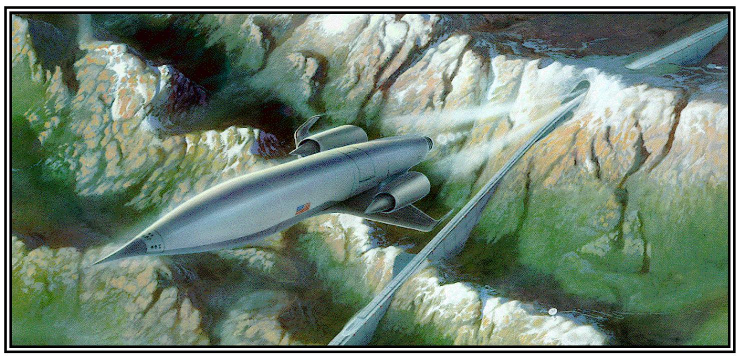
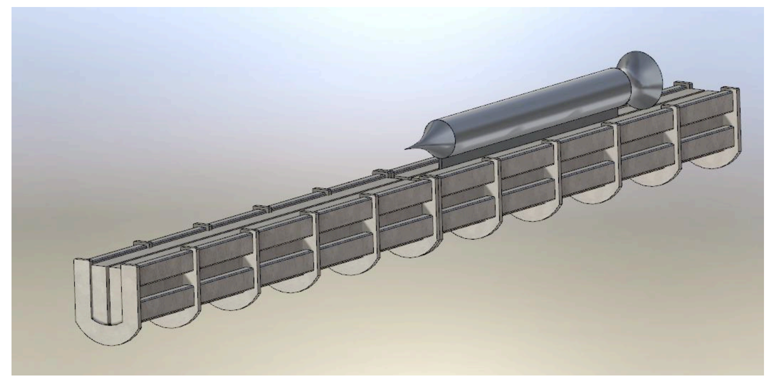
Preliminary Design of a Ramjet for Integration with Ground-Based Launch Assist





Emily L. Sayles

NASA MUST Intern

Summer 2008

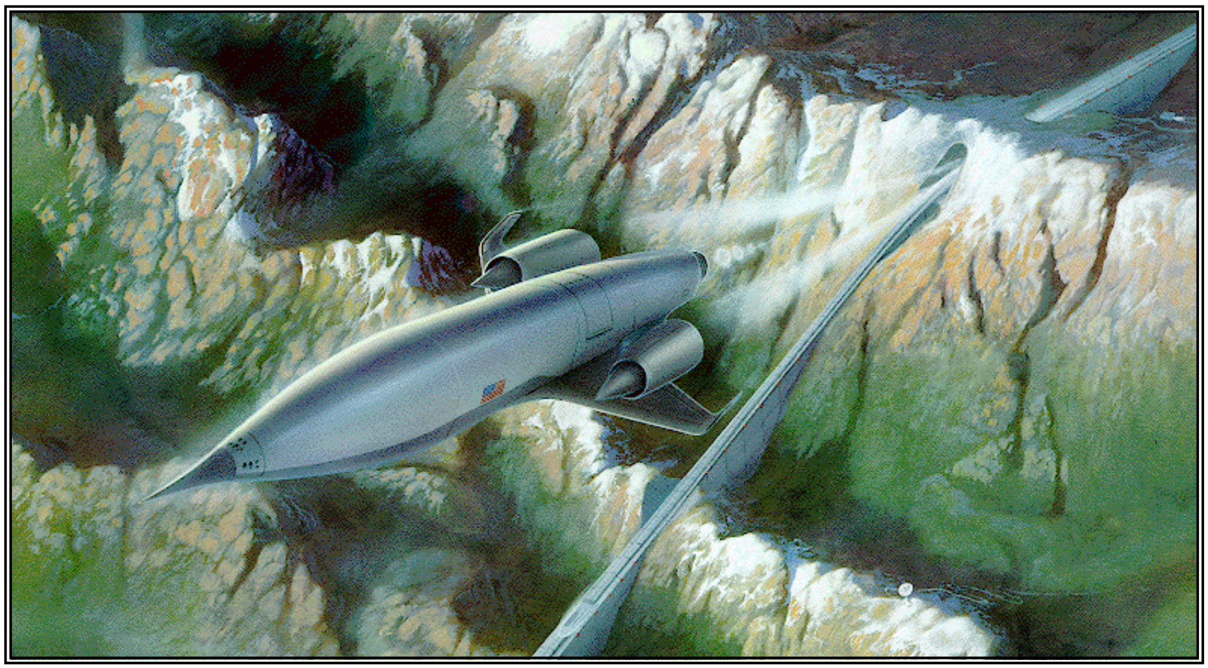
Outline

- Overview of Ground-Based Launch Assist
- OTIS and Trajectory Analysis
- Ramjet Performance Software Analysis
  - Ramjet Data
    - D-21
    - Stataltex
    - LASRM
  - Engine Performance Software
    - ONX
    - GECAT
- Next Steps

Ground-Based Launch Assist

Why?

- Reusable/Reliable
- Combination of E/M, air-breathing, and rocket propulsion
- Decrease in Weight=Increase in Payload
- Low Operational Costs



How?

- Launch to Orbit in Stages
  - Linear Induction Motors (0 to M1.5)
  - Ramjet (M1.5 to M4)
  - Scramjet (M4 to M10)
  - Rocket to Orbit

Launch Assist Benefit Analysis

Initial Velocity

Total ΔV is increased with an initial velocity

Coefficient of Drag

Launch assist will bypass $C_{D\ max}$ in the trans-sonic range

Decrease in Total Launch Weight per Payload Mass

Launch assist ΔV doesn't require on-board propellant

OTIS Simulations

Theory

OTIS: Optimal Trajectory by Implicit Simulation

Input: Flight Parameters

Output: Trajectory, Velocity, Drag, etc.

Experiment

"Flight Research of an Aerospike Nozzle Using High Power Solid Rockets"

AIAA 2005-3797

Bui, et al.

Flight Parameters: Drag Coefficient, Thrust

Flight data: Altitude, Mach Number

Verification of Simulation by Flight Data

Rocket Trajectory

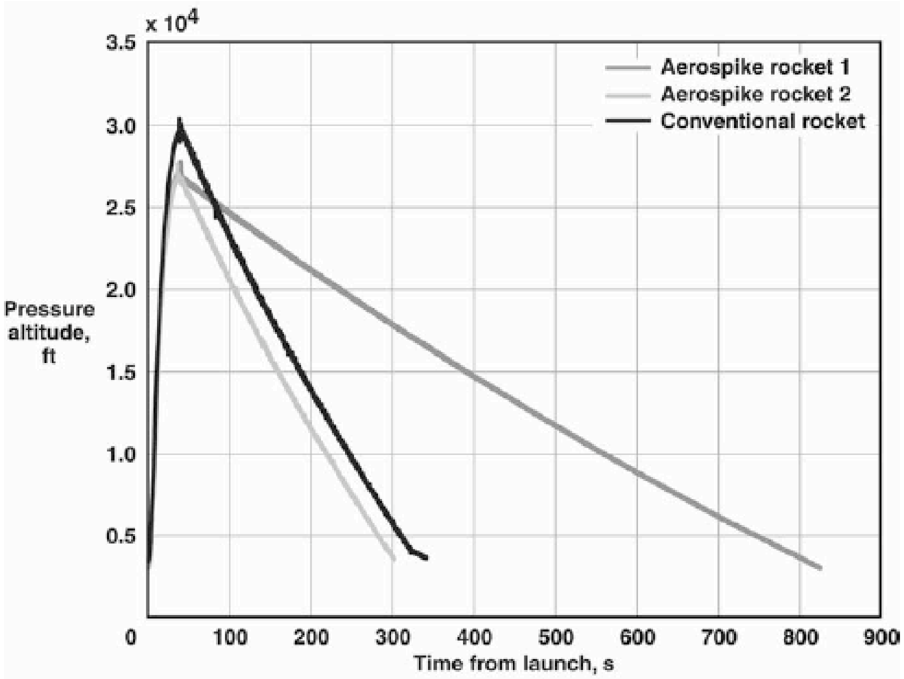
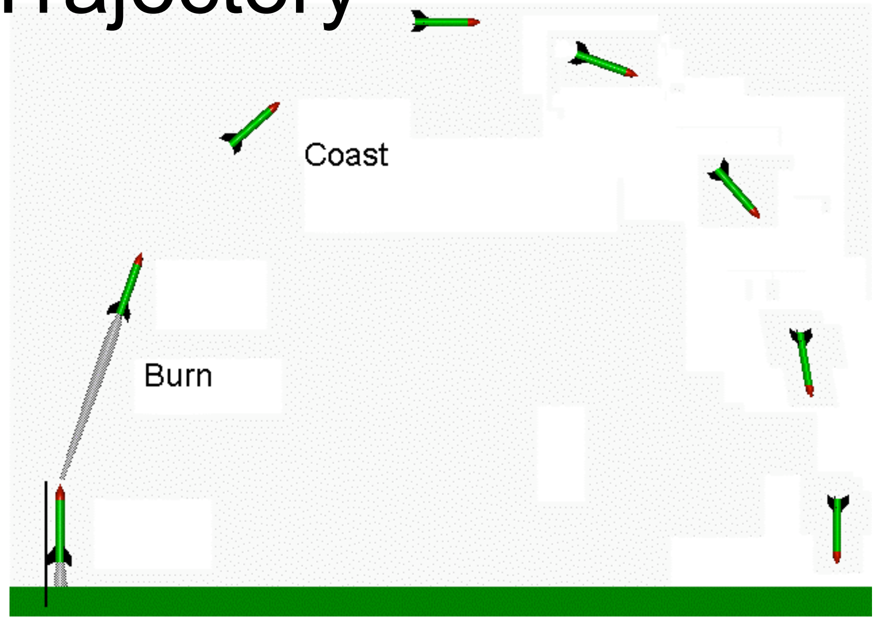


Figure 12. Pressure Altitudes for Three Rocket Flights.



2-Phase Model

Burn

- 7-Second Duration
- Average Thrust of 900 lbf
- Isp of 215 s
- With Drag

Coast

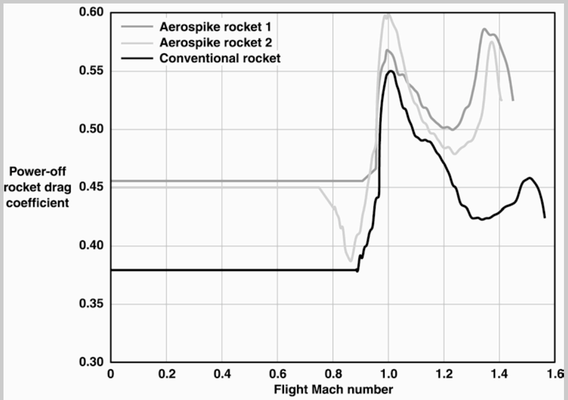
- Free-fall
- No chute
- With Drag

Max Velocity: ~1750 ft/s (M1.57); Max Altitude: ~27500 ft

OTIS Input Files

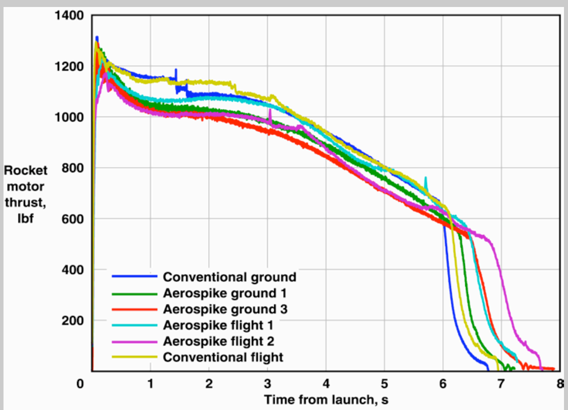
Experimental Data From Bui, et al.

Figure 14



Drag Coefficient

Figure 16



Thrust

otis.itd

Specific Initial Conditions

(V_0, h_0, γ, weight)

Atmospheric Model

1976 US Standard Atmosphere

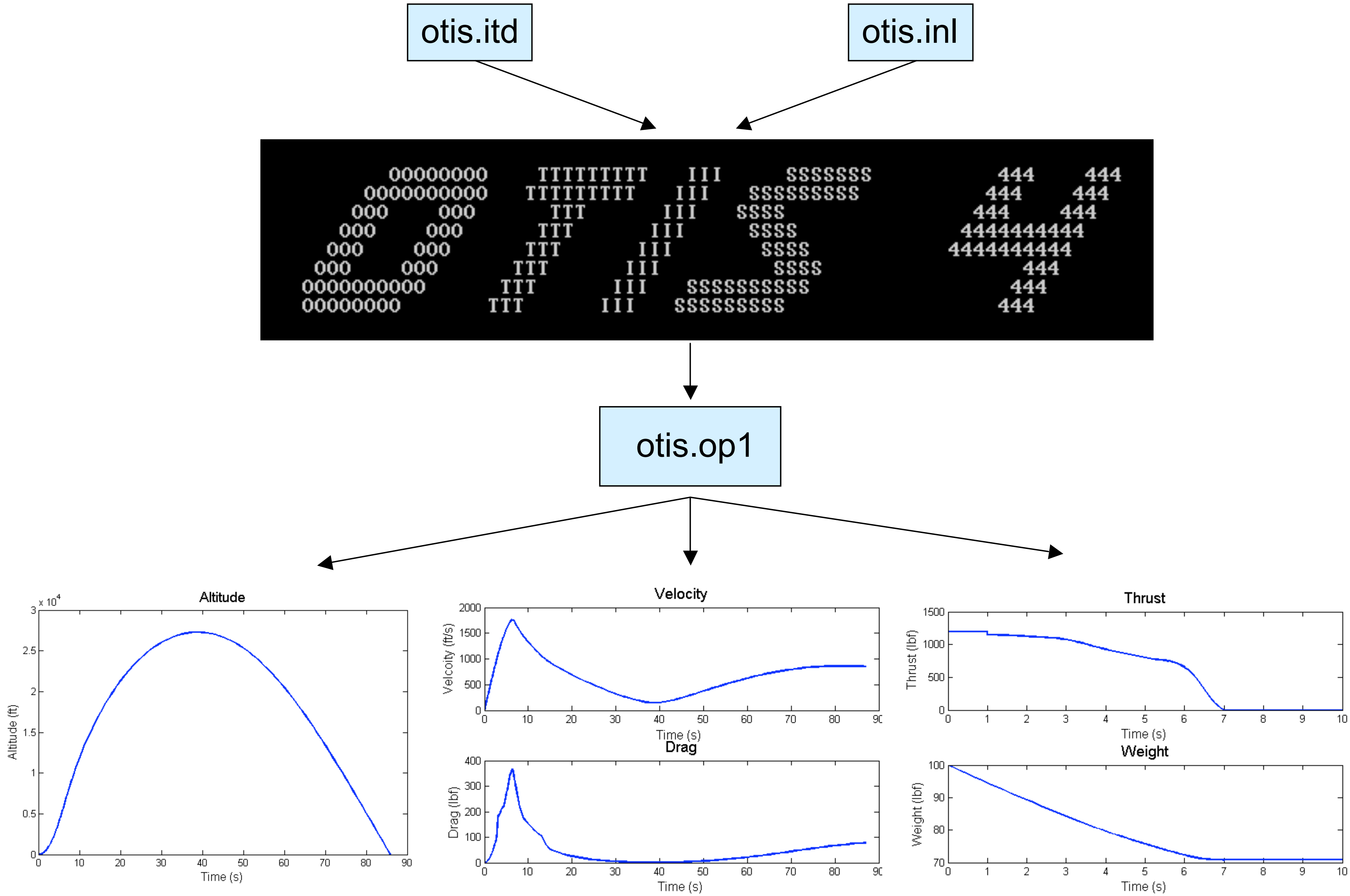
Engine Model

Thrust, Isp

Timing of Phases

otis.inl

OTIS Flowchart



Rocket Equation

$$\Delta V = Isp * g_0 * \ln\left(\frac{m_0}{m_{bo}}\right) - g_0 * t_{bo} - d$$

In a Vacuum

In an Atmosphere

	Rocket Parameters	Numerical Values From Bui, et al.
ΔV	Change in velocity (V_f-V_0)	1694 ft/s
Isp	Specific Impulse	215 s
m_0	Initial Mass	(100 lbs) / g_0
m_{bo}	Mass at Burn Out	(71 lbs) / g_0
t_{bo}	Burn Time	7 s
g_0	Gravitational Acceleration	32.2 ft/s^2
d	Drag Effects	Varies with time

Verification of Drag Effect's Existence

Comparison Between OTIS and Theory

Correction Term: d

Offset between ΔVs from OTIS and rocket equation at burn out

d = 497 ft/s

Comparison Within OTIS

"Turning off" the Atmosphere:

Removal of atmospheric model from otis.inl

Compute Offset between 2 OTIS models:

With Drag

Without Drag

$d = \Delta V_{no\ drag} - \Delta V_{with\ drag} =$ 509 ft/s

2.4% Difference

Values from both comparisons agree

→ OTIS is accurate in predicting the drag term ←

Method of Comparison:

Using the Concept of "Virtual Isp"

Different Scenarios Input to OTIS

Drag, Initial Velocity

OTIS Outputs a ΔV

Comparison of ΔVs

Rocket Alone vs. Combined System

Rocket Equation

Translate Change in ΔV to an Isp Gain

$$\Delta(\Delta V) = Isp_{gain} * g_0 * \ln\left(\frac{m_0}{m_{bo}}\right) - g_0 * t_{bo}$$

"Virtual Isp" = Normal Isp + Isp Gain

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Coefficient of Drag

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Decrease in Total Launch Weight per Payload Mass

Launch assist ΔV doesn't require on-board propellant

Initial Velocity Advantage

Variable Speed Launch Assist in a Vacuum

	Case	Drag	V_0 (ft/s)	Virtual Isp (s)	% Increase
Rocket Only	1	Vacuum	0	225	0
Combined System	2	Vacuum	440 (300 mph)	265	17.8
	3	Vacuum	880 (600 mph)	306	36
	4	Vacuum	1563 (M1.4*)	390	73.3

*at sea level

Launch Assist Benefit Analysis

Initial Velocity

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Coefficient of Drag

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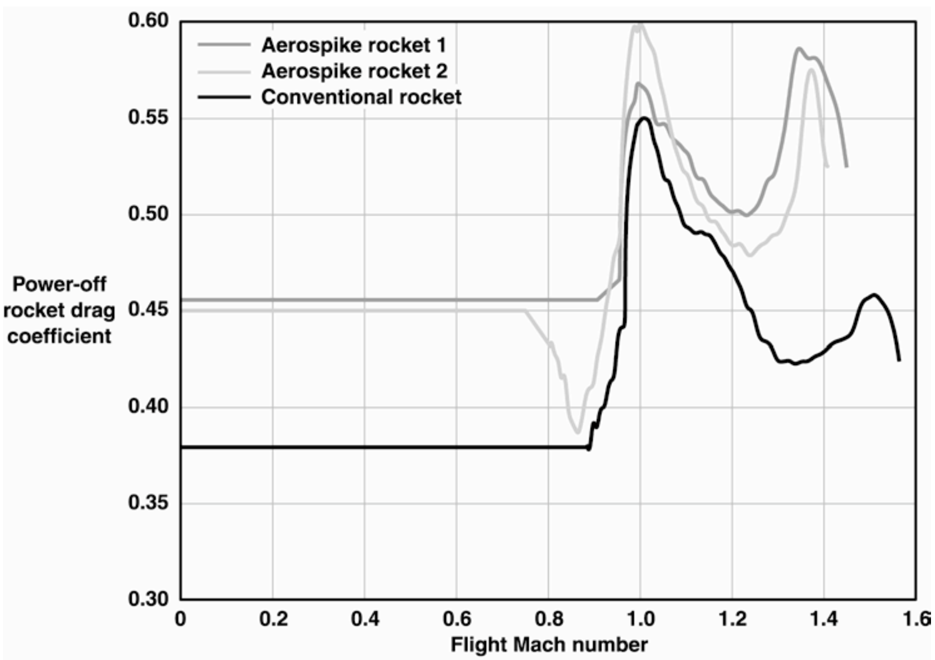
Decrease in Total Launch Weight per Payload Mass

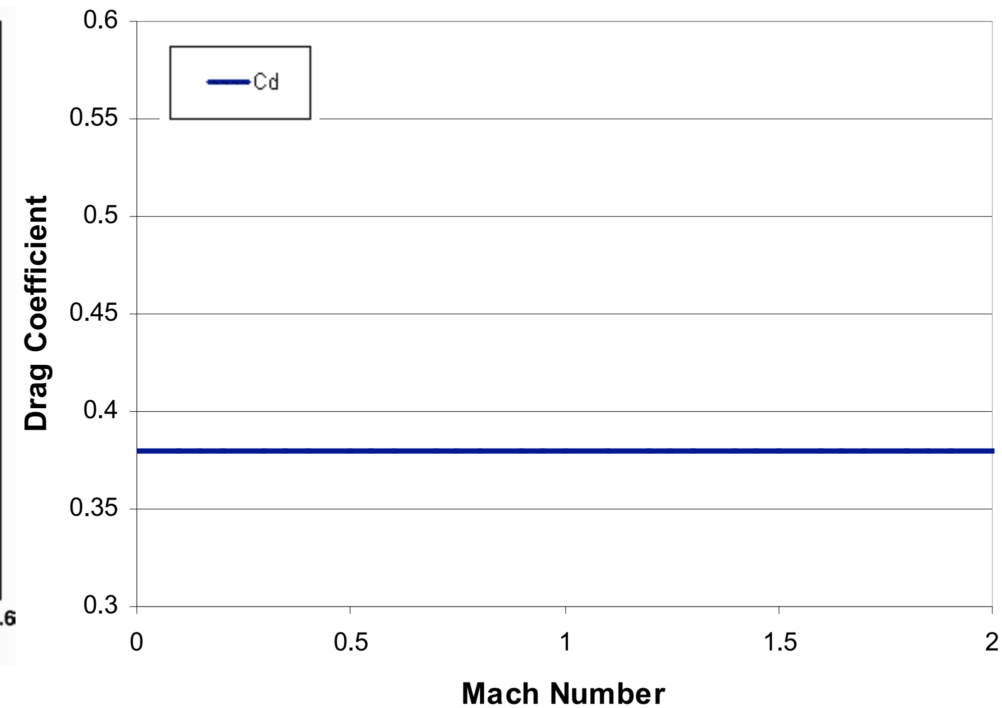
Launch assist ΔV doesn't require on-board propellant

Drag Coefficient Models

"Conventional"



"Constant"



Transonic peak

$$D = \frac{1}{2} C_D A \rho V^2$$

→ Drag force is directly proportional to coefficient of drag

Drag Coefficient Advantage

Case	Drag	V_0 (ft/s)	Virtual Isp (s)	% Increase
1	Conventional C_D	0	215	0
2	Constant C_D	0	243	13

Indicates possible gains from surpassing transonic peak

Variable Speed Launch Assist in Atmosphere

	Case	Drag	V_0 (ft/s)	Virtual Isp (s)	% Increase
Rocket Only	1	Conventional C_D	0	215	0
Combined System	2	Conventional C_D	440 (300mph)	227	5.6
	3	Conventional C_D	880 (600mph)	248	15.3
	4	Conventional C_D	1563 (M1.4*)	278	29.3

*At sea level

Launch Assist Benefit Analysis

Initial Velocity

Total ΔV is increased with an initial velocity

Decrease in Total Launch Weight per Payload Mass

Launch assist ΔV doesn't require on-board propellant

Coefficient of Drag

Launch assist will bypass $C_{D\ max}$ in the trans-sonic range

Motivation: Launch Assist can provide supersonic speeds thus allowing ignition of ramjet without an onboard compressor. This means a further reduction in total launch weight.

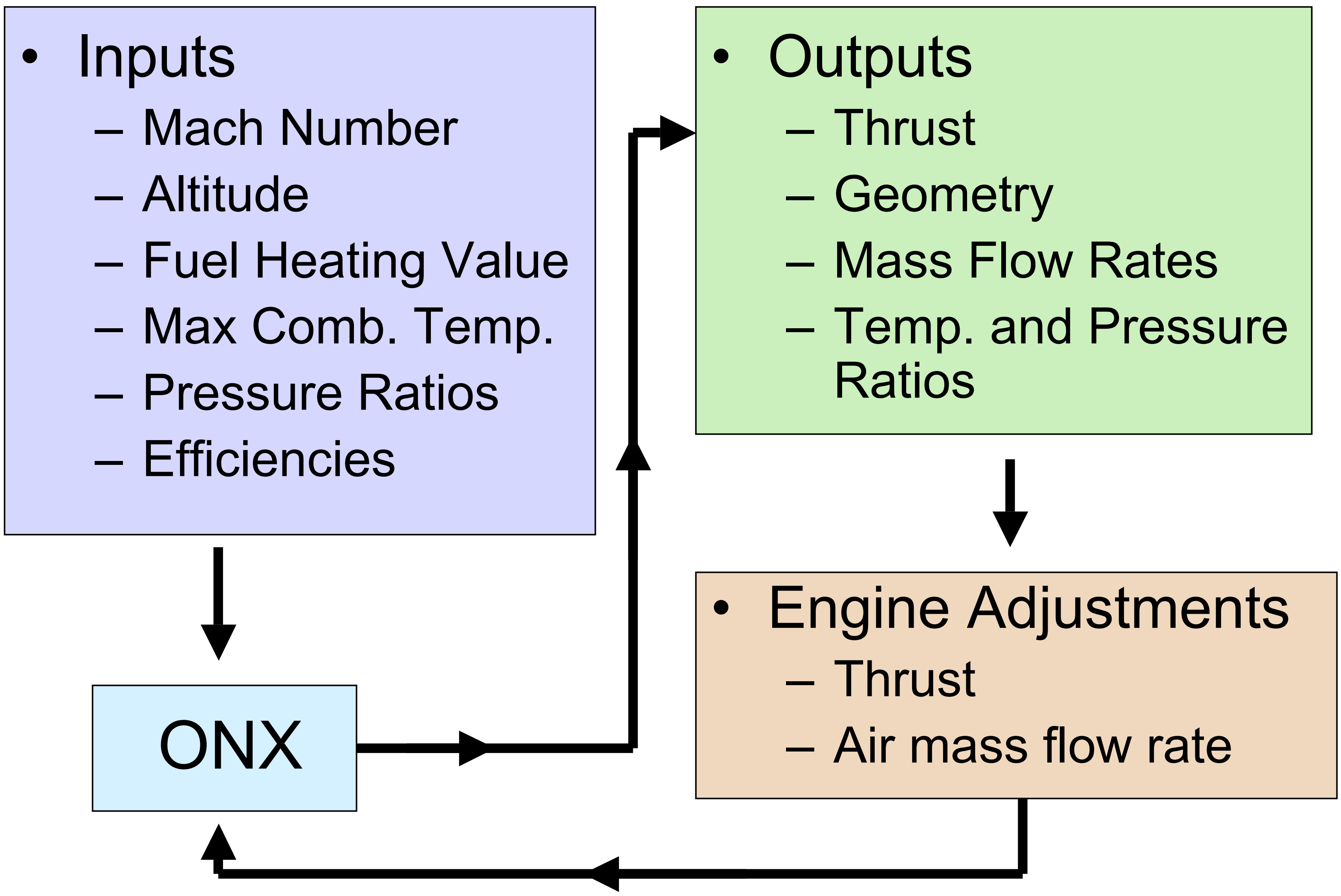
Outline

- Overview of Ground-Based Launch Assist
- OTIS and Trajectory Analysis
- Ramjet Performance Software Analysis
  - Ramjet Data
    - D-21
    - Stataltex
    - LASRM
  - Engine Performance Software
    - ONX
    - GECAT
- Next Steps

Outline of Ramjet Study

- Gather data from past, operational ramjets
  - LASRM
  - D-21
  - Stataltex
- Calculate missing parameters, if necessary
  - Mass Flow Rates
  - Pressure Recovery
- Input data to engine simulation software
  - ONX
  - GECAT
- Verify software outputs with real data
  - Geometry
  - Thrust

Structure of ONX Simulations



Verification of ONX with Holloman Sled Track Data

Experiment: "Feasibility of Ramjet Engine Test Capability on The Holloman AFB Sled Track"   McTaggart, 1973

Theory: ONX

Inputs from McTaggart:

•Mach number

•Diffuser Pressure Ratio

•Fuel and Air Mass Flow Rates

•Fuel Heating Value

Low **A**ltitude **S**hort **R**ange **M**issile (LASRM)

US Air Force, 1964-1967

Points of Verification

•Geometry

•Mass Flow Rates

Comments

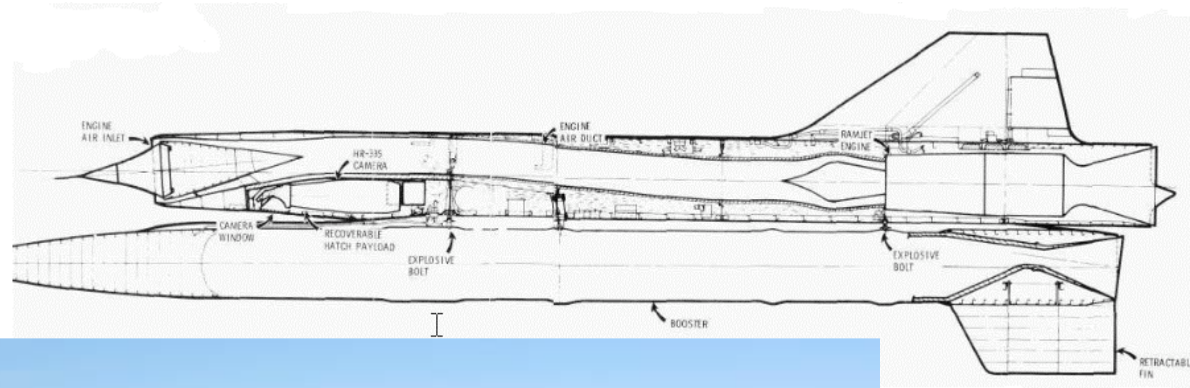
Allows for direct input of thrust

Does not allow for direct input of geometry

Intermediate Conclusions: Not enough LASRM data (no flight test thrust values)

Indications that the ONX program is not sufficient to meet our needs

D-21 Data



Known Parameters

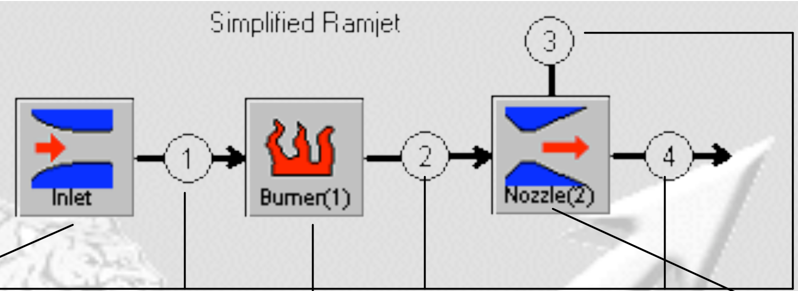
- Geometry:
  - Inlet Area
  - Nozzle Areas
  - Combustion Area
- Mach Numbers (Mach 3)
- Altitudes
- Thrust (1500 lbs)
- Specific Fuel Consumption
- Fuel Heating Value

Calculated Parameters

- Mass Flow Rate
- Pressure Recovery

Conclusions: ONX is not sufficient to meet our needs because of difficulty in entering and interpreting area data (unable to enter specific area data for each station)

GECAT Simulation Architecture



Station Numbers

Inlet Inputs

- Free Stream Mach Number
- Altitude
- Air Mass Flow Rate
- Pressure Recovery

Burner Inputs

- Efficiency
- Inlet Area
- Exit Temperature
- Mach Number at Burner Exit

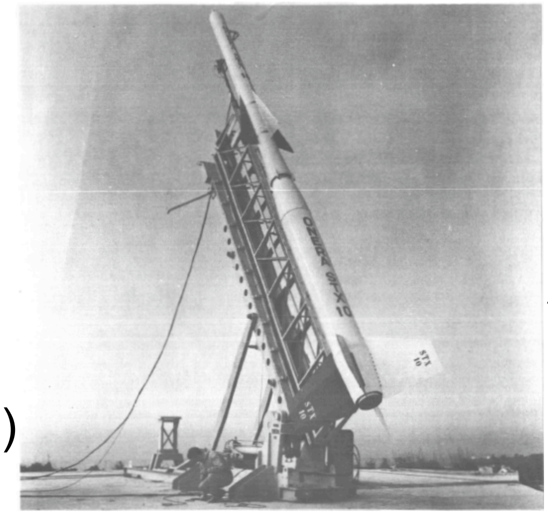
Nozzle Inputs

- Nozzle Type
- Entrance Area
- Throat Area
- Exit Area
- Throat Flow Coefficient
- Gross Thrust Coefficient

Stataltex Data

Known Parameters

- Geometry
  - Inlet Area
  - Nozzle Areas
- Fuel Heating Value
- Mach Numbers (Mach 3 to 5)
- Altitudes
- Thrust (max 4500 lbs)
- Combustion Temperatures
- Combustor Efficiency
- Inlet Efficiency

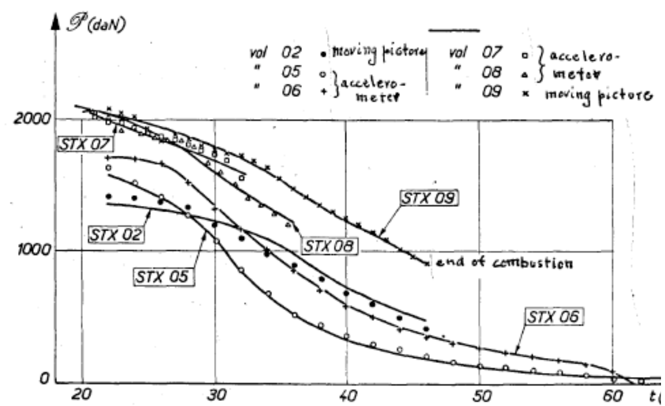


ONERA study, 1960-1964

Solid Fuel Booster plus Ramjet

Approached Mach 5

10 flights



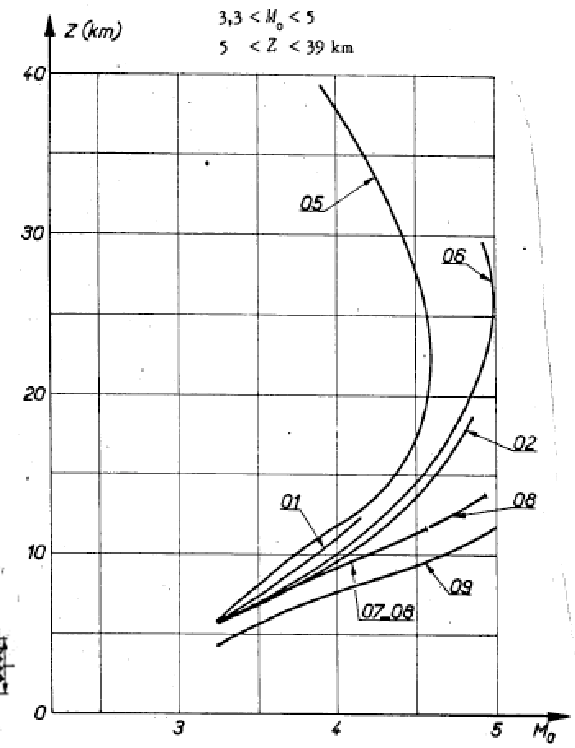


Figure 25. Range of flight investigated with ramjet propulsion.

Calculated Parameters

- Pressure Recovery
- Air Mass Flow Rate

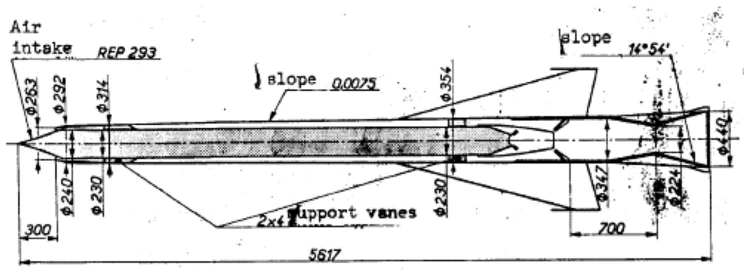
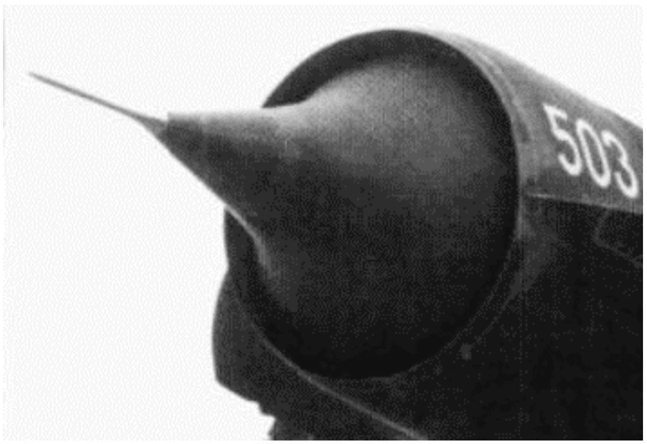
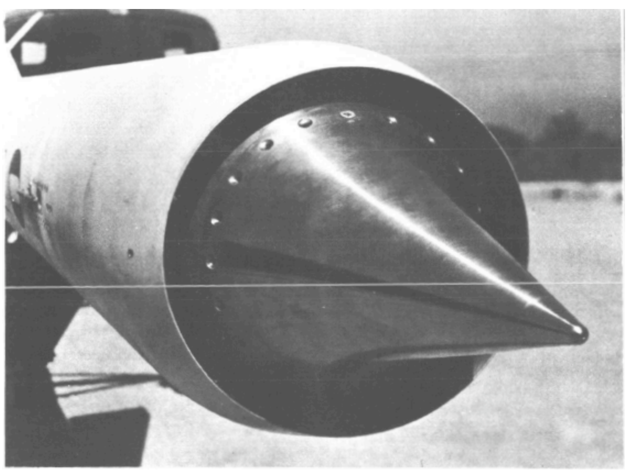


Figure 5. Internal geometry.

Calculation of Mass Flow Rates



D-21



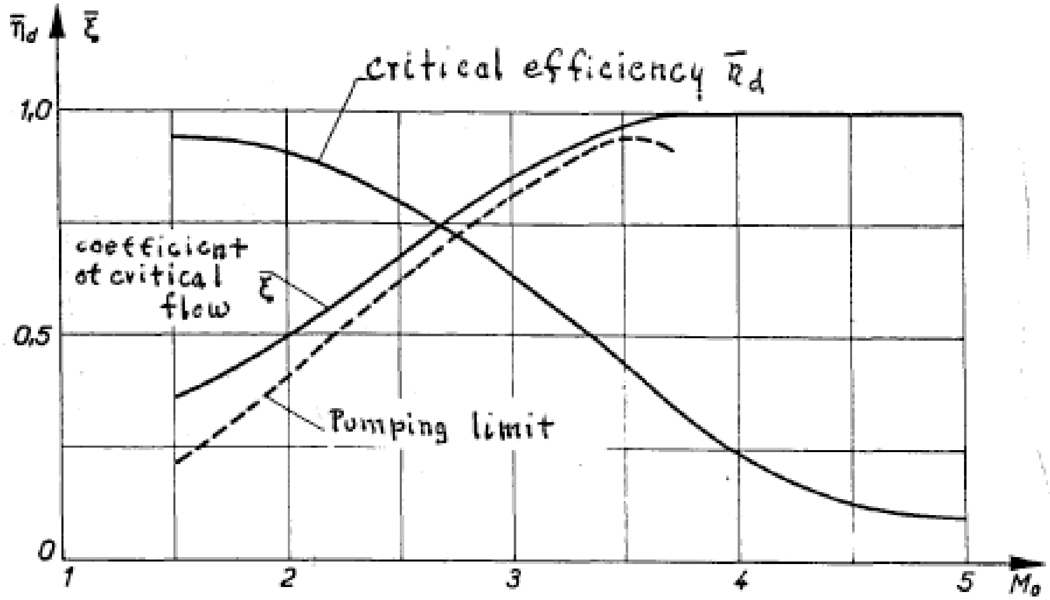
Stataltex

- Focus on Air Intake
  - Free-stream Mach number, altitude give densities and temperatures
- Isentropic Compression Along Spike
  - Prandtl-Meyer Compression Waves
- Normal Shock at Inlet
  - Normal Shock Relations give Mach number, density, temperature after the shock

$$\dot{m} = \rho A V$$

Calculation of Pressure Recovery (r_i)

- Measure of inlet performance
- Ratio of total pressure after inlet to free stream total pressure



Stataltex Inlet Efficiency (η_i) as a Function of Free Stream Mach Number

$$r_i = \eta_i \left(1 - 0.075(M-1)^{1.35}\right)$$

Verification of GECAT with Stataltex and D-21 Data

Input Parameters

- Geometry
- Flight Conditions
- Air Mass Flow Rate
- Fuel Heating Value
- Efficiencies
- Combustion Temperature

GECAT

Verification of Outputs

- Thrust
- Geometry

Adjustments

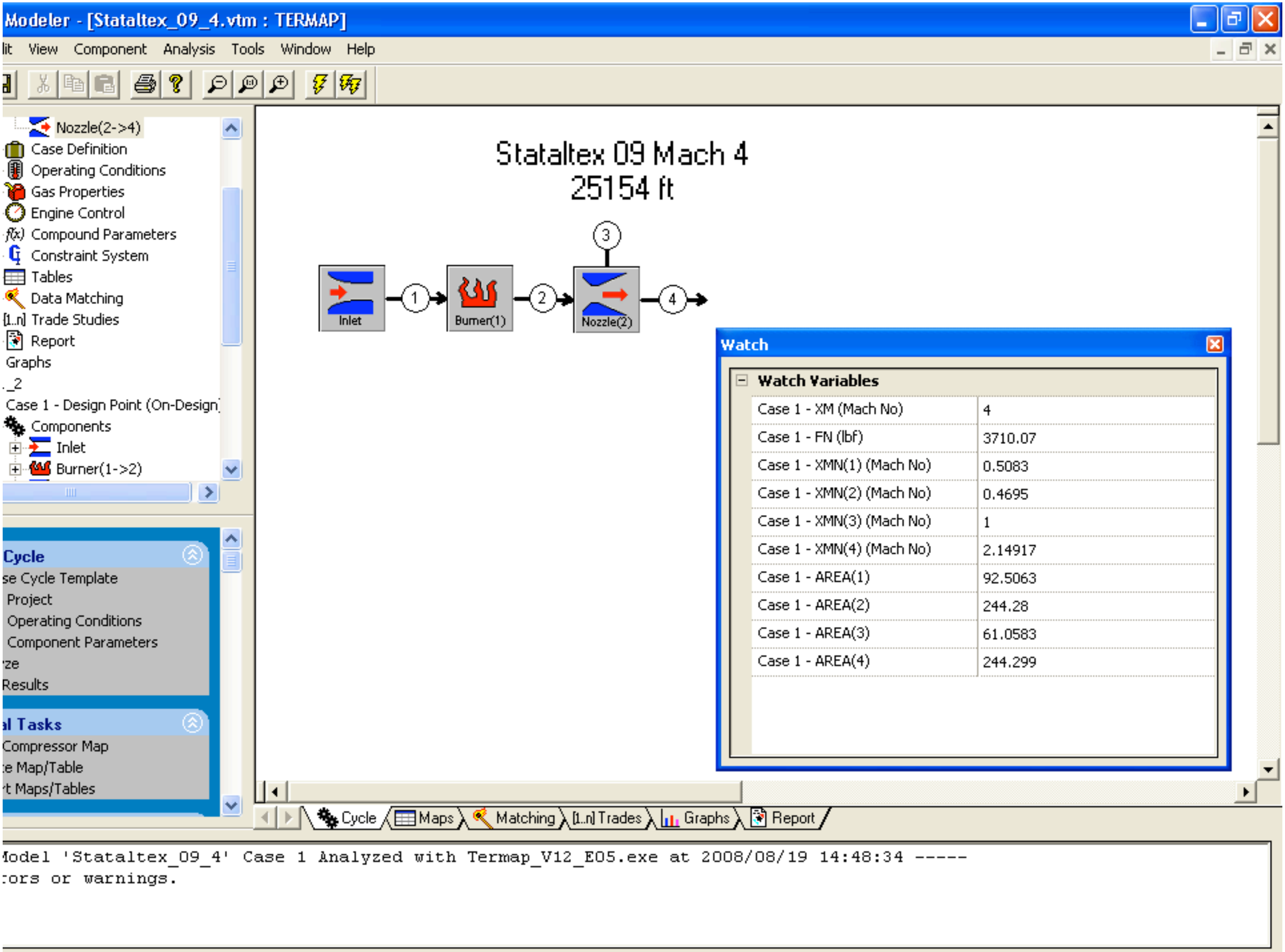
- Throat Flow Coefficient
- Gross Thrust Coefficient

Stataltex Flight Conditions

Flight Number	Mach Number	Altitude (ft)
06	4	32808
06	5	85630
09	4	25154
09	5	38278

D-21 Flight Conditions

Mach Number	Altitude (ft)
3.25	80000
3.3	80000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Nozzle(2->4)
Case Definition
Operating Conditions
Gas Properties
Engine Control
Compound Parameters
Constraint System
Tables
Data Matching
Trade Studies
Report
Graphs
_2
Case 1 - Design Point (On-Design)
Components
Inlet
Burner(1->2)
Cycle
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Operating Conditions
Component Parameters
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Results
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Stataltex 09 Mach 4
25154 ft
Inlet
Burner(1)
Nozzle(2)
1
2
3
4
Watch
Watch Variables
Case 1 - XM (Mach No) 4
Case 1 - FN (lbf) 3710.07
Case 1 - XMN(1) (Mach No) 0.5083
Case 1 - XMN(2) (Mach No) 0.4695
Case 1 - XMN(3) (Mach No) 1
Case 1 - XMN(4) (Mach No) 2.14917
Case 1 - AREA(1) 92.5063
Case 1 - AREA(2) 244.28
Case 1 - AREA(3) 61.0583
Case 1 - AREA(4) 244.299
Cycle
Maps
Matching
[1..n] Trades
Graphs
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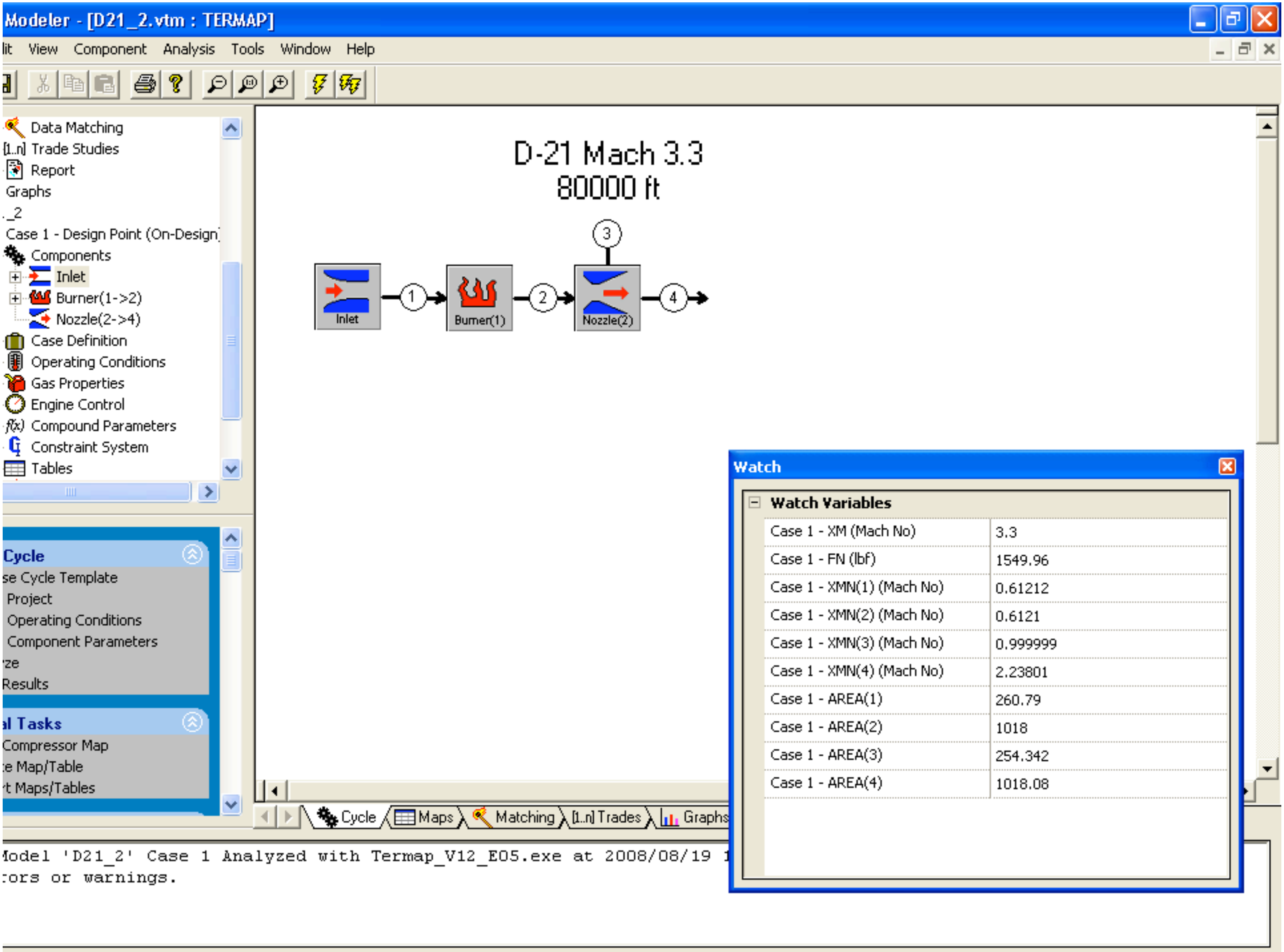

Modeler - [D21_2.vtm : TERMAP]
lit View Component Analysis Tools Window Help
Data Matching
[1..n] Trade Studies
Report
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._2
Case 1 - Design Point (On-Design)
Components
Inlet
Burner(1->2)
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Engine Control
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Constraint System
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Cycle
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D-21 Mach 3.3
80000 ft
Inlet
Burner(1)
Nozzle(2)
1
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3
4
Cycle
Maps
Matching
[1..n] Trades
Graphs
Model 'D21_2' Case 1 Analyzed with Termap_V12_E05.exe at 2008/08/19 1
ors or warnings.
Watch
Watch Variables
Case 1 - XM (Mach No) 3.3
Case 1 - FN (lbf) 1549.96
Case 1 - XMN(1) (Mach No) 0.61212
Case 1 - XMN(2) (Mach No) 0.6121
Case 1 - XMN(3) (Mach No) 0.999999
Case 1 - XMN(4) (Mach No) 2.23801
Case 1 - AREA(1) 260.79
Case 1 - AREA(2) 1018
Case 1 - AREA(3) 254.342
Case 1 - AREA(4) 1018.08

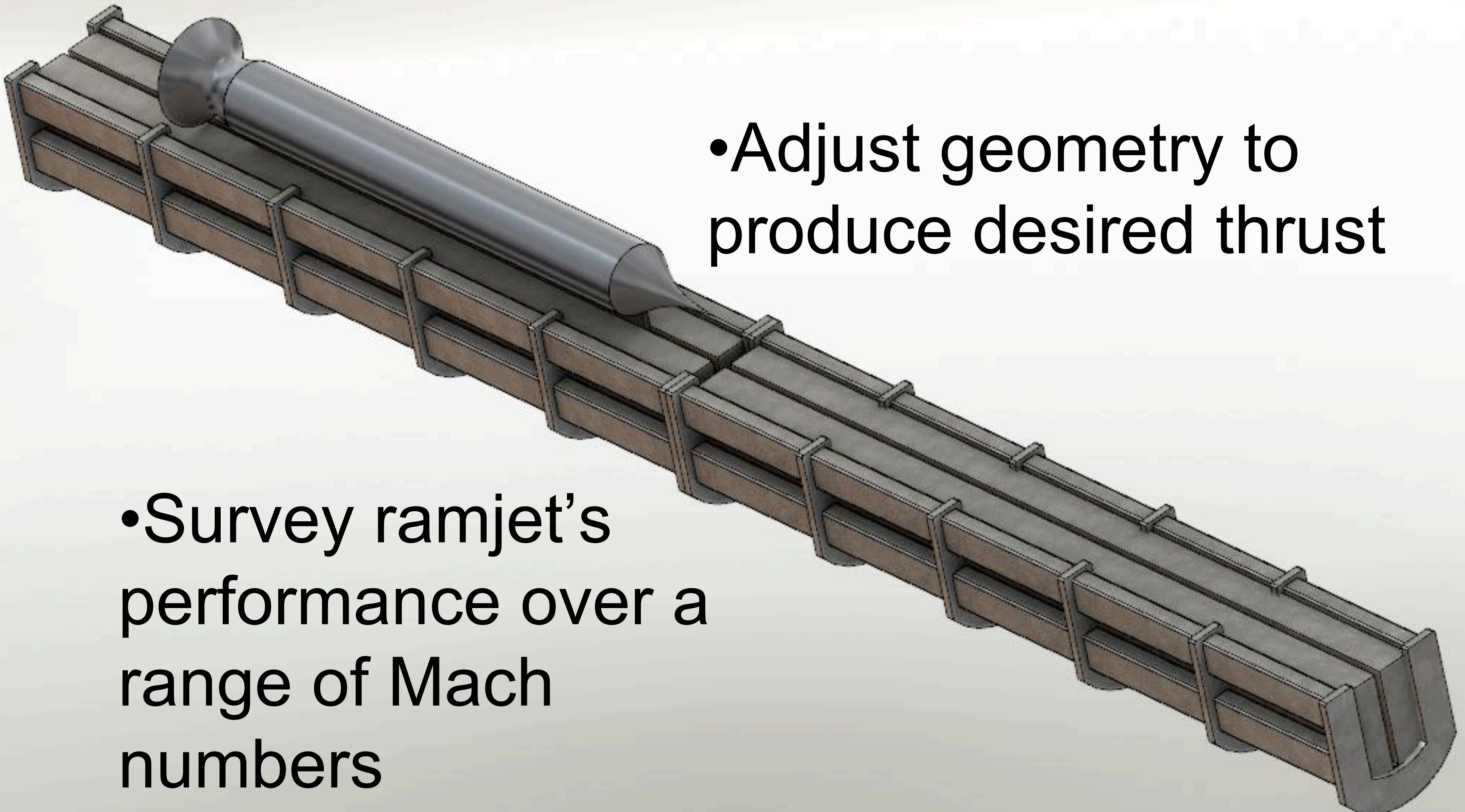
Comments on Software Analysis

	ONX	GECAT
Pros	✓Direct input of thrust	✓Specification of Geometry ✓Ability to Override Idealizations ✓Matching Capability ✓View Properties at Every Station
Cons	➢Geometry is calculated, not specified ➢Limited selection of inputs	➢Issues with Nozzle Exit Area Input ➢D-21 model was not geometrically accurate

- Not enough data to model the LASRM
- D-21 GECAT model at 2 points
- Successful Stataltex GECAT model at 4 points

Next Steps

- Create GECAT model of launch assist ramjet

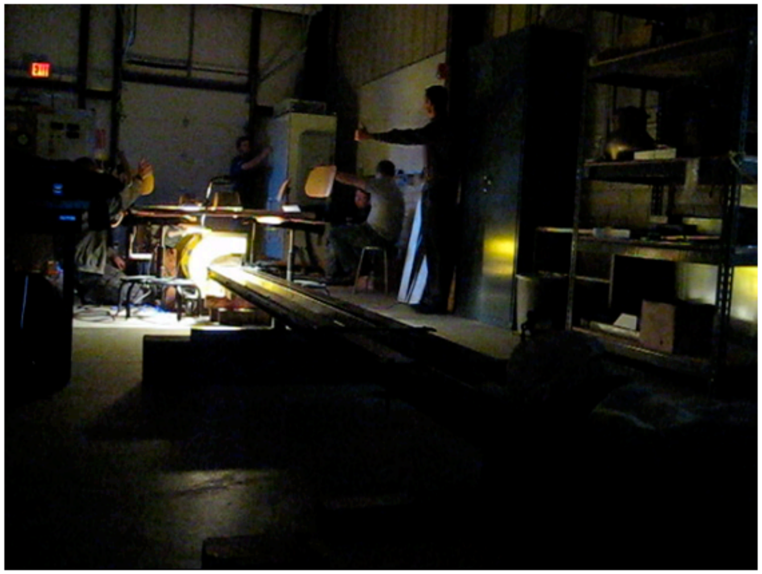


•Adjust geometry to produce desired thrust

•Survey ramjet's performance over a range of Mach numbers

Learned Solidworks

Linear Motor Research and Development



Phase 1 Motors Embry-Riddle-159 mph

Phase 2 Motors

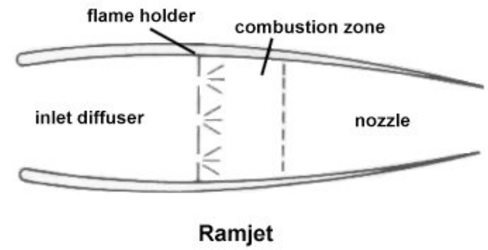
Phase 2 Motors-Manufacturing

Phase 2 Motors-Testing Fall 2008

Launch Assist Ramjet

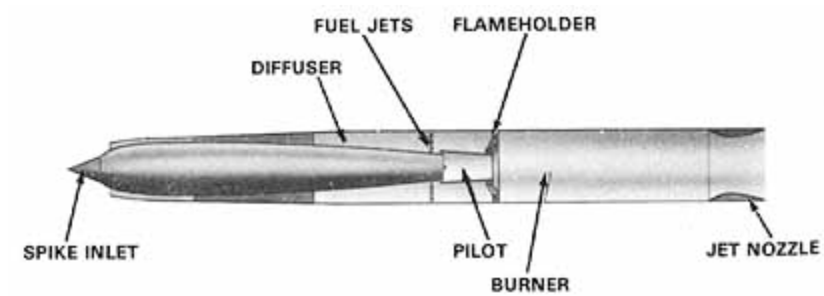
- Assumptions/Requirements
  - Sea level to 10,000ft operation
  - Mach Number 1.5 to 2
  - 2-5 seconds burn time
  - Gross wet weight between 50 and 100lbs
  - Detection limits 1-10g out of 500g
  - Type of Fuel? JP/kerosene

Inlet Considerations



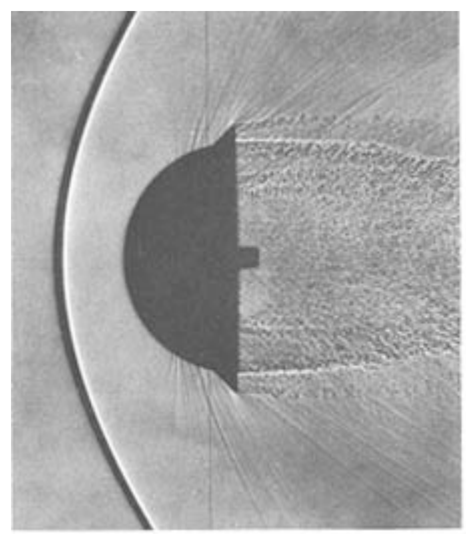
Inlet Geometry:

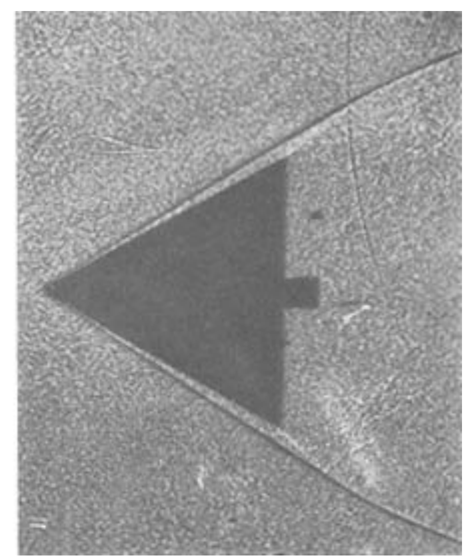
- •Hole
- •Cone
  - •Storage for instrument package



Shock Wave Model

- •Oblique
- •Normal
- •Detached Bow Wave
  - •Low supersonic speeds
  - •Cone half-angle





Preliminary Calculations

- Acceleration: 3-5 g's
- Burn Duration: 3-5 sec
- V_0 = M1.2
- V_f = M1.6-M1.9
- Propellant Mass Fraction: 1/3
- Total Ramjet Weight: 20 lbs
- Net Thrust: 60 lbs
- Fuel Density: 50 lbs/ft^3
- Fuel Volume (JP-4): 30-50 in^3

Trade Studies

Variable Parameters

- Flight Mach Number
- Inlet Efficiency
- Altitude
- Air Mass Flow Rate
- Combustion Temperature

Restrictions

- Cross-Sectional Areas
    - Inlet Area
    - Nozzle Throat Area
    - Nozzle Exit Area
- Net Thrust (0 – 100 lbs)

	On-Design →	Design Points →	Off-Design
What:	Start with Basic Cases	Change Parameters in Cases	Simulate Changing Flight Conditions
Why:		Find 60 lbs thrust cases	Examine Performance at Non-Ideal Conditions

GECAT Flow Chart

9 On-Design Cases

- Mach 1.2
- Altitudes: 0, 5000, 10000 ft
- Inlet Efficiencies: 75%, 85%, 95%
- Combustion Temperature: 3000 R
- Thrust = 60 lbs
- Mass Flow Rate: Determined on Case to Case Basis

↓

Off-Design Variable Parameters

- M1.2 to M2.0
- Altitude: 0 to 10000 ft
- Pressure Recovery: 0.5 to 1.0
- Combustion Temperature: 2000 to 4000 R
- Mass Flow Rate: 5 to 50 pps

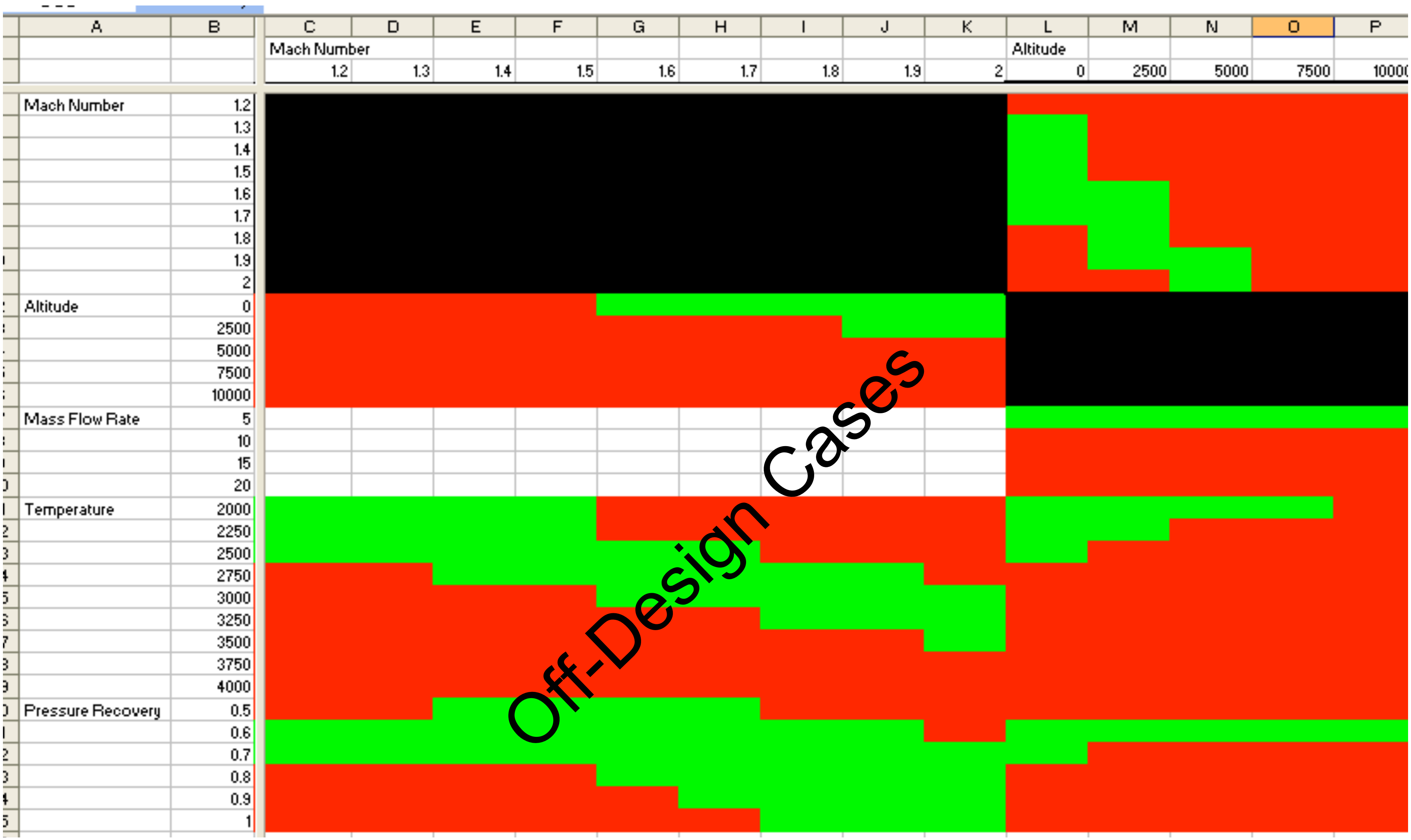
→ **Restrictions**

0 lbs<Thrust<100 lbs

Determination of Acceptable Flight Regimes

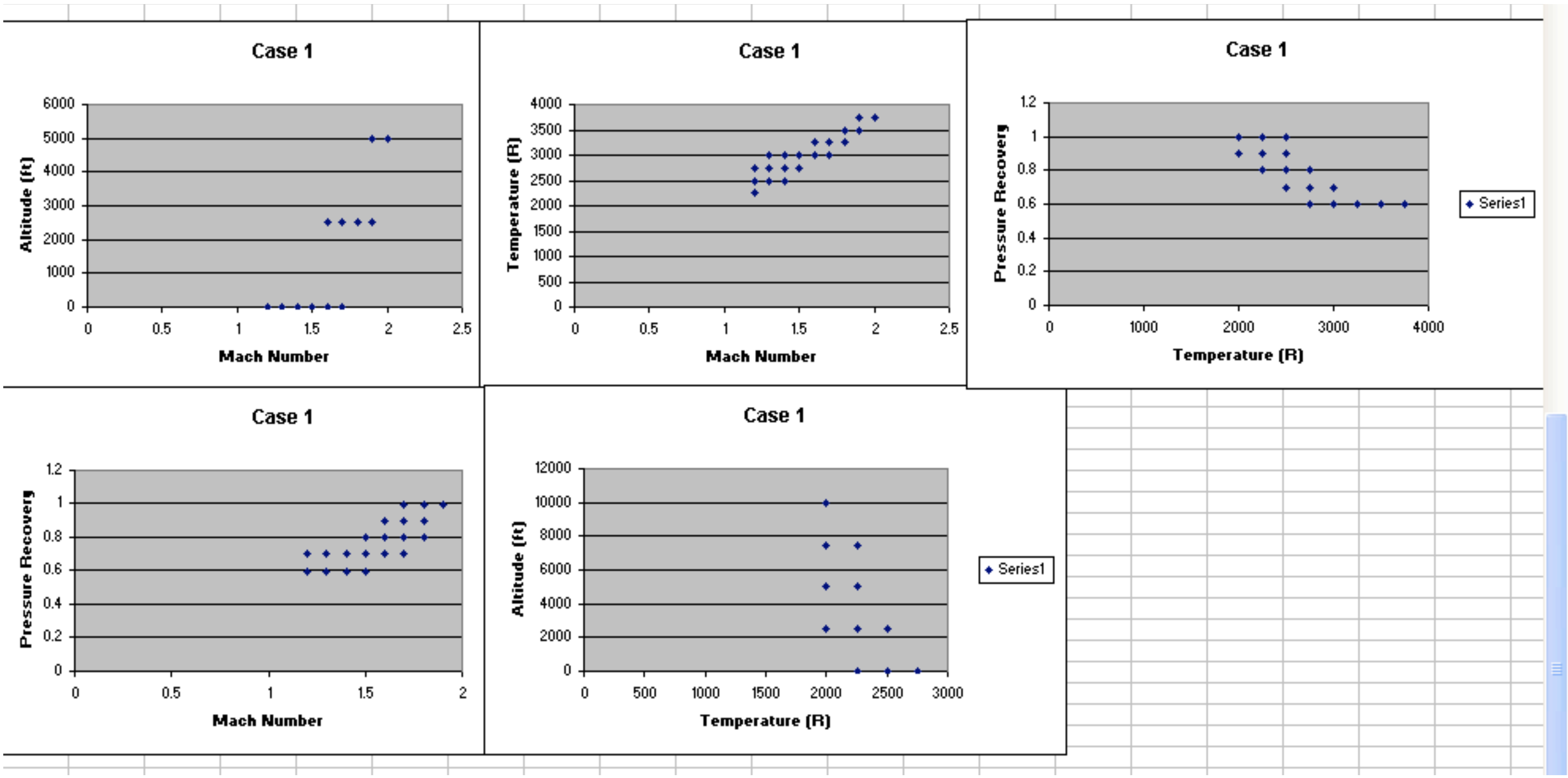
Green denotes 0 lbs<Thrust<100 lbs

Red denotes either Thrust >100 lbs or Thrust <0 lbs

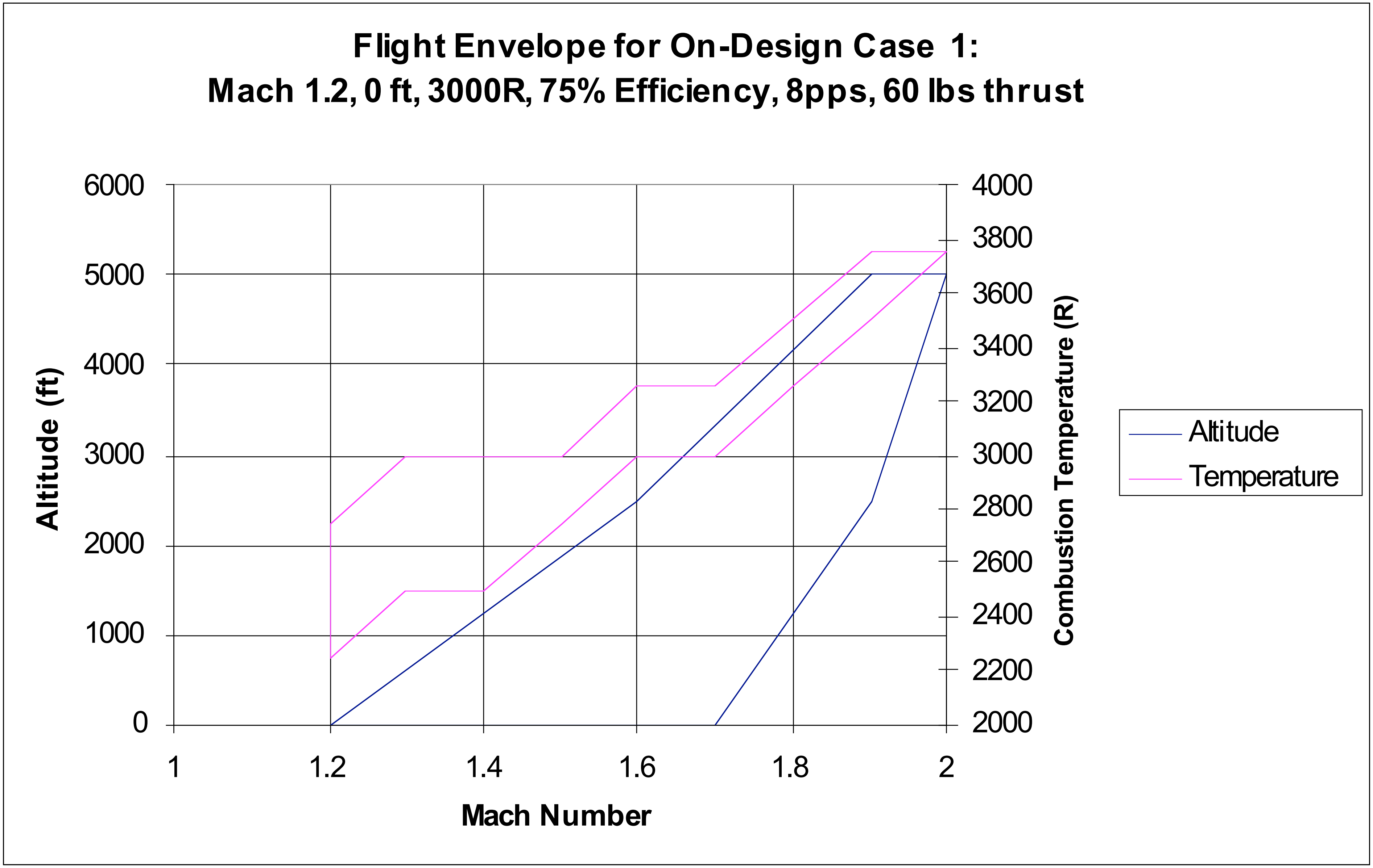


Determination of Acceptable Flight Regimes (cont'd)

Data points represent green areas from previous slide



Flight Envelope Graphs



Future Studies

- Continue/Complete Design of Launch Assist Ramjet for Existing Linear Motors
- Launch Assist Trajectory Analysis Including Air-Breathing Ramjet
- Big Air-Breathing Ramjet (BARJ)
  - 100,000 lbs of thrust

Acknowledgments

Kurt Kloesel

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Jonathan Pickrel

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Tiffany Scott

Krista Shipley

Softball Buddies


Questions?