Rapid Prediction of Aftbody Nozzle Performance in SCCREAM
AIAA-2002-3650

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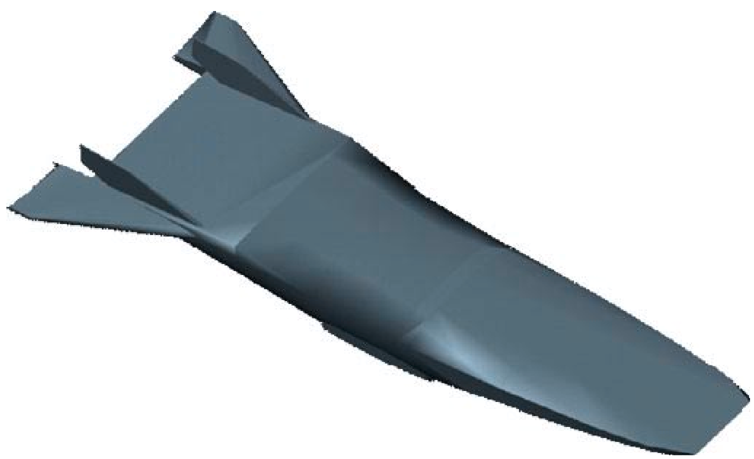
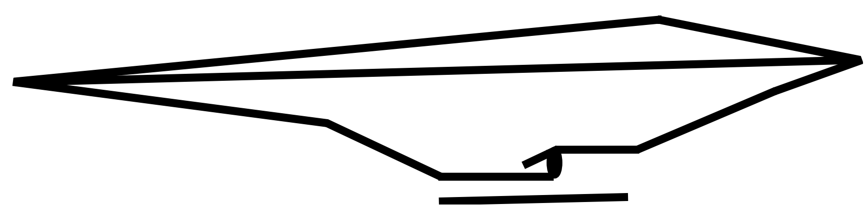
Objective

- Allow improved performance predictions for A/B and RBCC engines in conceptual-level vehicle design.
- Enable capability of optimizing complete vehicle engine/airframe flowpath.
- Allow for static stability vehicle analysis in trajectory simulations.





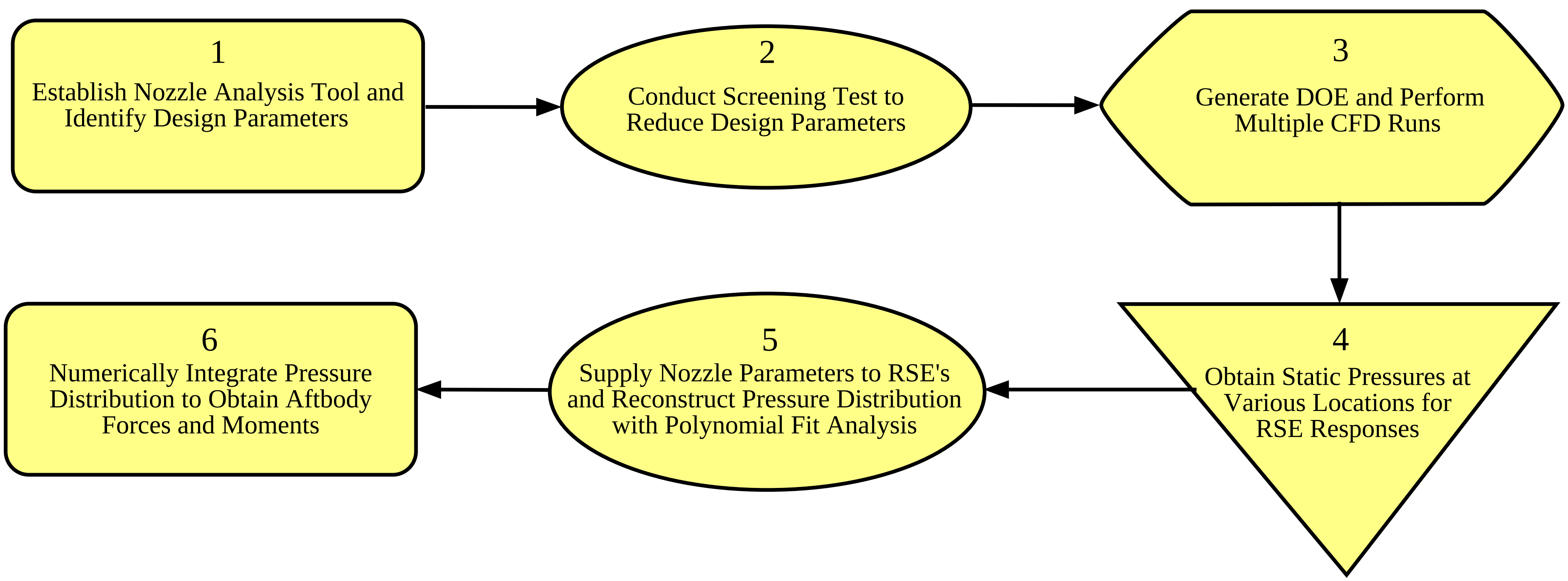
Approach

- **Create a meta-model of the aftbody flowfield**
  - **Input parameters:**
    - **Engine exit flow properties, freestream conditions, and nozzle geometry**
  - **Output parameters:**
    - **Pressure ratios at select axial locations**
  - **Use predicted pressure ratios to reconstruct complete pressure distribution at any axial location**
  - **Integrate distribution to obtain forces and moments**

- **Incorporate meta-model into *SCCREAM* analysis tool**
  - **Already capable of optimizing forebody and internal flowpath**

Note: Current approach is only focusing on supersonic flight condition cases with an underexpanded nozzle.

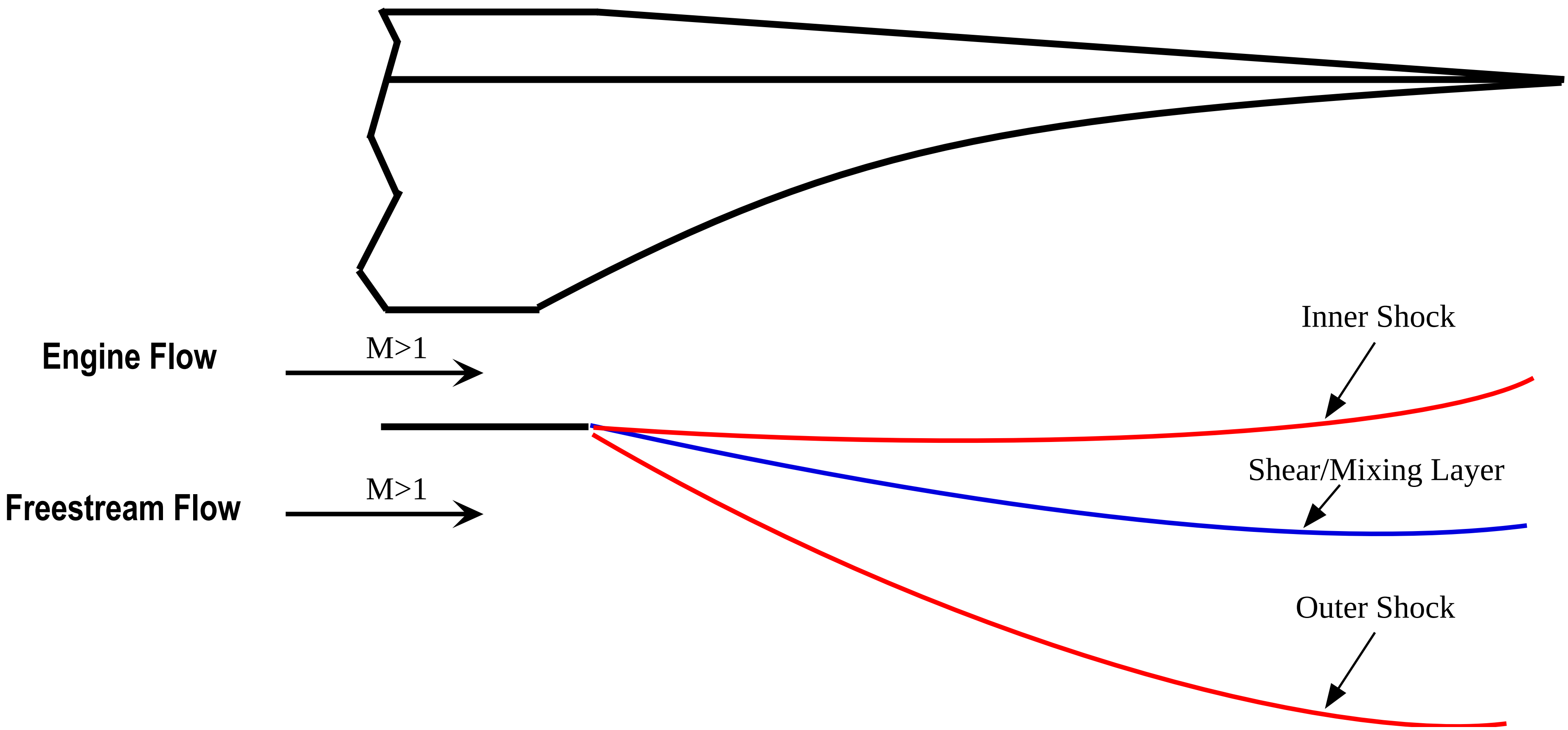
Meta-Model Generation



- **Meta-model of choice is Response Surface Equation (RSE)**
- **Steps 2-4 constitute Response Surface Methodology (RSM)**
- **Step 5 uses 5^{th} order polynomial w/ weighted least squares analysis**

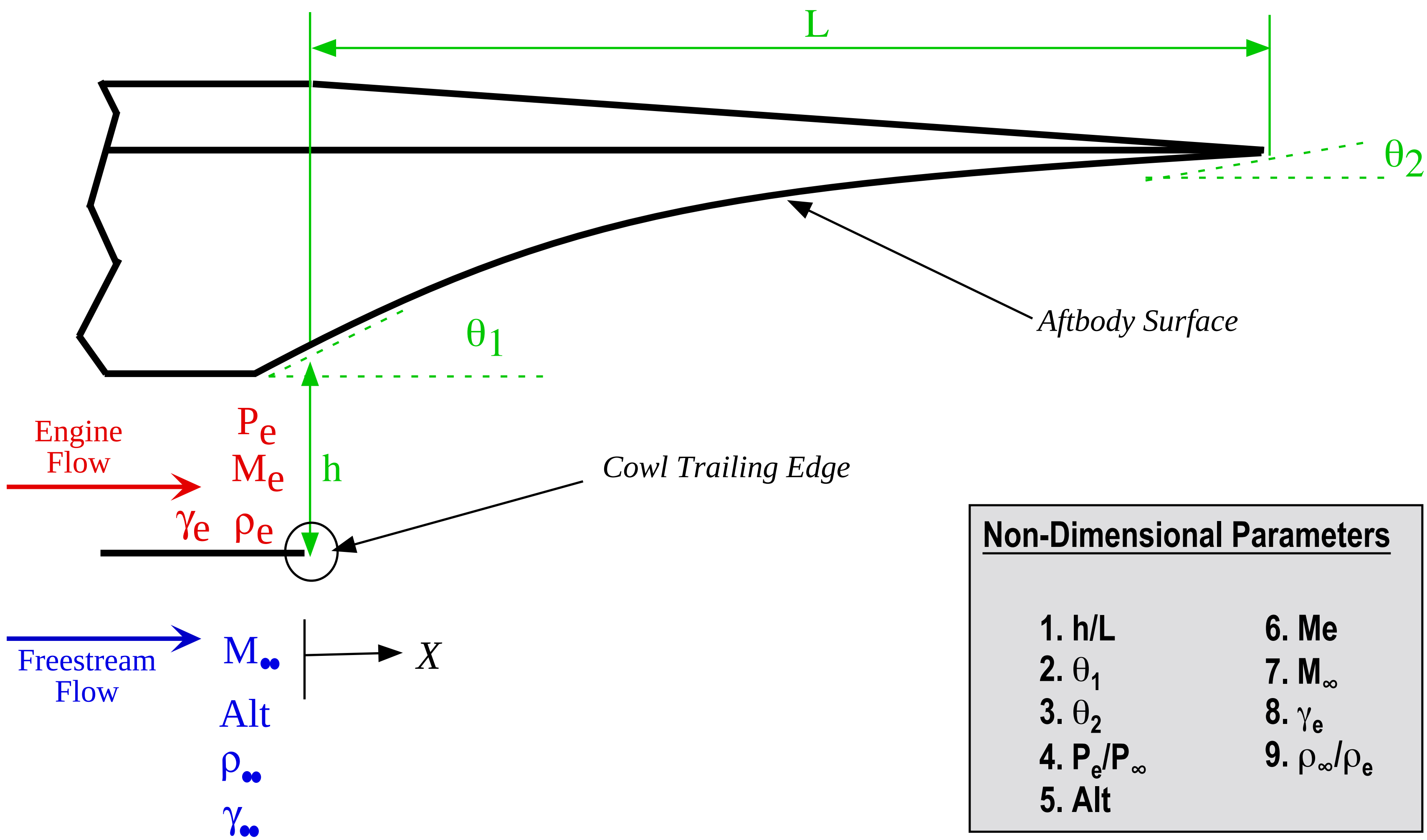
Aftbody Model

Flowfield Features



- Supersonic engine exit and freestream flows
- Underexpanded engine exhaust flow

Aftbody Nozzle Model and Variables



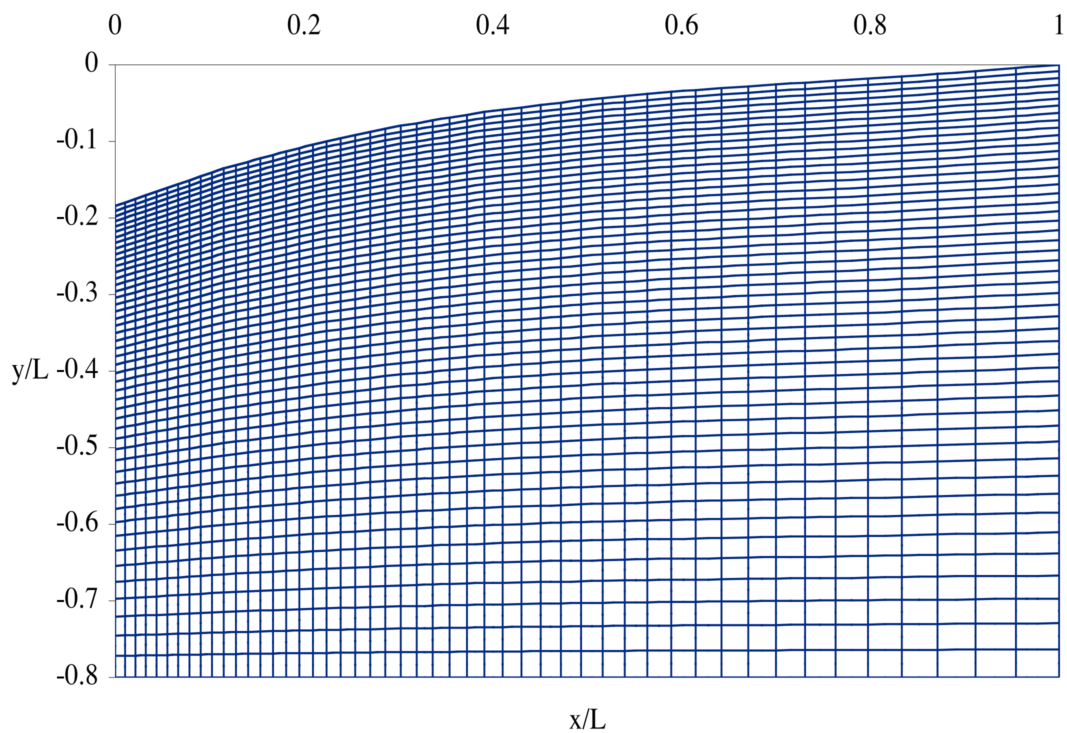
Non-Dimensional Parameters

1. h/L
2. θ_1
3. θ_2
4. P_e/P_∞
5. Alt
6. Me
7. M_∞
8. γ_e
9. ρ_∞/ρ_e

Flowfield Solver

- **Algebraic grid generator with stretching functions in axial and normal directions**
  - **Typical grid resolution 150x150 (22,500 points)**

- **2-D Implicit, Euler solver with Roe Averaging**
  - **Shock capturing method**
  - **Assumes perfect gas**
  - **Linear variation of 1-D exit velocity from $\theta=\theta_1$ to $\theta=0^o$ at cowl trailing edge**

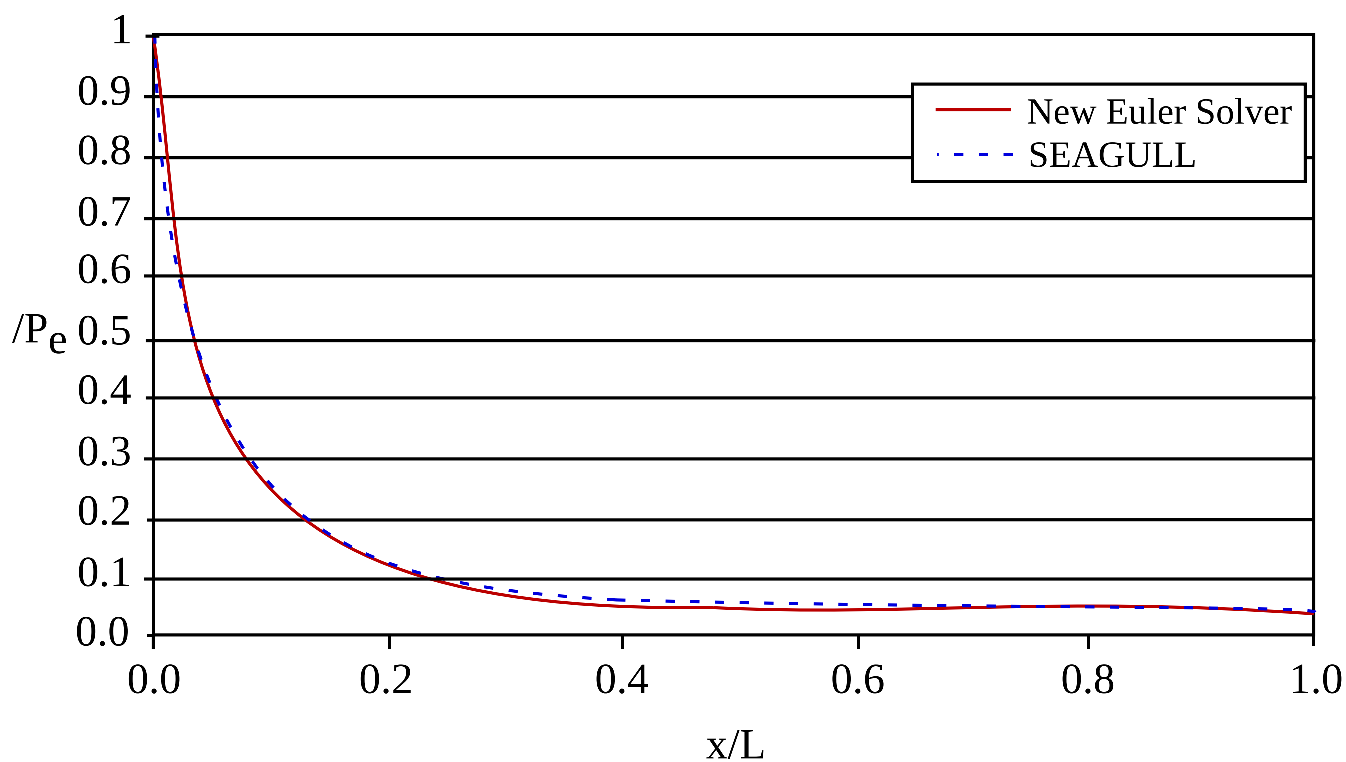


Sample 50x50 Grid

Aftbody Flowfield Verification Case

- **New CFD tool compared with results from SEAGULL**

Variable	Setting
θ'_s	various
h/L	0.05
M_e	1.368
P_e/P_∞	45.8
r_∞/r_e	0.314
γ_c	1.25
Alt (Kft)	80.0
M_∞	7.0

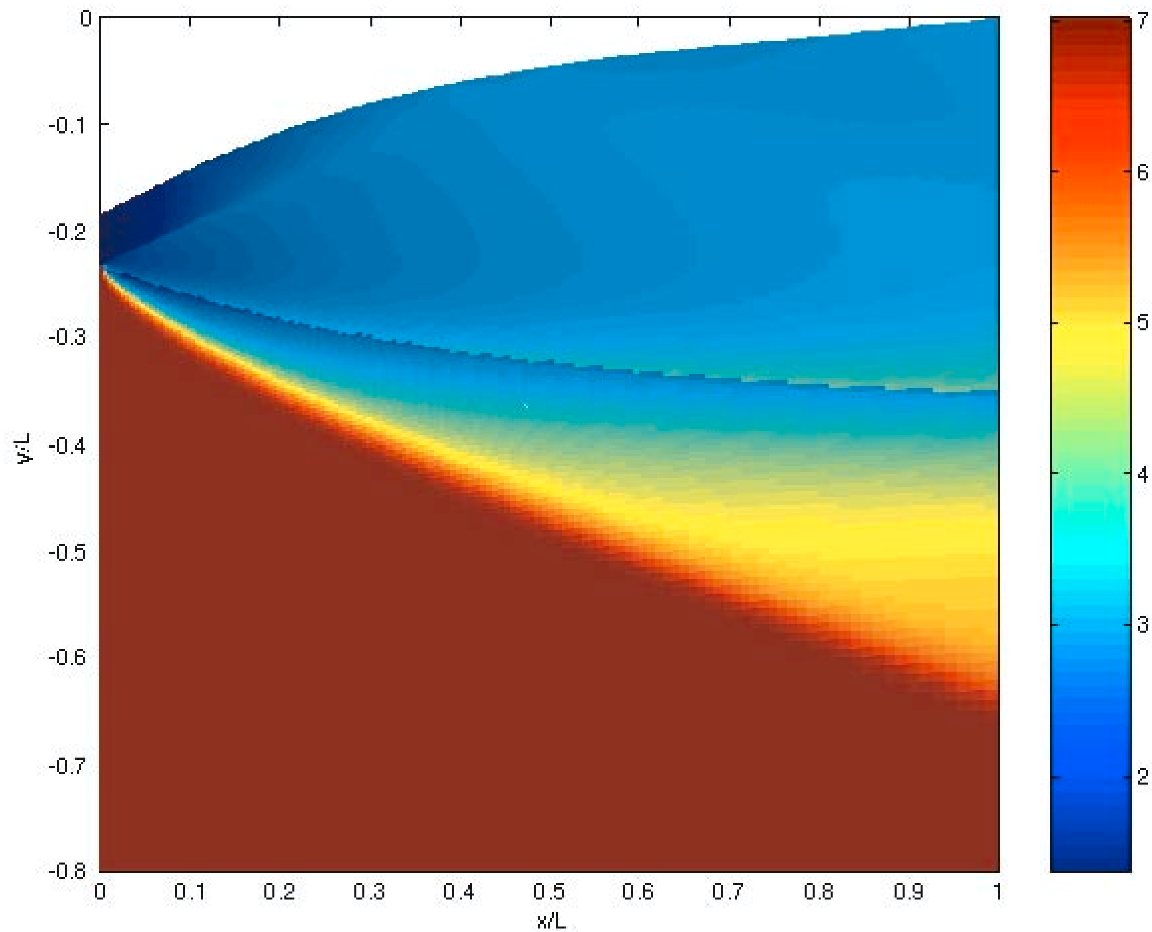


*** Relative error in integrated pressures < 0.7%**

Aftbody Flowfield Solver Verification Case: Mach Number Contour Plot

Variable	Setting
θ's	various
h/L	0.05
M_e	1.368
P_e/P_∞	45.8
r_∞/r_e	0.314
γ_c	1.25
Alt (Kft)	80.0
M_∞	7.0

y/L



x/L

Chi-Square Problem Formulation:

$$\min \chi^2 = \sum_{i=1}^{N} \left(\frac{\left(\frac{P_e}{P}\right)_i - \left(\frac{P_e}{P}\right)(x_i, a_0 \ldots a_5)}{\sigma_i} \right)^2$$

$$\text{with:} \quad \sigma_i = \left(1 + \frac{(i-1)(1000-1)}{N-1}\right)$$

Polynomial Fit:

$$\frac{P}{P_e} = \frac{1}{a_0 + a_1\left(\frac{x}{L}\right) + a_2\left(\frac{x}{L}\right)^2 + a_3\left(\frac{x}{L}\right)^3 + a_4\left(\frac{x}{L}\right)^4 + a_5\left(\frac{x}{L}\right)^5}$$

Response Surface Methodology And Results

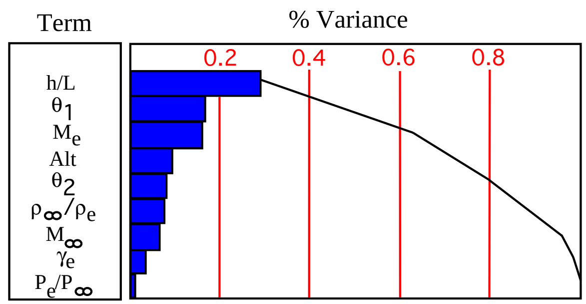
Screening Test Variable Settings

Variable	*Supersonic Set*	*Hypersonic Set*
θ_1(°)	10 - 25	10 - 25
θ_2(°)	0 - 10	0 - 10
h/L	0.05 - 0.15	0.05 - 0.15
M_e	1.2 - 3	1.2 - 4
P_e/P_∞	10 - 100	5 - 100
ρ_∞/ρ_e	0.1 - 5.0	0.1 - 5.0
γ_e	1.2 - 1.4	1.2 - 1.4
Alt (Kft)	40 - 90	70 - 120
M_∞	2.5 - 6	6- 12

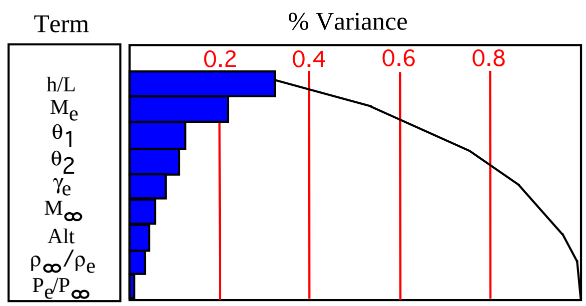
- 12 CFD runs required to complete DOE array for each set
- Responses are 3 integrated effects: axial force, normal force, and moment arm

Supersonic Set Screening Test Results

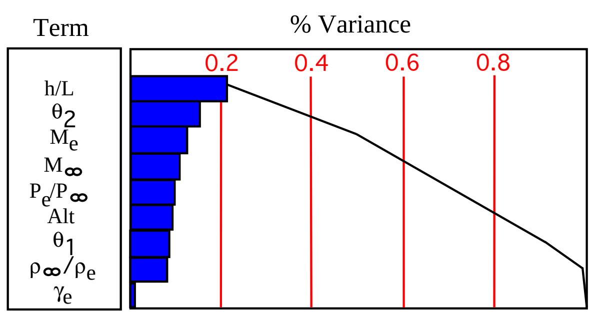
Axial Force



Normal Force



Moment Arm



Most Significant

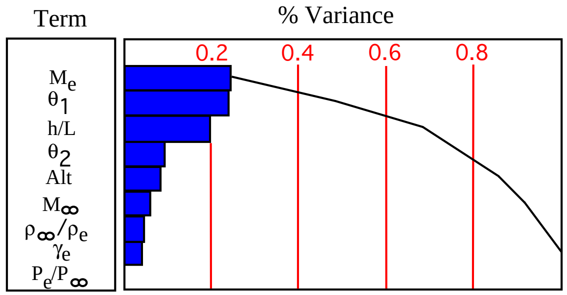
1. h/L
2. θ_1
3. M_e

Least Significant

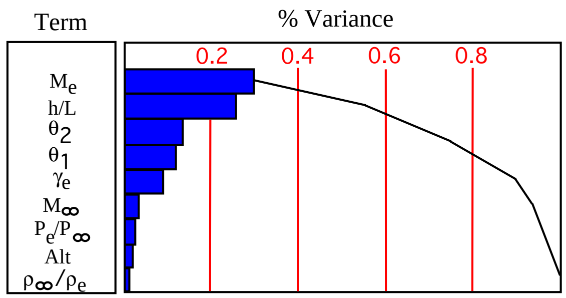
8. γ_e
9. P_e/P_∞

Hypersonic Set Screening Test Results

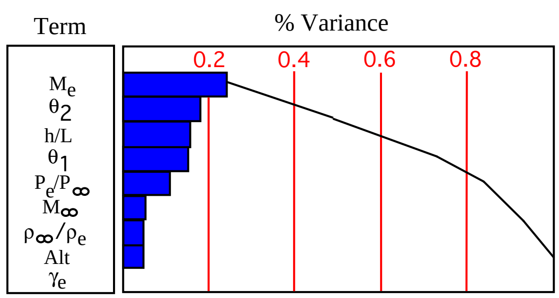
Axial Force



Normal Force



Moment Arm



Most Significant

1. h/L
2. θ_1
3. M_e

Least Significant

8. P_e/P_∞
9. ρ_∞/ρ_e

- 7 variable Central Composite Design (CCD)
  - 143 runs per set
  - *Supersonic Set* screened variable nominal values:
    - γ_e = 1.3
    - P_e/P_∞ = 40.0
  - *Hypersonic Set* screened variable nominal values:
    - ρ_∞/ρ_e = 1.05
    - P_e/P_∞ = 52.5
- 5 Responses
  - Pressure ratios at: $x/L)_{0.1}$, $x/L)_{0.2}$, $x/L)_{0.6}$, $x/L)_{0.9}$, and $x/L)_{1.0}$
  - $x/L)_{0.0}$ is always 1.0
- Total of 286 CFD runs completed
  - Approximately 250 total CPU hours
  - Execution scripted and automated on multiple R-12000 UNIX workstations

Supersonic Set

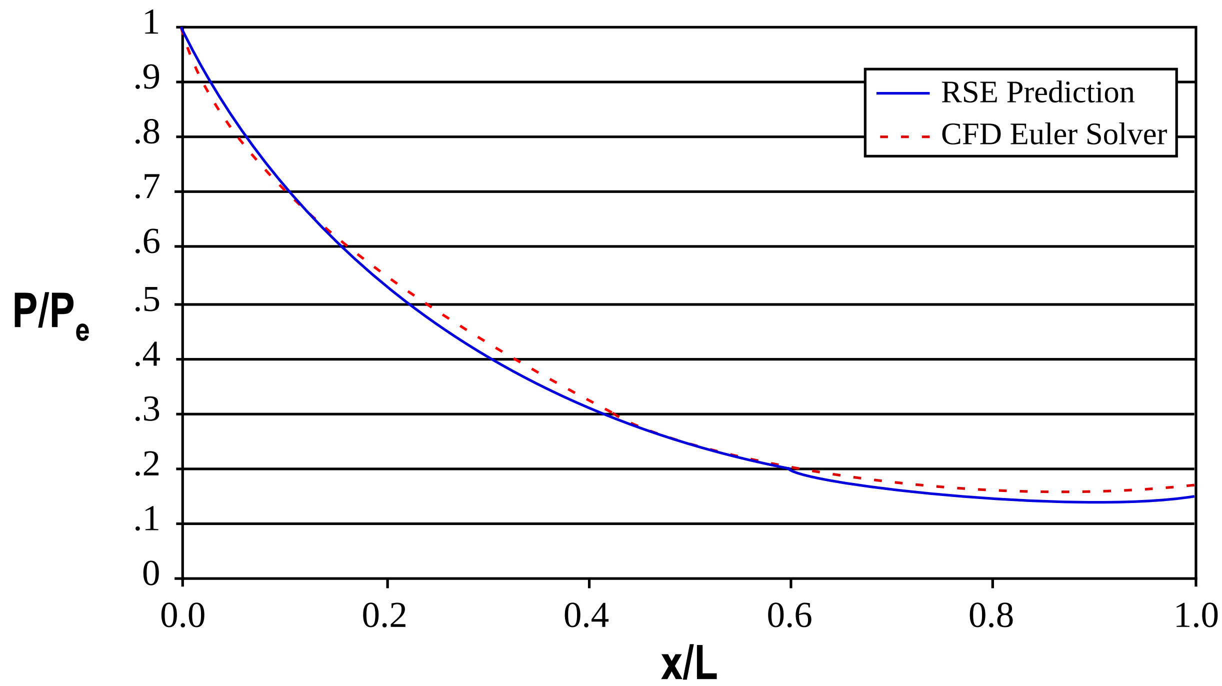
	R^2	Adjusted-R^2
$X/L)_{0.1}$	0.9842	0.9799
$X/L)_{0.3}$	0.9973	0.9965
$X/L)_{0.6}$	0.9912	0.9883
$X/L)_{0.9}$	0.9878	0.9838
$X/L)_{1.0}$	0.9852	0.9804

Hypersonic Set

	R^2	Adjusted-R^2
$X/L)_{0.1}$	0.9709	0.9614
$X/L)_{0.3}$	0.9840	0.9788
$X/L)_{0.6}$	0.9786	0.9716
$X/L)_{0.9}$	0.9670	0.9561
$X/L)_{1.0}$	0.9632	0.9512

Supersonic Test Case

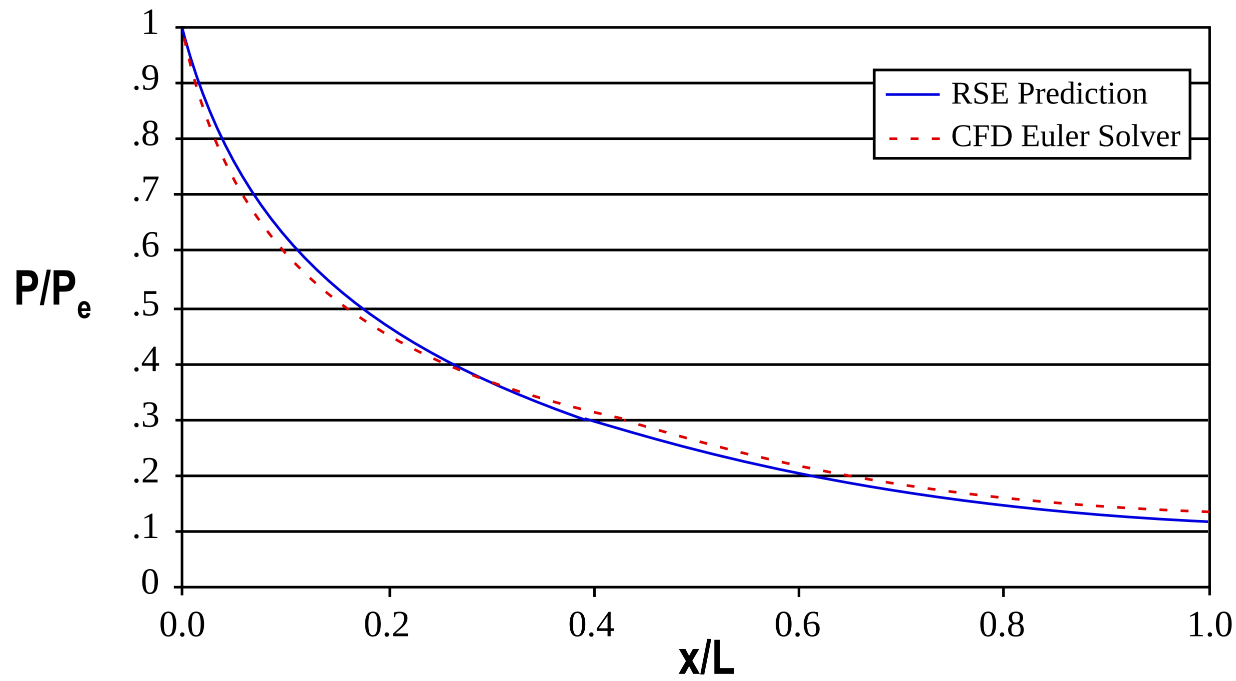
θ_1	= 15.0°
θ_2	= 2.0°
h/L	= 0.12
M_e	= 2.0
P_e/P_∞	= 5.0
ρ_∞/ρ_e	= 1.0
γ_e	= 1.386
Alt (Kft)	= 50
M_∞	= 2.5



- Axial force relative error: -1.85%
- Normal force relative error: -3.18%
- Moment arm relative error: -1.79%

Hypersonic Test Case

θ_1	= 20.0°
θ_2	= 9.0°
h/L	= 0.08
M_e	= 3.3
P_e/P_∞	= 60.0
ρ_∞/ρ_e	= 0.15
γ_e	= 1.285
Alt (Kft)	= 115
M_∞	= 12.0

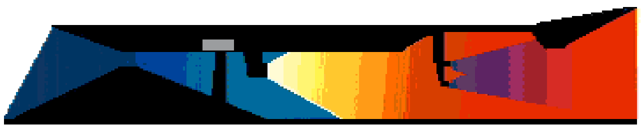


- Axial force relative error: -0.77%
- Normal force relative error: -2.34%
- Moment arm relative error: -3.41%

SCCREAM Performance Tool

Description and Modeling Assumptions

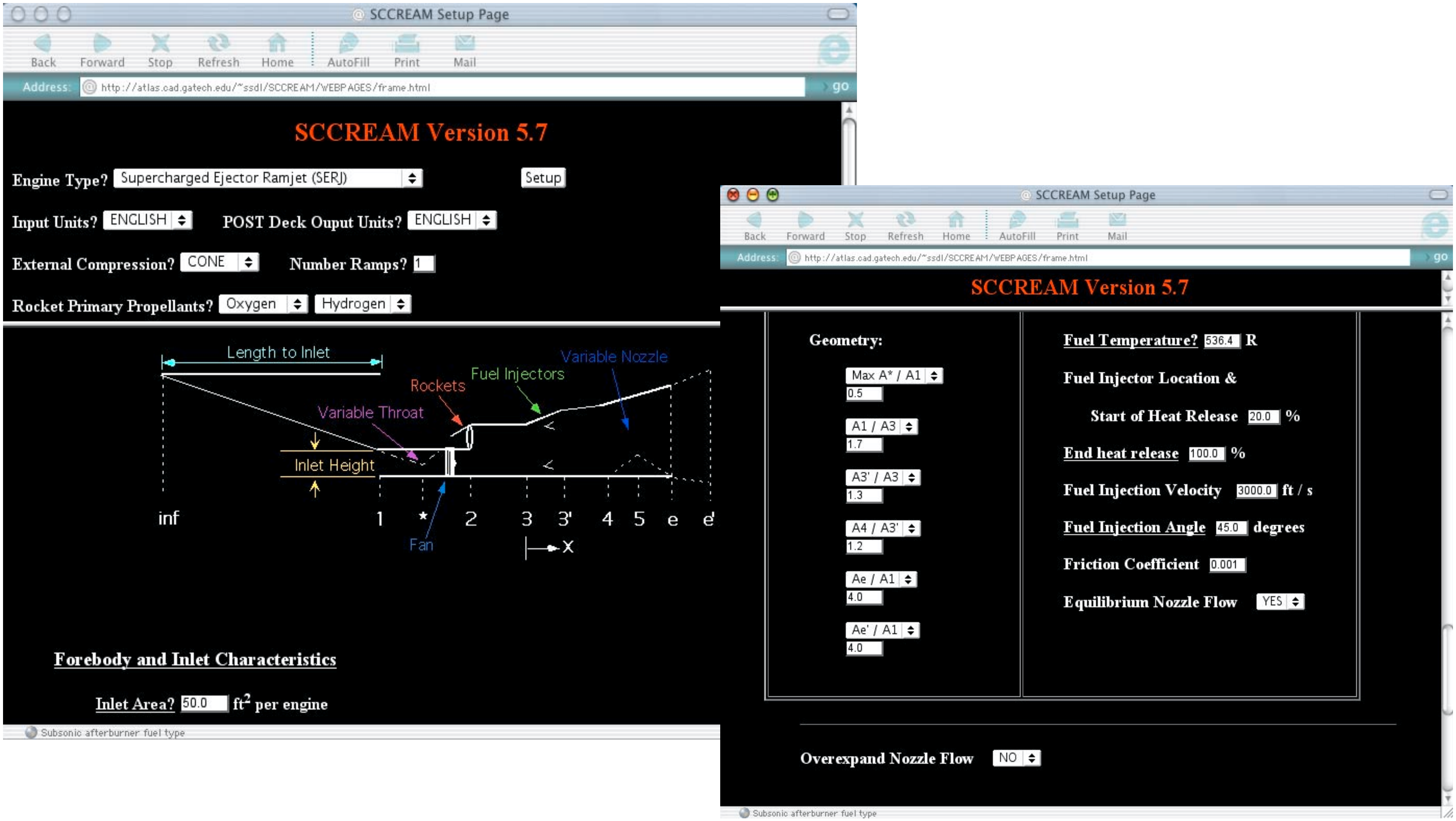
SCCREAM



Simulated Combined Cycle Rocket Engine Analysis Module

- Conceptual design tool for A/B and RBCC Propulsion system analysis
- Object-oriented C++
- Analyzes all engine operating modes
  (AAR, RJ, FRJ, SJ, SR, all-rocket)
- Text, web, and ModelCenter User Interfaces
- Automatically generates POST engine deck
- Execution time on the order of few minutes

Assumptions	
Forebody	Multi-ramp 2D, single-angle cone, or mixed cone-to-2D; user specified Cf
Inlet/Isolator	assumed to be variable geometry with subsonic combustion : MIL-SPEC inlet total pressure recover schedule with supersonic combustion : single reflected oblique shock based on final flow turn angle
Rocket Thruster and Combustor Options	Fuel: Hydrogen, Propane, Methane, JP-5, JP-10, Hydrogen Peroxide Oxidizer: Oxygen, Hydrogen Peroxide
Mixer	constant area process with equilibrium flow at exit and efficiency factor; check for choking condition at exit plane; automatic inlet throat area adjustment to unchoke flow
Combustor	1-D marching solution with fuel injection, friction, non-constant area; User specified heat release profile, fuel velocity/angle, and friction coefficient
Nozzle	throat is assumed to be variable geometry frozen or equilibrium nozzle flow; frictionless; area or ambient expansion
Force Accounting	tip-to-tail or nose-to-tail



SCCREAM Setup Page
Back Forward Stop Refresh Home AutoFill Print Mail
Address: http://atlas.cad.gatech.edu/~ssdl/SCCREAM/WEBPAGES/frame.html
SCCREAM Version 5.7
Engine Type? Supercharged Ejector Ramjet (SERJ)
Setup
Input Units? ENGLISH
POST Deck Ouput Units? ENGLISH
External Compression? CONE
Number Ramps? 1
Rocket Primary Propellants? Oxygen Hydrogen
Length to Inlet
Variable Nozzle
Fuel Injectors
Rockets
Variable Throat
Inlet Height
inf 1 * 2 3 3' 4 5 e e'
Fan
x
Forebody and Inlet Characteristics
Inlet Area? 50.0 ft² per engine
Subsonic afterburner fuel type
SCCREAM Setup Page
Back Forward Stop Refresh Home AutoFill Print Mail
Address: http://atlas.cad.gatech.edu/~ssdl/SCCREAM/WEBPAGES/frame.html
SCCREAM Version 5.7
Geometry:
Max A* / A1
0.5
A1 / A3
1.7
A3' / A3
1.3
A4 / A3'
1.2
Ae / A1
4.0
Ae' / A1
4.0
Fuel Temperature? 536.4 R
Fuel Injector Location &
Start of Heat Release 20.0 %
End heat release 100.0 %
Fuel Injection Velocity 3000.0 ft / s
Fuel Injection Angle 45.0 degrees
Friction Coefficient 0.001
Equilibrium Nozzle Flow YES
Overexpand Nozzle Flow NO
Subsonic afterburner fuel type

Aftbody RSEs Incorporated into SCCREAM

- Both supersonic and hypersonic RSE sets added as nozzle analysis option. User can select to use this method or prior expansion method to specified exit area
  - Chi-Square fitting algorithm also added
- Users specifies θ_1, θ_2, and h/L . SCCREAM provides M_e, M_∞, ρ_∞/ρ_e, γ_e, and Alt parameters to RSEs
- Each variable has upper and lower bounds that are used if SCCREAM or user specified parameters are violated
  - Output parameters (trajectory deck) modified to include propulsive lift and moment coefficients

Output Options

Detailed Output File	**Table formatted output with all variable values for each run analyzed. File generation is optional to speed execution.**
Tabular Output File	**Same data contained in 'Detailed' output file, but space delimited for insertion into spreadsheets.**
Combustor Details	**Provides combustor properties (area, Mach number, pressure, temperature, mole fractions) at each discretized combustor step, for every run analyzed. File generation is optional.**
Trajectory Performance Deck	**Either 2-D or 3-D table formats for POST automatically generated** **Independent variables: Mach number, altitude, *throttle** **Dependent variables: thrust/thrust coefficient, Isp, Cl,prop, Cm,prop, and Ps,max**
Plotting	**Web-interface provides 2-D plots of engine performance**

```
c Ramjet Mode Isp Values
l$tab table=5hisp3t,3, 3heta, 4hmach,
5hgdalt, 4,4,5,27*1,
 50000,
  2.0,
      1.0,    1413.12, / inlet is unstarted
    0.667,    1612.06, / inlet is unstarted
    0.333,    1845.88, / inlet is unstarted
      0.0,        0.0, / inlet is unstarted
  5.0,
      1.0,    1460.47, / inlet is started
    0.667,    1572.53, / inlet is started
    0.333,    1738.73, / inlet is started
      0.0,        0.0, / inlet is started
  7.0,
      1.0,    1338.87, / inlet is started
    0.667,    1372.43, / inlet is started
    0.333,    1221.65, / inlet is started
      0.0,        0.0, / inlet is started
```

Conclusions and Recommendations

Conclusions and Results Summary

- A new flowfield solver, written in C++ and executable on any platform, was developed and shown to be in excellent agreement with an existing solver (SEAGULL)

- A screening test performed on the aftbody design variables shows that for the:
  - *Supersonic Set*: γ_e and P_e/P_∞ have minor contributions to the pressure distribution
  - *Hypersonic Set*: P_e/P_∞ and ρ_∞/ρ_e parameters are minor contributors

- Performing an RSM resulted in the generation of RSE's that predict the pressure ratio at select axial locations for a wide range of nozzle designs and flight/engine conditions

- Using the RSE's and Chi-Square analysis, it was shown that the integrated axial and normal force predictions consistently provide results within +/-5% of the CPU intensive, 2-D Euler flow solutions
  - These RSE execute instantaneously and thus are easily implemented into the conceptual design process

- Note that method is independent of the flowsolver
  - Euler code could be replaced with TPG, chemically reacting flow, or Navier Stokes solver

- Current work is examining other meta-models in place of RSE's (e.g. neural networks)

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