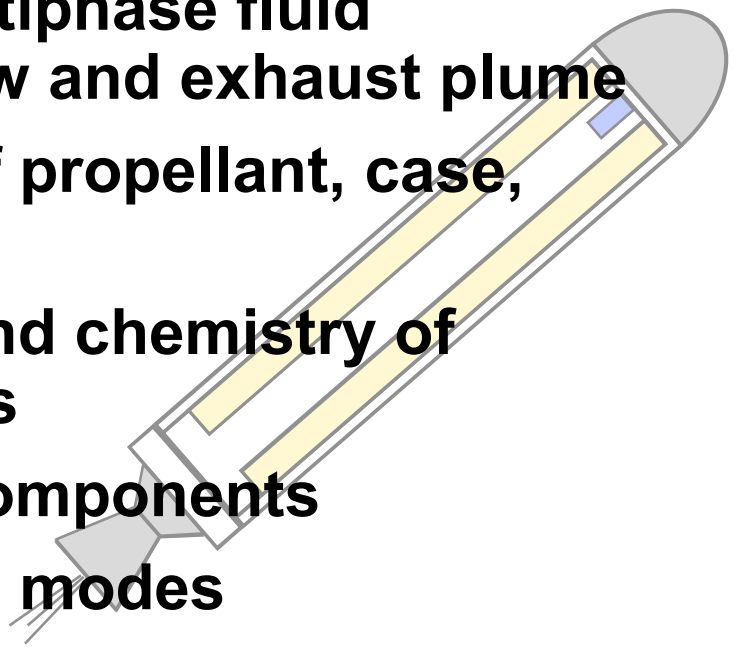
Goals

Overarching Goal: Full 3-D simulation of SP rockets from first principles

- Detailed, whole-system simulation of solid propellant rockets under normal and abnormal operating conditions
- Accurate models of physical components
- Subscale simulations of materials and accident scenarios
- Software framework to facilitate component integration
- Computational infrastructure to support large-scale simulations
- Research collaborations with government laboratories and rocket industry

Research Issues in Rocket Simulation

- Ignition and combustion of composite energetic materials
- Turbulent, reactive, multiphase fluid dynamics of interior flow and exhaust plume
- Structural mechanics of propellant, case, liner, and nozzle
- Fundamental physics and chemistry of materials and processes
- Aging and damage of components
- Various potential failure modes



Challenges in Rocket Simulation

- Full 3-D modeling essential to capture physics
- Strong, nonlinear coupling among components
- Complex, dynamically changing geometry
- Extremely diverse spatial and temporal scales
- Complex material properties and physical processes
- Enormous computational capacity required for high-resolution simulation of full burn
- Scalability to 1000s of processors essential

Multi-Scale Applications with Common Framework

Fluid-solid interaction with energy, mass, and momentum transfer across reactive, moving interface

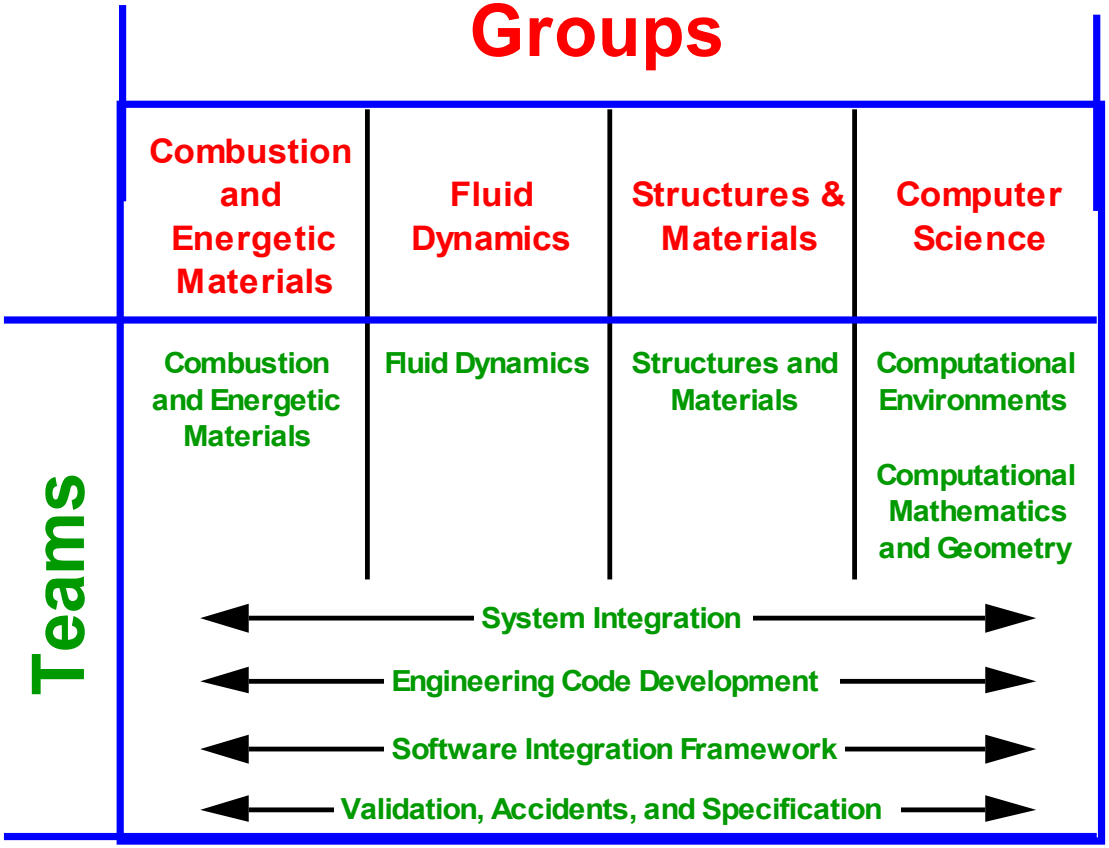
Phenomenon	Overall Scale	Resolution
Global response	10s of meters	cm
Crack propagation	meters	mm
Surface combustion	mm	micron

Organization

And

Technical Roadmap

CSAR Research Teams



Participating Units

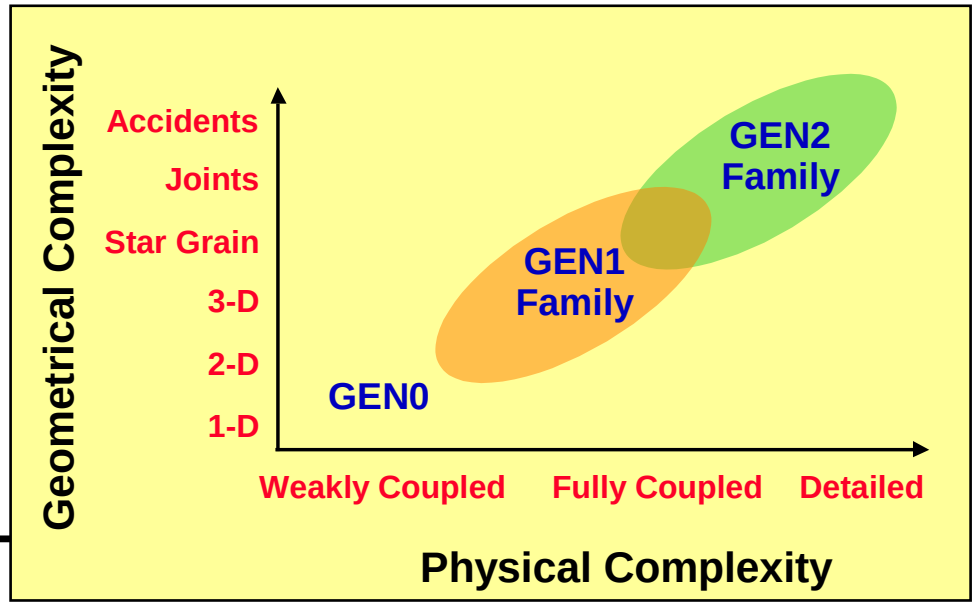
- Aeronautical and Astronautical Engr
- Astronomy
- Chemistry
- Civil and Environmental Engineering
- Computational Science and Engineering
- Computer Science
- Materials Science and Engineering
- Mechanical and Industrial Engineering
- NCSA
- Nuclear Engineering
- Physics
- Theoretical and Applied Mechanics

CSAR Staffing

	Current	Projected (FY02)
Senior investigators	40	40
Technical staff	30	32
Administrative staff	3	3
Graduate students	42	40
Undergraduate students	5	10
Total	120	125

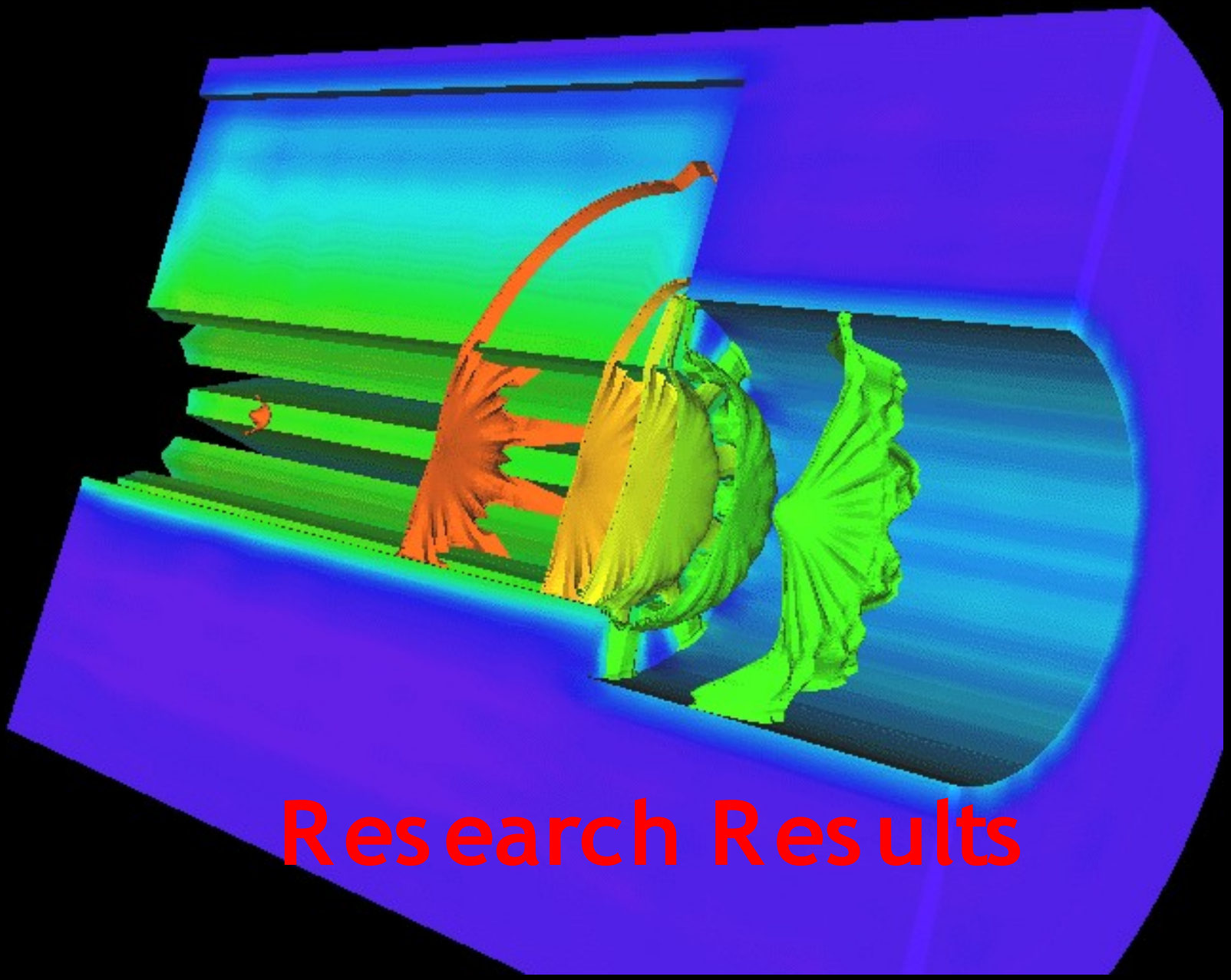
Staged Approach

- **GEN0:** system integration exercise
  - 2-D ideal rocket based on Space Shuttle parameters — completed 5/98



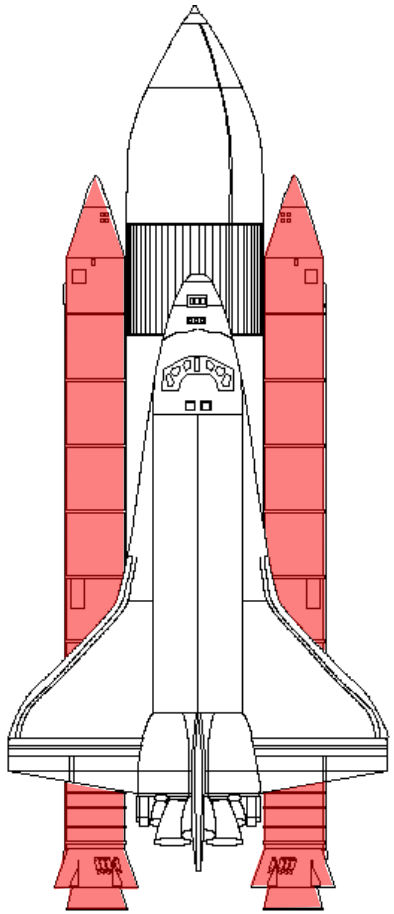
- **GEN1:** prototype 3-D whole-system simulation code
  - Basic component models
  - Full component interactions
  - Feedback for subsequent design — completed 1/01

- **GEN2:** fully capable rocket simulation tool
  - Detailed component models
  - Complex component interactions
  - Subscale simulations supported


Research Results

Initial Simulation Target: Space Shuttle RSRM

- Typical modern large solid rocket booster
- Height: 38 m, Diameter: 3.7 m
- Weight: 70 ton empty, 590 ton full
- Manufactured and shipped in four segments
- Aluminized ammonium perchlorate propellant
- Burns for 126 seconds, to altitude of 40 km and speed of 5000 km/h



11-point star at head end

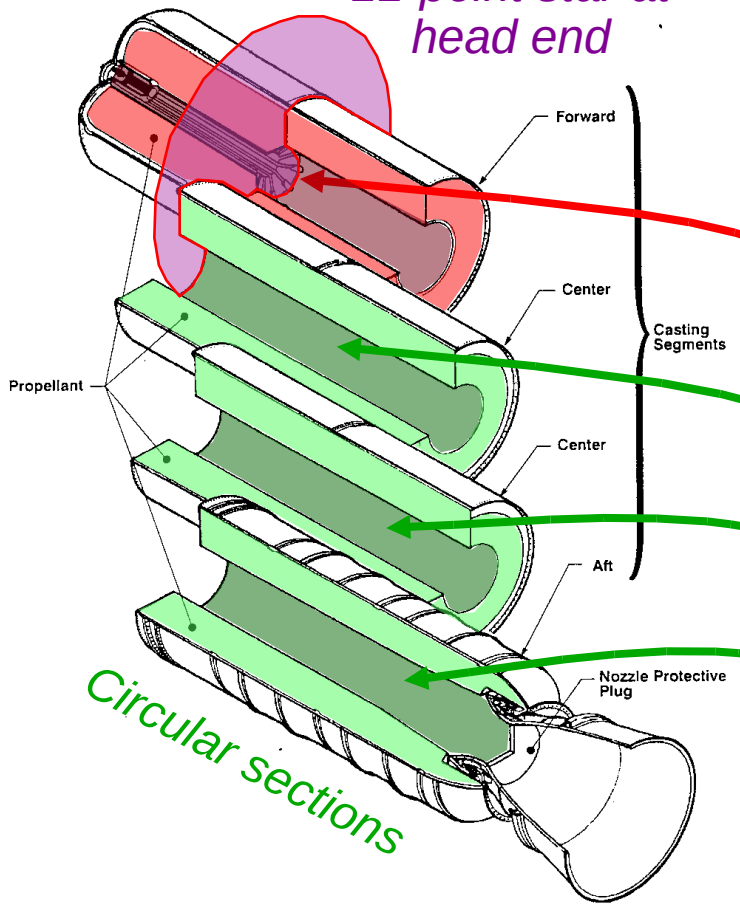


Figure 4.3-1. RSRM Propellant Configuration A036657aDDB

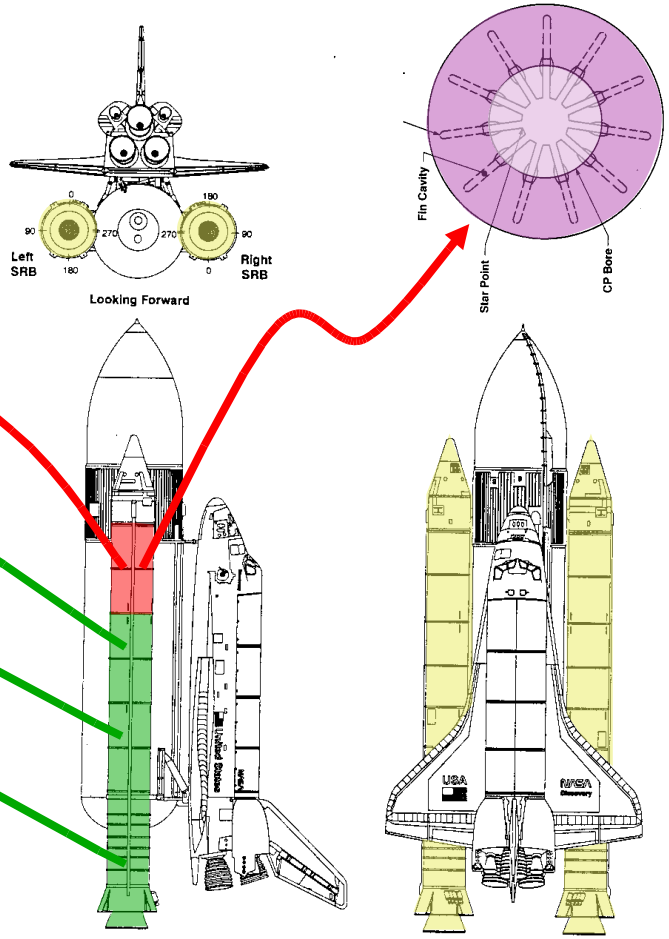
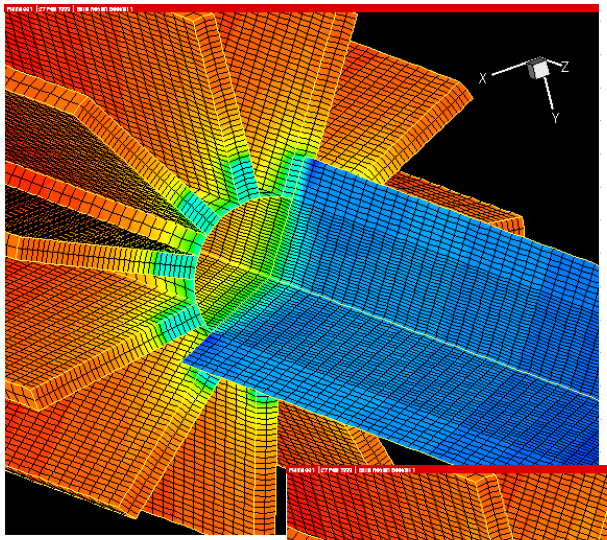
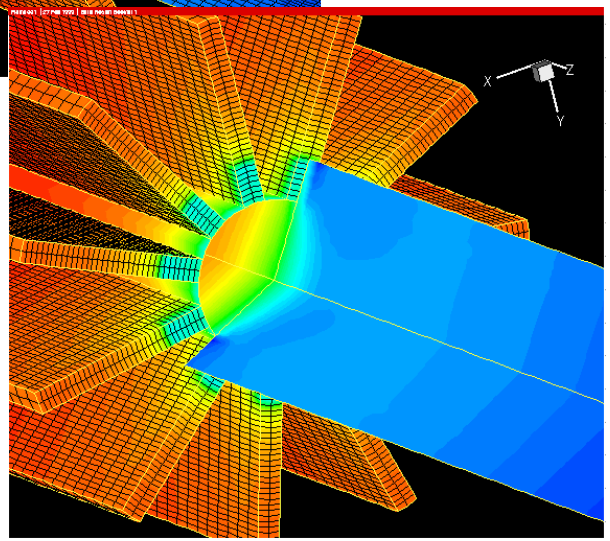
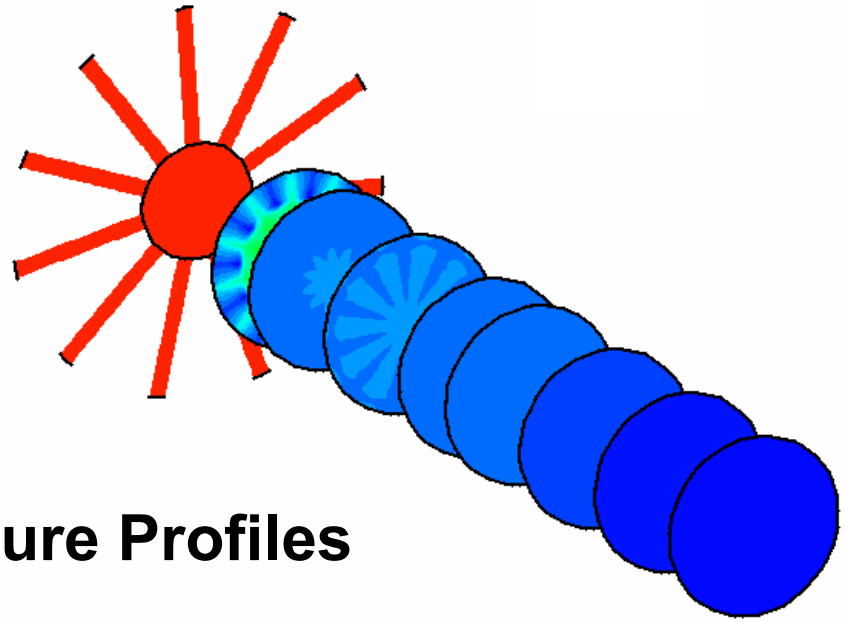


Figure 3.1-1. Boosters Attached to External Tank A038406a DDB

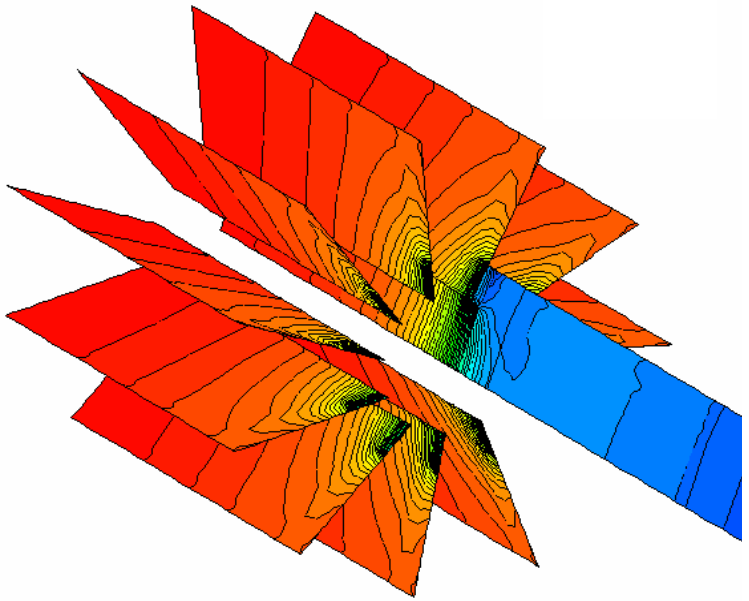
GEN1 Fluid Axial Profiles







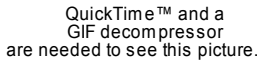
Pressure Profiles



Center for Simulation of Advanced Rockets

University of Illinois at Urbana-Champaign

GEN1 Integrated Results
Stresses in Solid — Pressure in Fluid

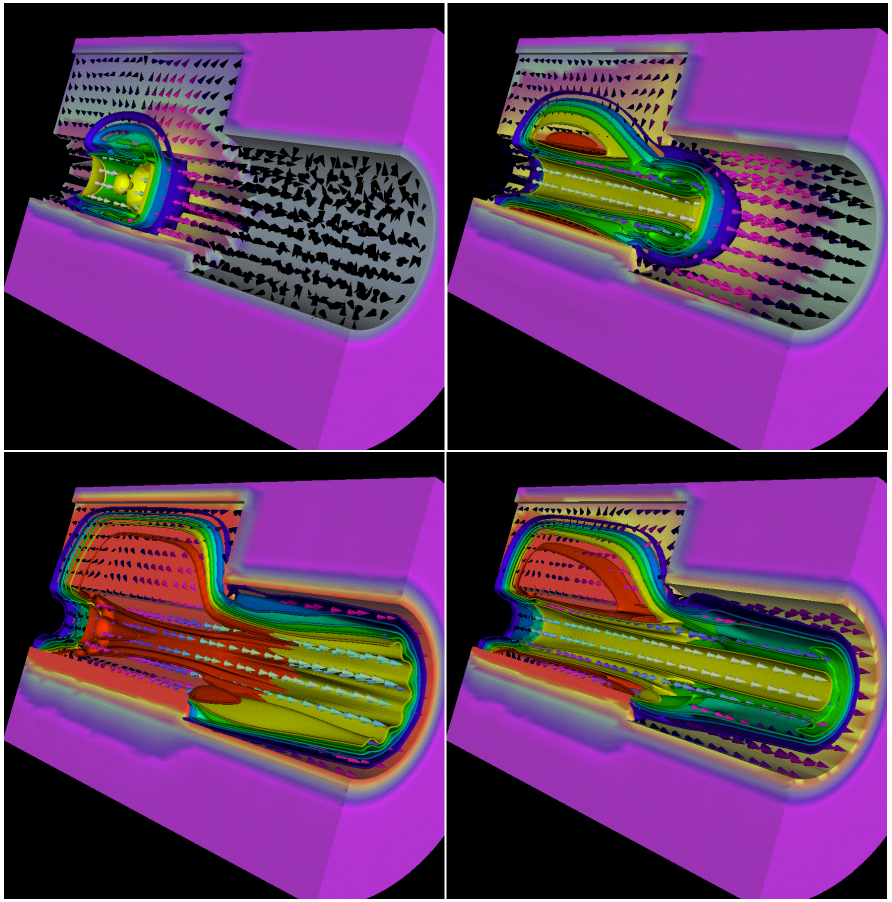


- Fully coupled 3-D simulation of star grain in Space Shuttle RSRM
- Stress in propellant and gas pressure isosurfaces in slots and core region
- Executed on 256-processor SGI Origin2000
- Visualized with CSAR *Rocketeer*

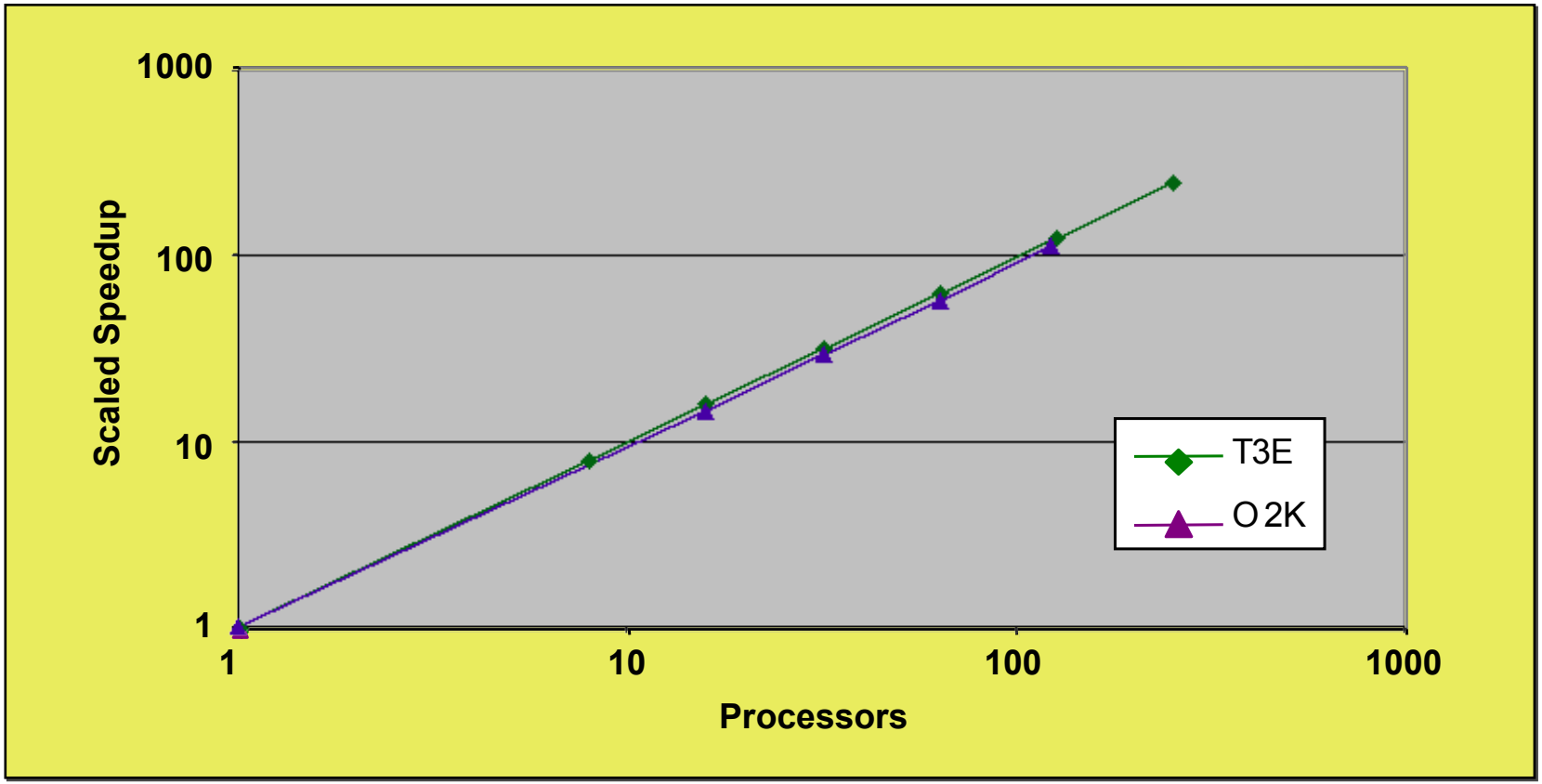
GEN1 Integrated Results

Ignition Transient with Velocity Vectors

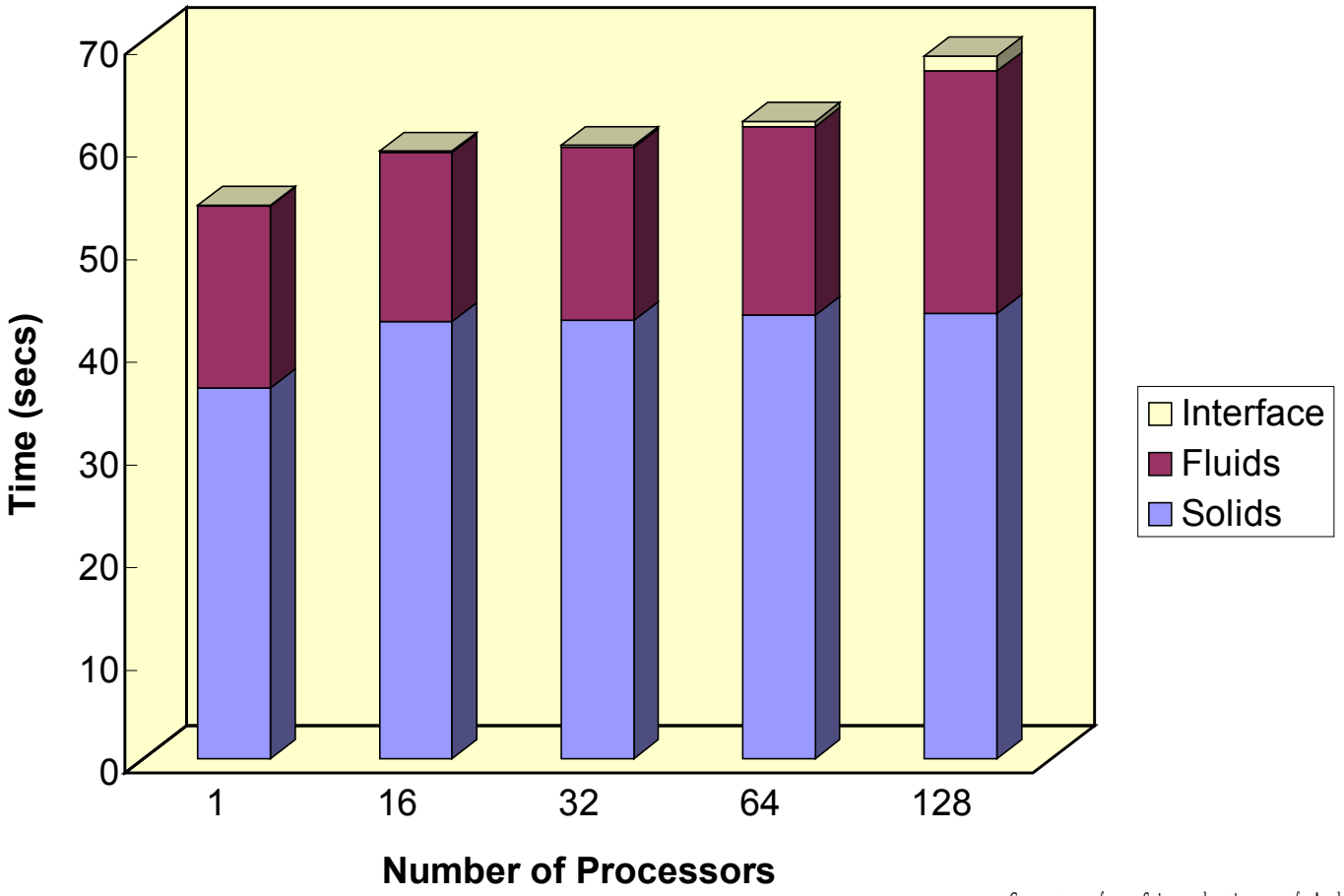
QuickTime™ and a
GIF decompressor
are needed to see this picture.



Scalability of GEN1 for RSRM Problem



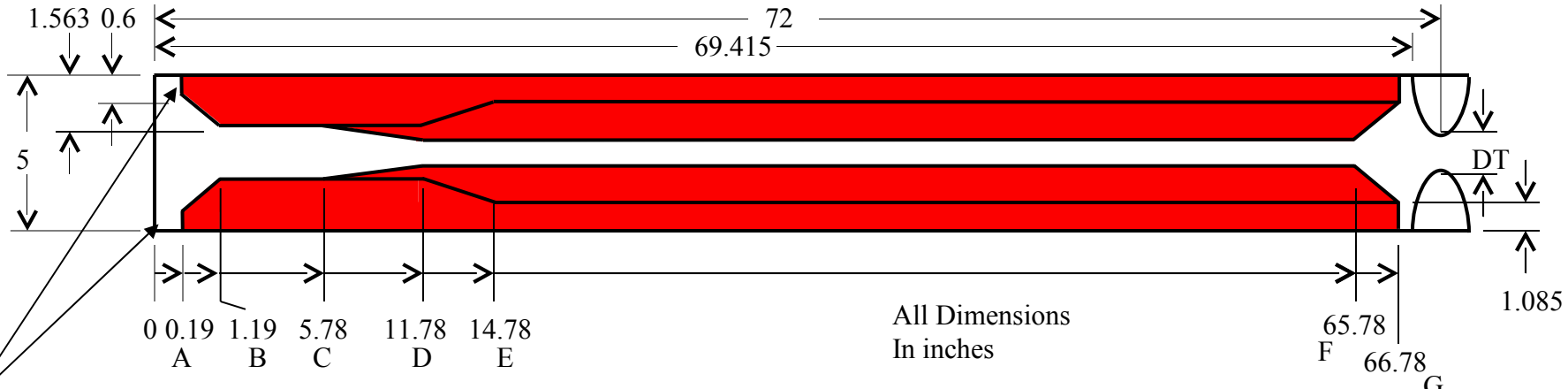
GEN1 Time Breakdown (SGI Origin)

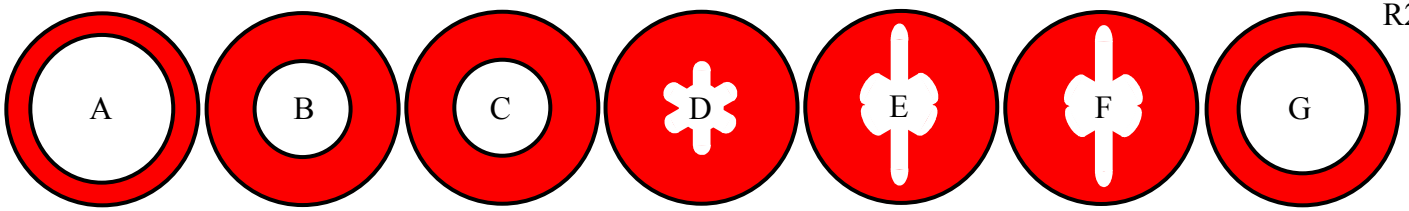


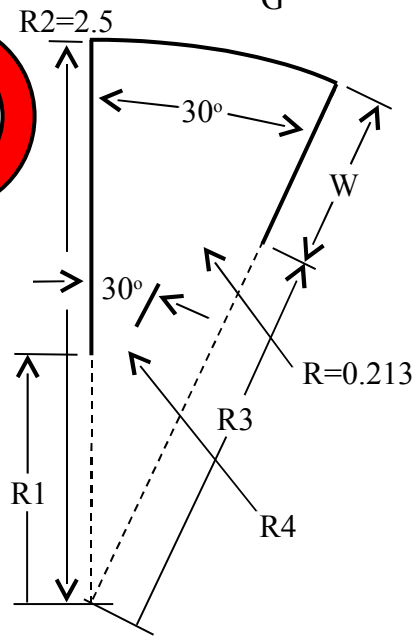
Verification and Validation

- **Component codes**
  - Standard test cases with known solutions
  - Data from laboratory experiments at UIUC and elsewhere
  - Lab-scale rockets (China Lake, Edwards)
- **Integrated codes**
  - Flat panel
  - AGARD wing
  - Shuttle inhibitors
  - Titan IV propellant slumping
  - Additional normal and accident scenarios for real rockets

Motor Geometry for Motors Nos. 1 and 2 (and 3 and 4) Referred to in AIAA Paper No. 98-3557







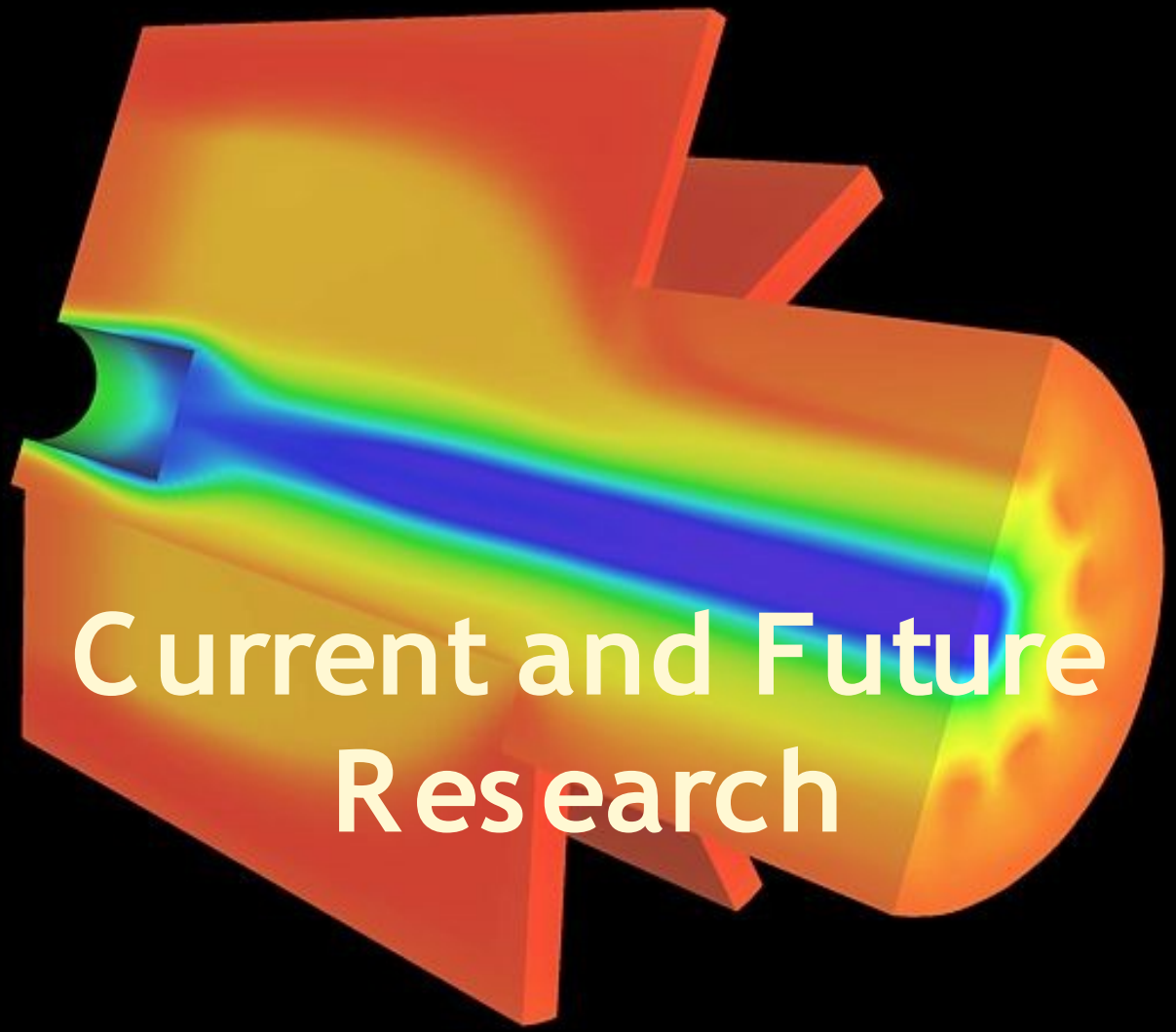
Forward End Face Inhibited, This gap was To allow the pulsers and instrumentation to be open to the chamber at all times

DT= 1.84” for Motor No. 1, 1000 psi
DT= 1.60” for Motor No. 2, 1500 psi

At station D the mandrel comes apart and is removed at each end

Station A: W=0.600, R1=1.900, R3=1.900
Station B: W=1.563, R1=0.937, R3=0.937
Station C: W=1.568, R1=0.932, R3=0.932
Station D: W=1.568 R1=0.618, R3=0.932, R4=0.192
Station E: W=1.133, R1=0.618, R3=1.367, R4=0.192
Station F: W=1.085, R1=0.620, R3=1.415, R4=0.194
Station G: W=1.085, R1=1.415, R3=1.415

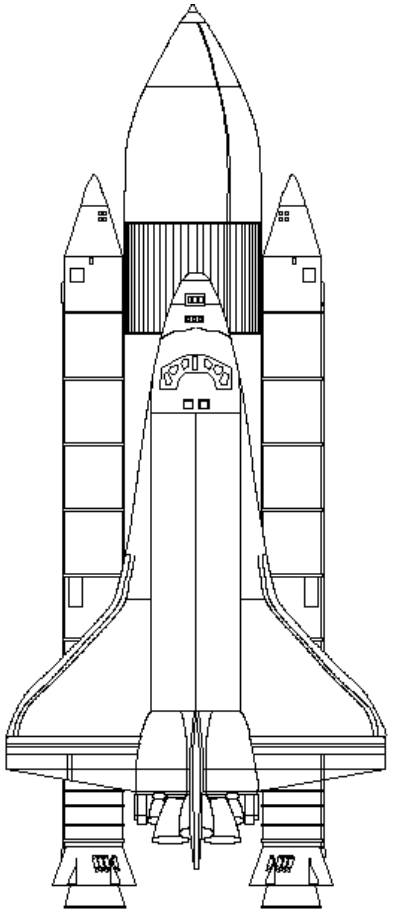
For any questions, please contact Fred Blomshield At 760-939-3650 or blomshieldf@navair.navy.mil



Current and Future Research

Goals for GEN2

- **Detailed full system simulations of solid propellant rockets**
  - Space Shuttle booster
  - Titan IV
  - Lab scale test motors
- **Keep run times reasonably short**
  - Bridge wide ranges of length and time scales
    - Homogenization of subscale models
    - Sequence of quasi-steady states
  - Advanced capabilities
    - Pressurized crack propagation
    - Joint failure
- **Complete project in ~2 year time frame**



GEN2 Roadmap

CASE & LINER

Thermo-elastoplastic

MTS model

PROPELLANT

Nonlinear thermo-viscoelastic

Heterogeneous, voids, dewetting

NOZZLE

Thermoelastic

Slag formation

IGNITER

2-phase turbulent inlet conditions

CORE FLOW

Improved model LES

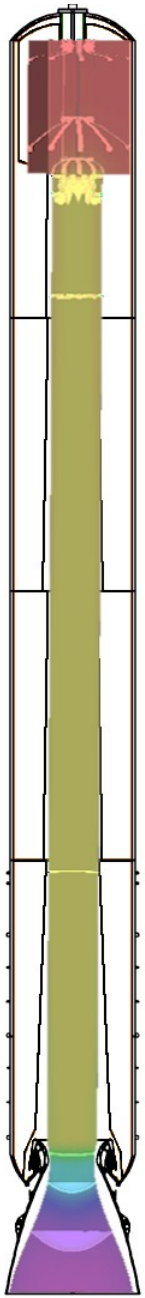
Al droplets, Al_2O_3 smoke

Radiation hydrodynamics

COMBUSTION

P, *T* dependent regression

Heterogeneous propellant burn

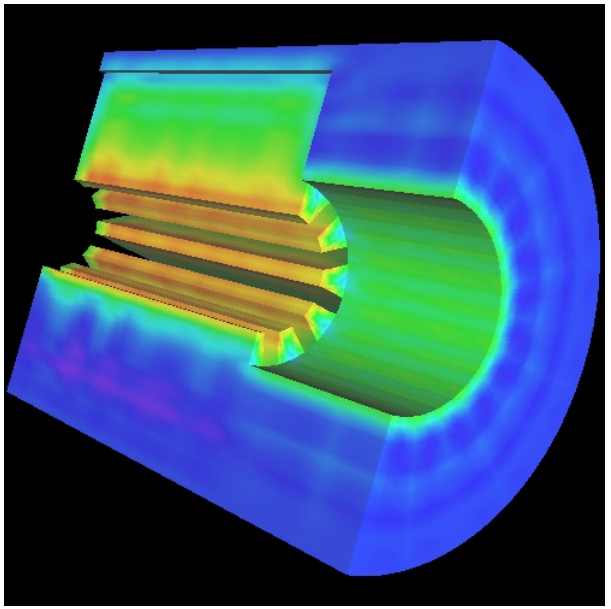


GEN2 Geometry

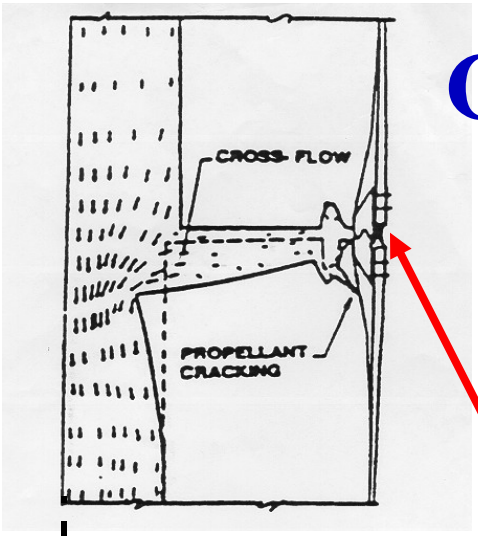
- **Whole system simulations**
  - Full 3-D, no symmetry
  - Star grain at head end
  - Joints
  - Inhibitors
  - Igniter
  - Submerged nozzle
- **Capabilities**
  - Crack propagation
  - Joint failure
  - Plume

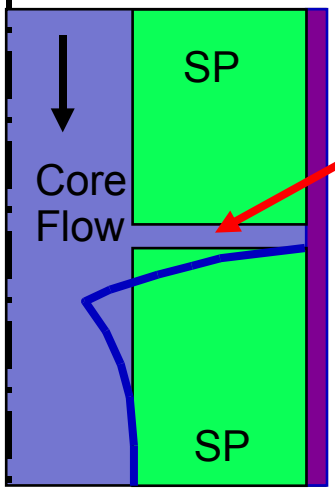
Structures & Materials

- **Physics (*Rocsolid* extensions)**
  - Large deformations
  - Materials in contact
  - Temperature throughout propellant
  - Material properties
    - Propellant: non-linear visco-elastic, heterogeneous
    - Case: Mechanical Threshold Stress model
- **Subscale models/capabilities**
  - Crack propagation (cohesive finite elements for solids, unstructured mesh for fluids)
  - Joint failure
  - Constitutive relations

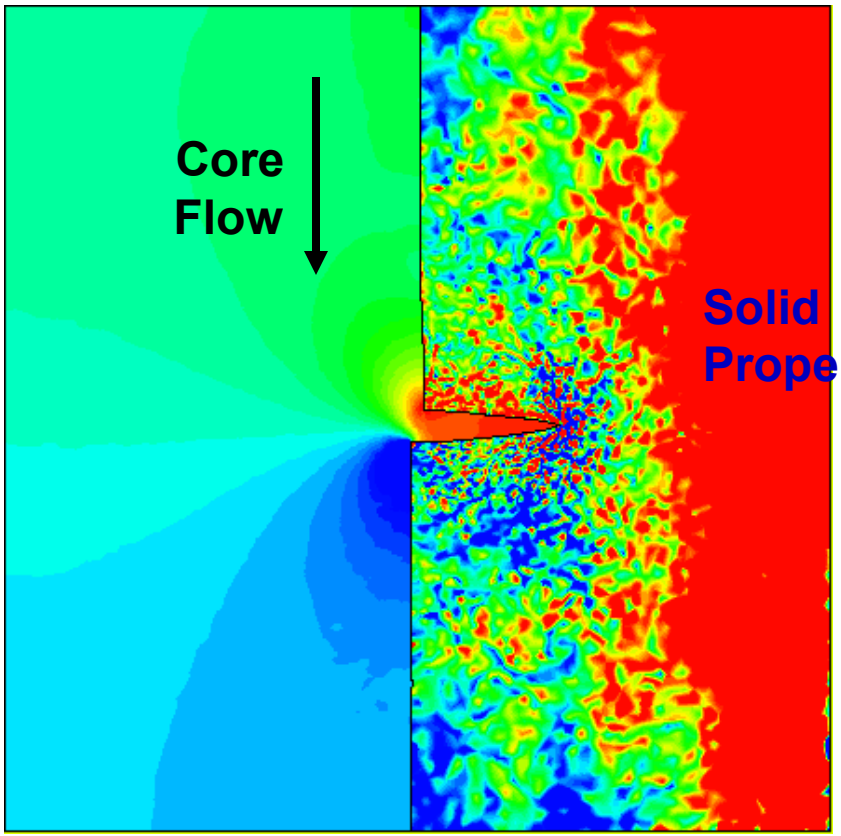


Simulation of Titan IV Grain Collapse Accident (1991)

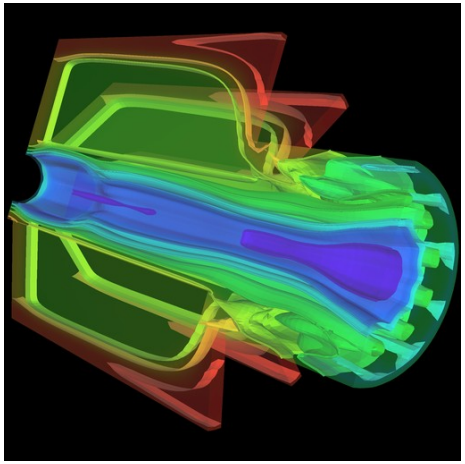




Grain Joint



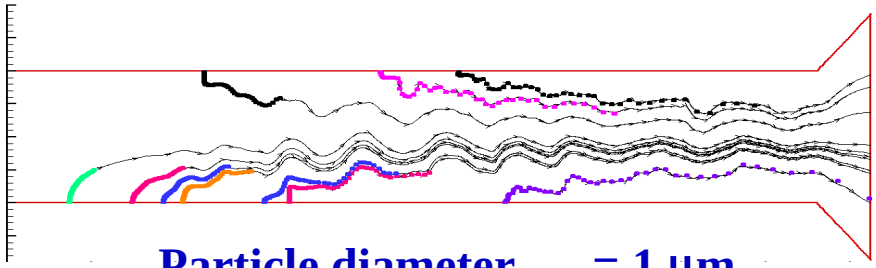
Fluid Dynamics



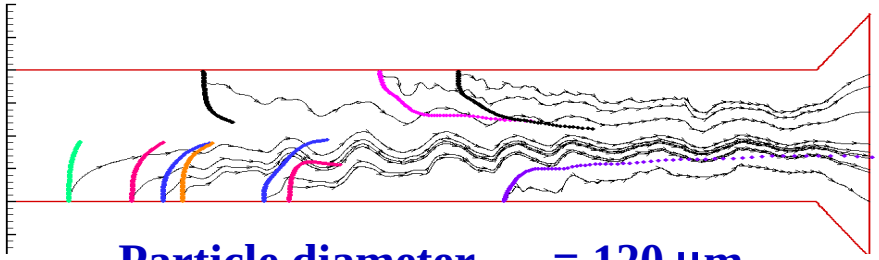
- **Physics (*Rocflo* extensions)**
  - Burning Al droplets (Lagrangian superparticles)
  - Al_2O_3 smoke (Fast Eulerian)
  - LES turbulence (higher spatial order?)
  - Radiation (diffusion, multigroup)
  - Slag formation
- **Subscale models/capabilities**
  - Crack propagation (Unstructured AMR)
  - Direct Numerical Simulation of turbulence
  - Chemical reactions
  - Plume

QuickTime™ and a
GIF decompressor
are needed to see this picture.

2-D Aluminum Particle Flows



Particle diameter$_{mean}$ = 1 μm



Particle diameter$_{mean}$ = 120 μm

QuickTime™ and a
BMP decompressor
are needed to see this picture.

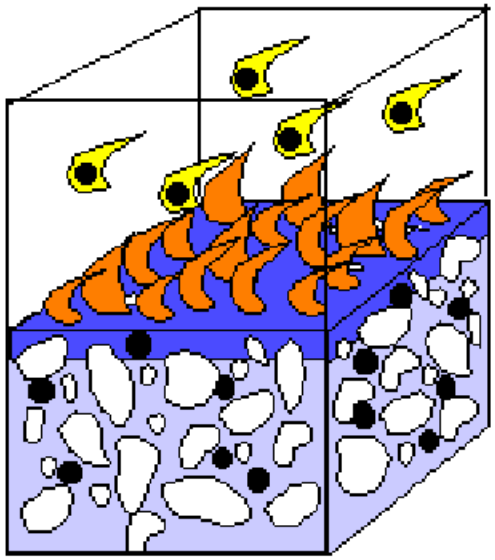
Particle diameter$_{mean}$ = 35 μm; t = 3.0ms

Aluminum Particle Flows

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Combustion & Energetic Materials

- **Physics (derived from subscale models)**
  - Unsteady burn rate
  - Burning Al droplets
  - Erosive burning
  - Heterogeneous propellant (rough surface)
  - Realistic reaction kinetics
  - Turbulent inlet boundary conditions (based on particle packing)
- **Subscale models/capabilities**
  - Combustion interface propagation (level sets, marker particles)
  - 1-D and 3-D flame models
  - Detailed reaction kinetics
  - Plume (chemistry, radiation)



2-D Model of Burning Propellant

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Research in Computer Science

- **Computational Mathematics and Geometry**
  - Linear solvers
  - Mesh generation and adaptation
  - Interface propagation and interpolation
- **Computational Environment**
  - Software integration framework
  - Parallel I/O and data migration
  - Performance tools and techniques
  - Computational steering
  - Visualization

Computer Science/System Integration

- **Algorithms**
  - Characterize/compare temporal coupling schemes
  - Multigrid method for non-symmetric syster
  - Mesh adjustment and adaptation
- **Software Integration Framework**
  - Library for communication, mesh association, interpolation
  - Coding style specification for MPI codes
  - Automatic conversion tools for adding modules
  - Flexible orchestration
  - Automatic load balancing (Charm++)
  - Interactive steering (Autopilot)
  - Performance monitoring (SvPablo)

Center for Simulation of Advanced Rockets

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http://www.csar.uiuc.edu

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