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IHPRPT Phase III
Solid Rocket Motor Modeling Program

Status of Advanced Boundary Layer Code Development for SRM Nozzle Ablation Including Two Phase Flow Effects (109-A0032)

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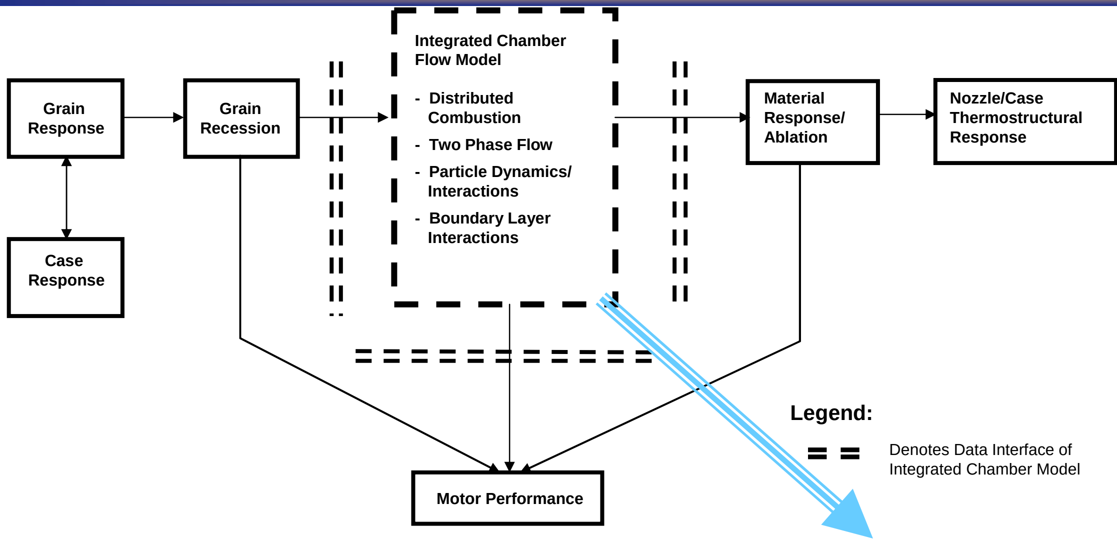
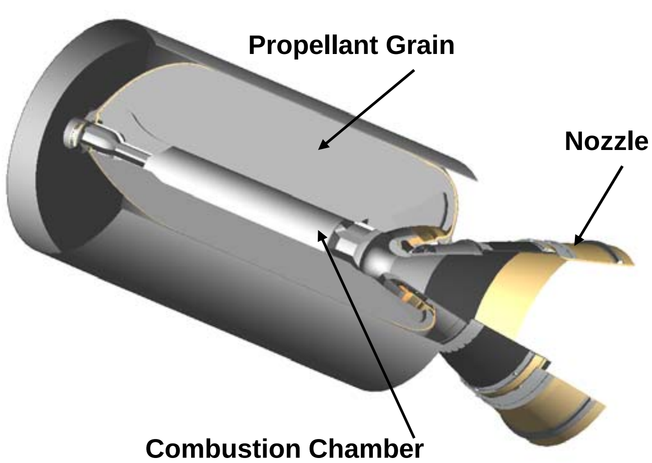
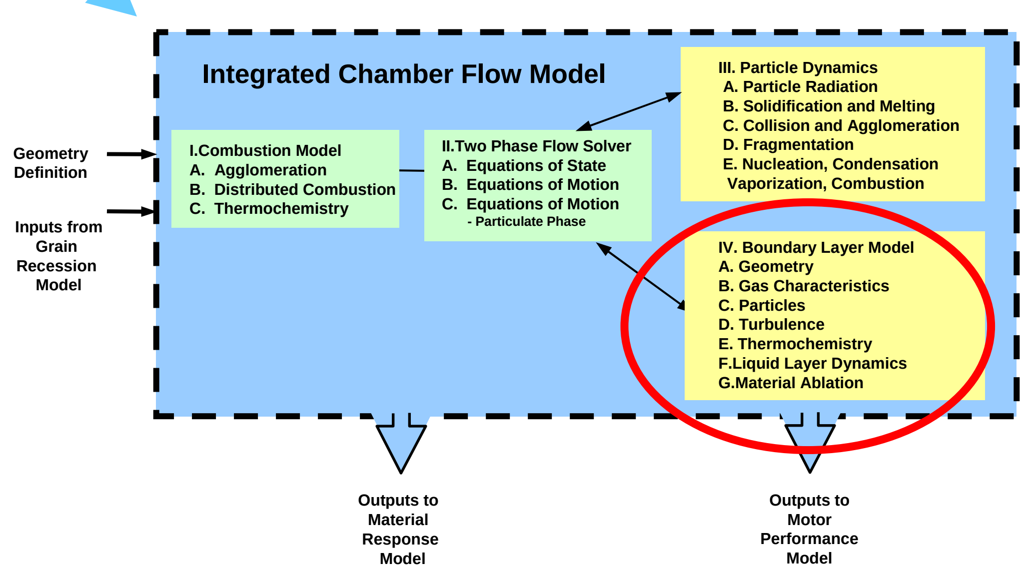
Aerojet Release No. 070-04

Air Force Release No. AFRLGRSPAS04-178

Overview & Flow of Solid Rocket Motor Analysis Activities

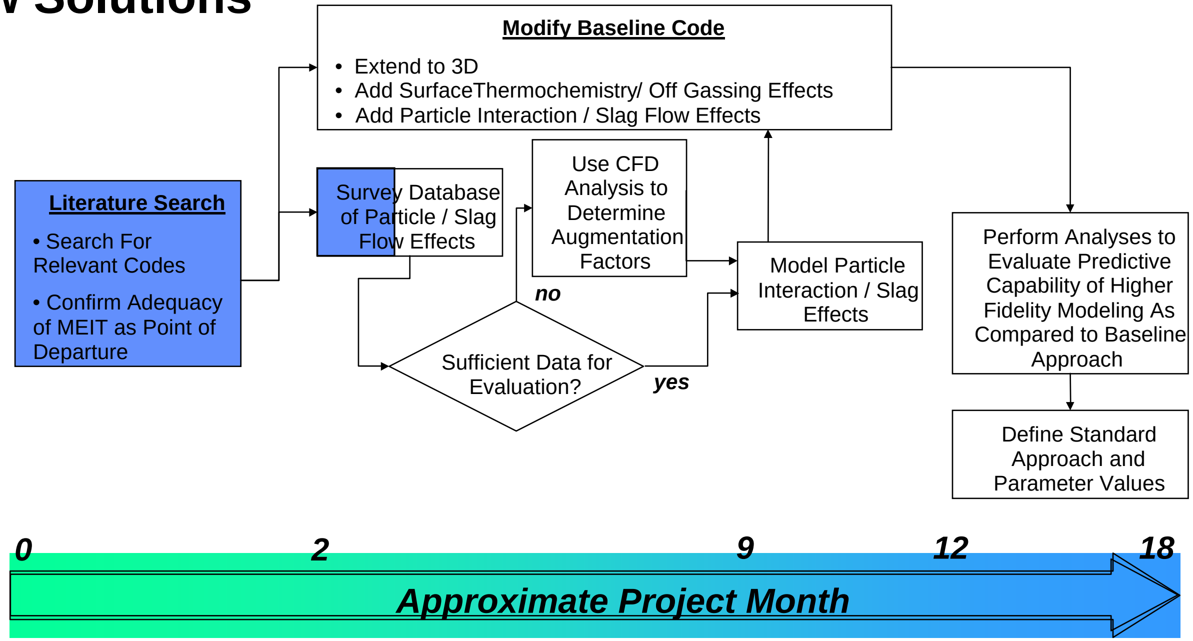




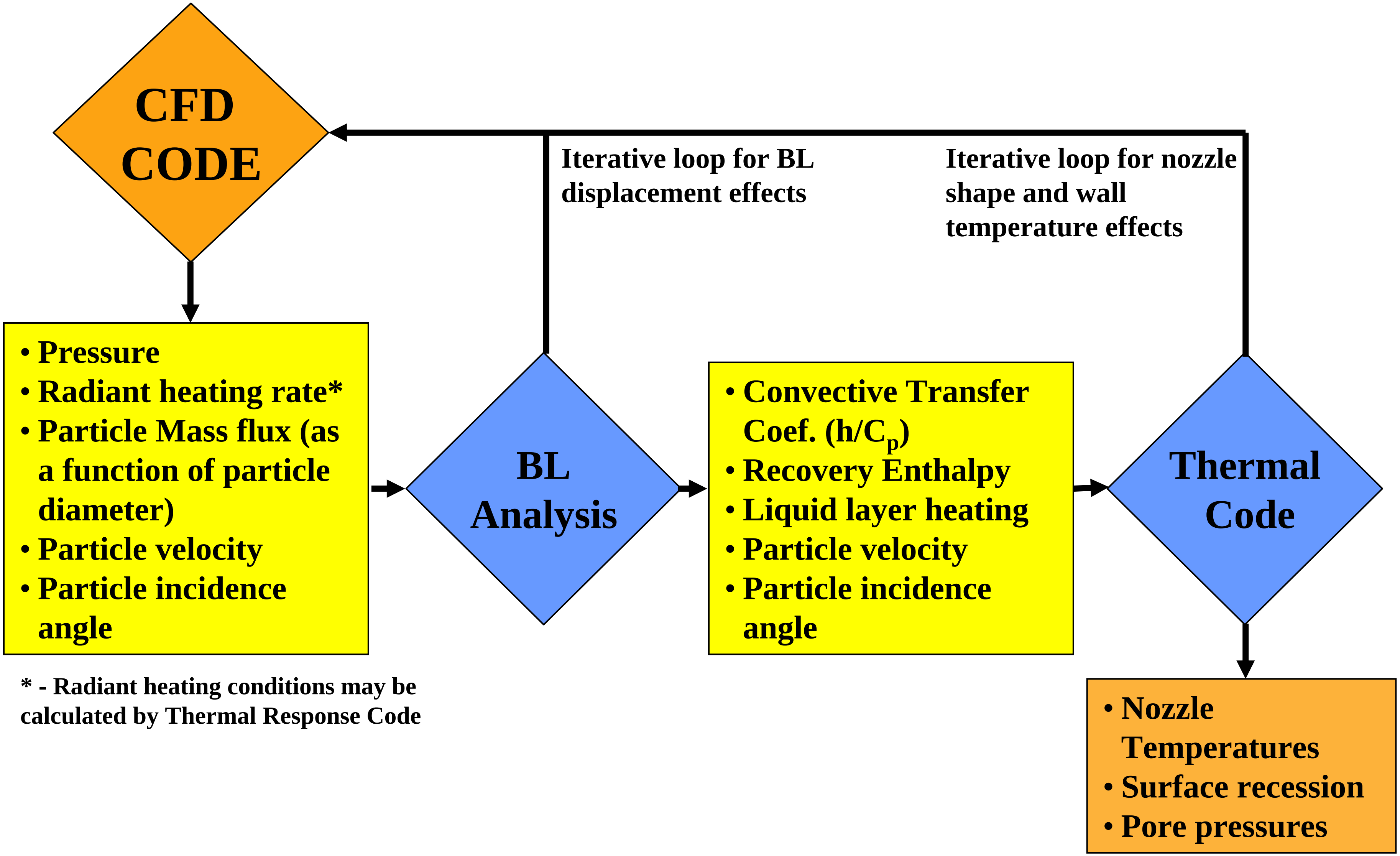


Boundary Layer Modeling Effort Summary

- **Improved Boundary Layer Module Under Development**
  - **Added Phenomena To Represent Physics Present in SRM's**
  - **Coupling With Improved Flow Models Adds Fidelity To Thermal Boundary Conditions**
  - **Coupling With Material Thermal Response Modeling Provides Accurate Wall Decomposition and Thermal Response And Returns Data For Further Flow Solutions**



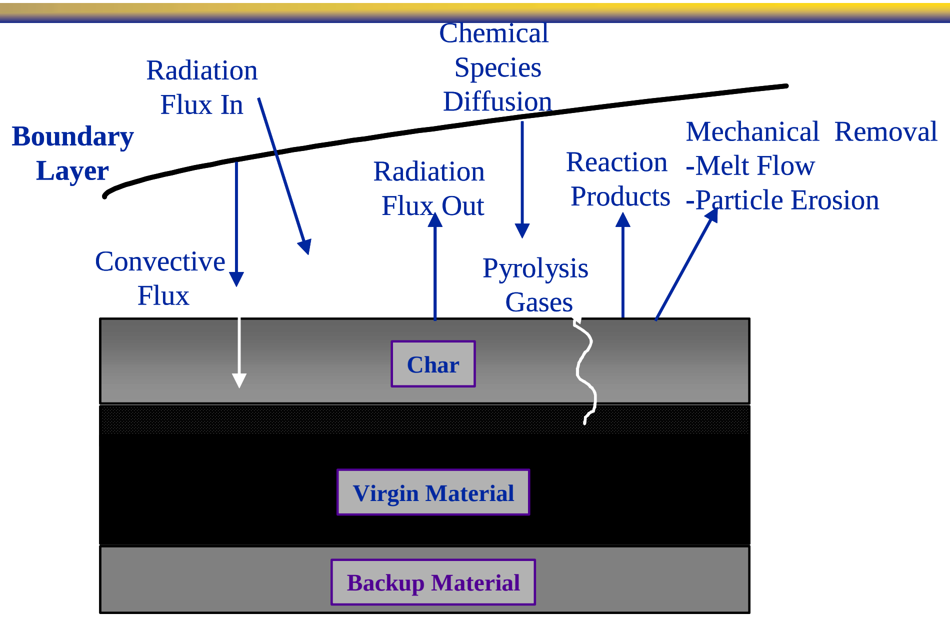
Coupling CFD And Thermal Response Models



* - Radiant heating conditions may be calculated by Thermal Response Code

Boundary Layer Modeling

- Boundary Layer Influences and Heat Transfer Mechanisms
  - **Radiation Heating**
  - **Convective heating**
  - **Material off gassing**
  - **Particle impingement**
  - **Liquid Slag flow**
  - **Combustion Gas Surface thermochemistry**
  - **Particle (Al/Al2O3) chemical reactions with insulation ablatives**
- Boundary Layer Calculations must be tightly coupled with both 2 phase flow and material response models to be effective.



- Description of Planned Work
  - **Develop Boundary Layer and Surface Heat Transfer Models that include dominant phenomena that cause nozzle heating and material ablation**

Comparison of Current and Proposed Boundary Layer Modeling

Analysis Type	Current Methodology	Proposed Modeling Solution
Flow Field	**1-D Isentropic Expansion** ***Bartz, Seider-Tate Heating, etc. Correlation***	**MAXS 2-Phase Flow Field Solution**
Thermo-Chemistry	**One Dimens. Equilibrium** ***SPP, ARCHEM, CEA***	**Distributed Combustion Chemistry**
Kinetic/Diffusion Through BL	**MEIT Boundary Layer Code**	**Finite Difference Code**
Particles	**Ignored** ***Heavy Gas Approximation***	***Particle Stirring***
Liquid Layer	**Ignored** ***Heavy Gas Approximation***	***N-S Film Boundary Layer***
Wall Conditions: **Local Recovery Temperature:** **Pyrolosis:** **Roughness**	**1-D Isentropic Expansion** **ACE/Gasket** **Roughness Ignored**	**Couple Flow Field/BL Solutions to CMA/ASTHMA Codes** **Modify ARCAST To Include New BL Model + Add'l Thermochemistry Input**
Chemical Reactions **Gas:** **Liquid:**	**Not Handled Explicitly** **Not Handled Explicitly**	**Include Aluminum Carbide Reactions If Present**

Dominant Erosion Phenomena

- **Surface recession of ablatives occurs due to three primary phenomena**
  - **<u>Thermochemical erosion</u> due to reactions with the hot gas products. The amount of the material removal is controlled by the gas species and mass transfer conditions**
    - **Equilibrium reactions are predicted by the ACE code**
    - **Materials for which kinetically controlled reactions are important (e.g., carbon/carbon, graphites, etc.) are predicted with the GASKET code**
  - **<u>Mechanical erosion</u> occurs where particles impact on nozzle surfaces and the impact energy can result in removal of the outer regions of the nozzle surface.**
    - **G-law models are available from the PIE program to predict this phenomena**
    - **This phenomena is strongly dependent on the particle velocity, mass and impact angle**

Dominant Erosion Phenomena

- **Surface recession of ablatives occurs due to three primary phenomena**
  - **<u>Chemical erosion</u> of particles occurs when the molten particles chemically react with the nozzle materials and the resulting reactants are removed in the gaseous state or are readily swept away by the shear forces of the gas flow.**
    - **This phenomena has been observed in various ground motor tests conducted by AFRL**
    - **Furnace tests conducted under the PIE program substantiated these reactions**
    - **Arcjet testing in the PIE program was conducted to develop a preliminary model of this phenomena, but was done in an inert envionment (i.e, the absence of H_2O which might act as a catalyst)**

Boundary Layer Modeling Plan

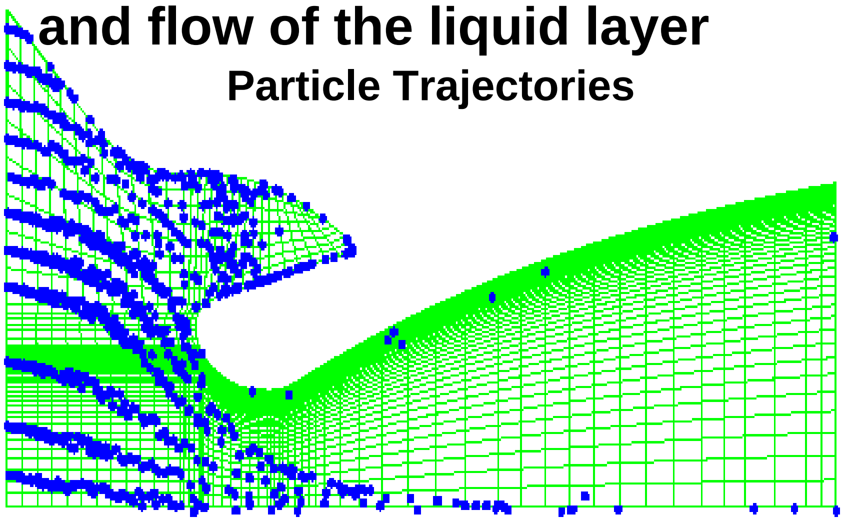
- **Boundary layer development plan intended to provide growth path from simple to complex:**
  - Develop Near Term Working Models, With Growth to More Complex Models in the Future As Computational Capabilities Improve
  - Integrate MEIT to Interface with Two Phase CFD Flow and Material Response Models
    - (Simplified Model) - 5-10% of effort
  - Develop Finite Difference Boundary Layer Solution Approach with Two Phase Flow Effects
    - (Engineering Model) - 60-80% of effort
  - Evaluate CFD Integrated Solution With Interface to Surface Thermochemistry and Material Response Models
    - (Research Model) - 15-20% of effort

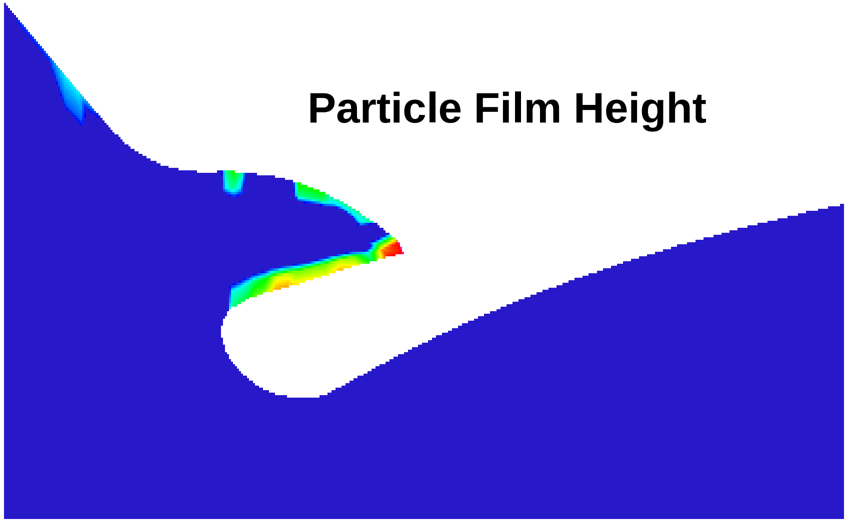
Liquid Layer Model Evaluation

Three approaches to modeling the liquid layer are being considered:

- Particle film model
- Integral model
- Thermal solver with simplified liquid layer assumptions

The MNASA motor firing case is being used to model the impact and flow of the liquid layer





Chemical Erosion due to Particles

- As part of the PIE program, carbon reactions with both pure aluminum and alumina (Al_2O_3) were found to occur. These tests were conducted in an inert environment. Carbide (Al_4C_3) is produced in the reaction with alumina. This carbide can be readily swept away by the shear forces of the hot gases
- $Al_2O_3 + C \rightarrow [\ Al_4C_3 - Al_2O_3]$ (slag) + [CO-Al_2O-Al](gas)
- Other testing suggests that H_2O may act as a catalyst in these reactions
- Analysis and testing are needed to understand and quantify this phenomena

Particle Impact Erosion Experiments

- **Erosion experiments conducted in Aerotherm arc plasma generator**
  - Gas, particle, and test specimen temperatures were representative of nozzle entrance section
  - Nitrogen gas to eliminate thermochemical ablation
  - G-90 Graphite
  - Surface temperature of 5000 ºR
  - Carbon (non reactive), aluminum, and alumina particle types
- **Methods developed under the PIE program attribute the increased erosion in nozzle entrance regions to mechanical and chemical attack of the alumina and aluminum particulates**
- **Procedures yielded good comparisons to test data from IUS, and MNASA motors.**

Modeling Procedures

- CMAE code developed to predict erosion of nozzle entrance regions
  - Special version of Aerotherm's CMA computer code
  - Calculates particle erosion due to impacts of both alumina and aluminum particles
  - Erosion occurs due to themochemical (gas reactions) and particle (mechanical and chemical) erosion
  - Surface energy balance methods of CMA used to calculate surface recession
  - Total erosion taken as the sum of the three components

MNASA 48” Baseline Comparison

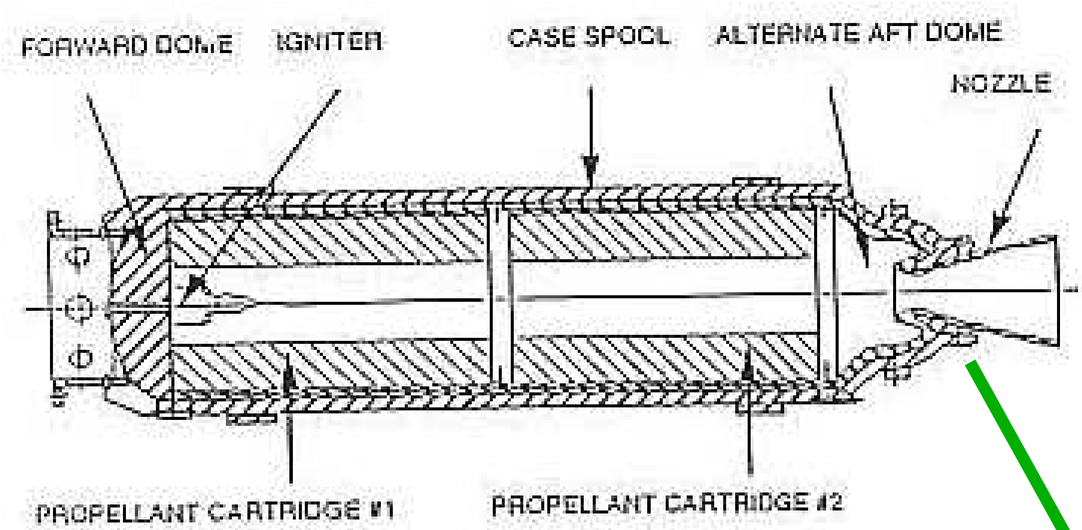
- **IHPRPT Tools Will Be Incrementally Applied To MNASA Analysis**
- **MNASA Motor Analysis Approach:**
  - **Repeat ITT Effort From 1991 To Use As Baseline Comparison**
  - **Include G-Law Relationship In Aerojet ARCAST Code**
    - **Re-run MNASA analysis using 2-D Axisymmetric ARCAST model for thermal response of the nozzle**
  - **Replace NAT Code With MAXS CFD Code**
    - **Re-run 2-D ARCAST model using MAXS inputs to boundary layer Model**
  - **Replace the MEIT boundary layer with finite difference boundary layer model under development**

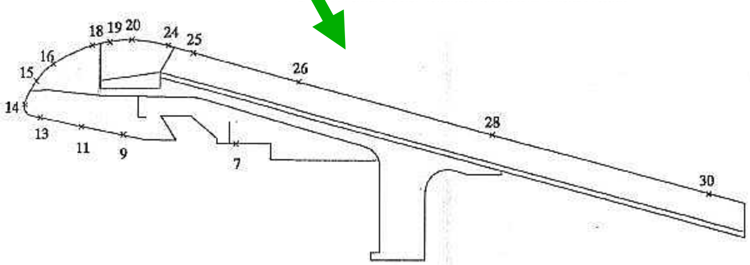
MNASA MOTOR

- MNASA motors were fired in the early 1990's to support the ASRM program development
- 48" diameter CP grain
  - ASRM Propellant
  - Configurations included blast tube and no blast tube
    - blast tube configurations provided a test section for internal insulation development
- Large body of data exists on MNASA motors
  - Prior modeling efforts by industry and NASA provide comparative baseline

MNASA Modeling Experience

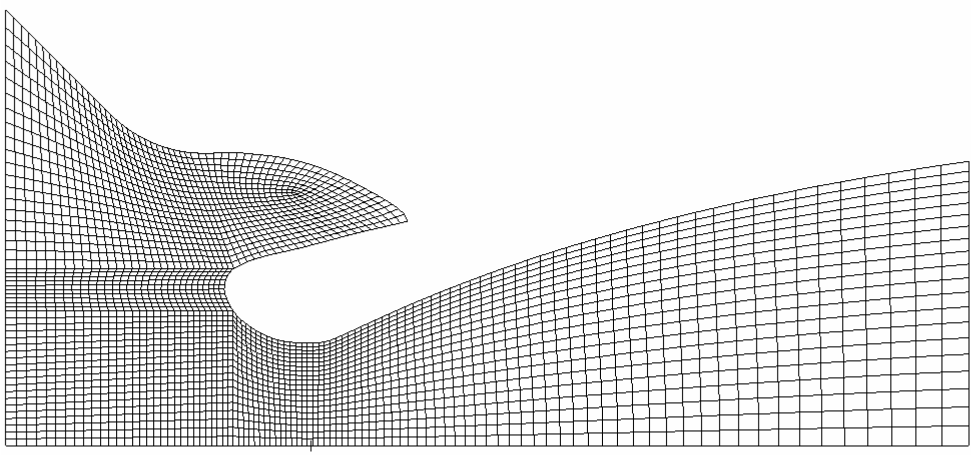
- **Prior analyses of MNASA Motor provide useful benchmarking of SOTA codes from early 1990's**





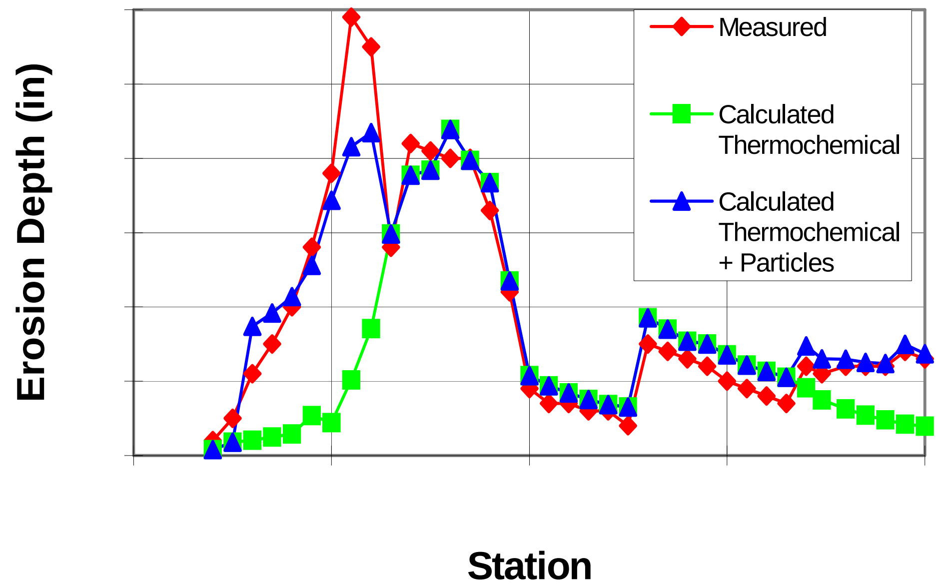
1990's MNASA Modeling Summary

- Model domain includes the aft-dome and nozzle.
- Uniform reservoir inlet boundary condition entering the domain.
- Converged flow solution seeded with particles.
- Data passed from CFD to the MEIT code at the boundary includes:
  - Pressure
  - Velocity
  - Temperature
  - Density
  - Enthalpy

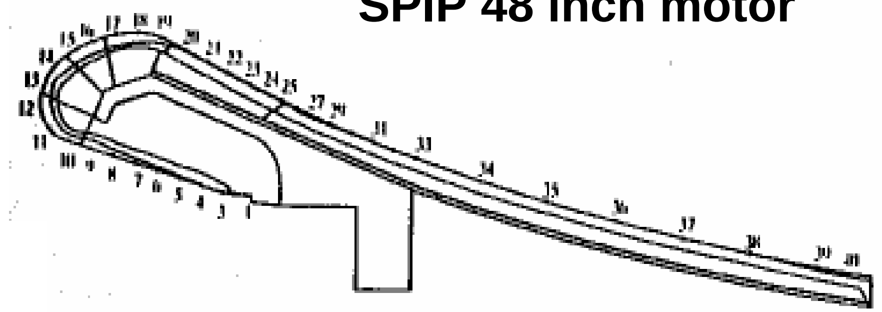


Application of PIE Erosion Models To MNASA Analysis

- **ITT Aerotherm Modeled MNASA 48-5 In 1991**
- **Erosion of MNASA motor was calculated with and without particle erosion models**
- **Nozzle AeroThermochemistry (NAT) computer code used to calculate nozzle flowfields, including particle impingement locations and conditions**
- **MEIT used to calculate boundary layer heating**
- **CMAE used to calculate nozzle erosion**
- **Good agreement with the data was obtained**



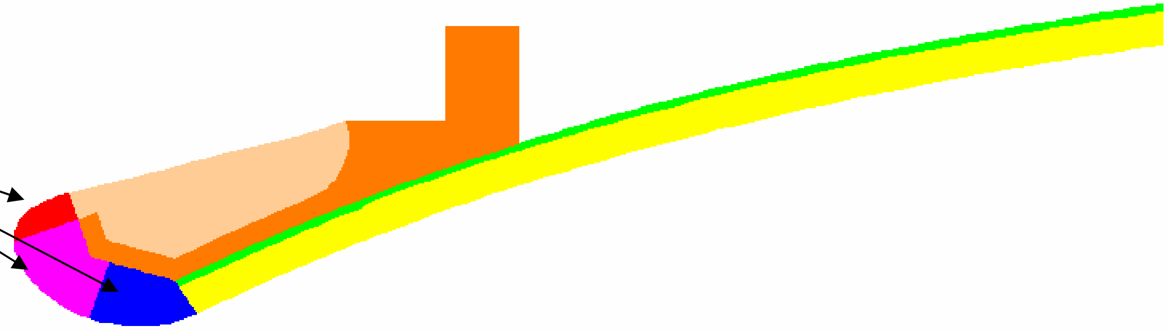
Measured Erosion Locations SPIP 48 inch motor



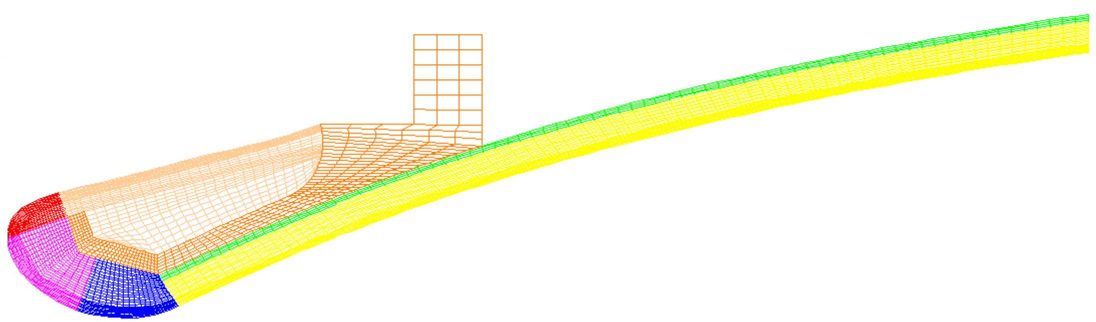
MNASA ARCAST Modeling

ARCAST allows extension of 1-D CMAE material response to 2-D axisymmetric analysis

Nosecap Material Angle Modeled for Each Component

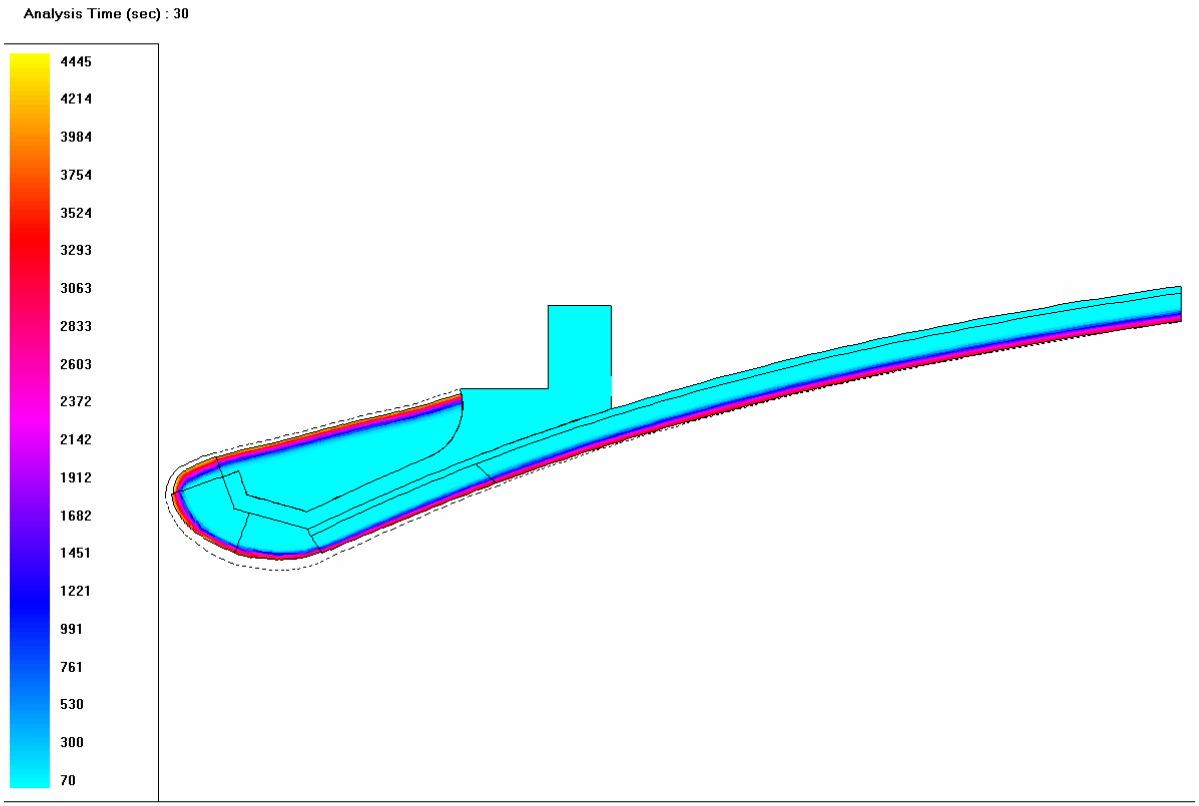


ARCAST Model Consists of ~4700 Elements



Preliminary 2-D MNASA Results

- **Preliminary results end of burn profile shows good agreement at throat and exit cone**
- **Modification to ARCAST in work to include G-Law to improve nosecap and submerged region correlation**



Extended Analysis: MaxS/ARCAST

- This analysis task will extend the modeled domain upstream to include the chamber and burning surfaces.
- This will allow us to model various particle sizes as they leave the burning surface and track them through the flow field eliminating the assumption of a uniform inlet to the domain with a uniform particle distribution.
- Two tested MNASA chamber geometries of interest that will lead to very different aft end flow field results:
  - Close proximity of the grain to the aft dome.
  - Long blast tube with the grain much further upstream.
- Various burn back conditions may then be modeled allowing the distribution of the particles to change as the grain regresses.
- Modeling of various time steps will require a coupling from ARCAST back into MaxS to alter the insulation surface geometry as it ablates over time.

Current Activities

- **Literature searches will be conducted to aid in quantifying the reactions of carbon with Al_2O_3 and Al**
- **Equilibrium thermochemistry calculations for comparison to the PIE data. Calculations will be conducted for Al_2O_3 and Al impacting carbon. Comparsions will be made with and without the presence of H_2O.**
- **A test methodology/series will be formulated to investigate and quantify these reactions and the effect of H_2O**