Inviscid Design of Hypersonic Wind Tunnel Nozzles for a Real Gas

(AIAA Paper 2000-0677)

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38th Aerospace Sciences Meeting & Exhibit, Jan. 2000, Reno, NV

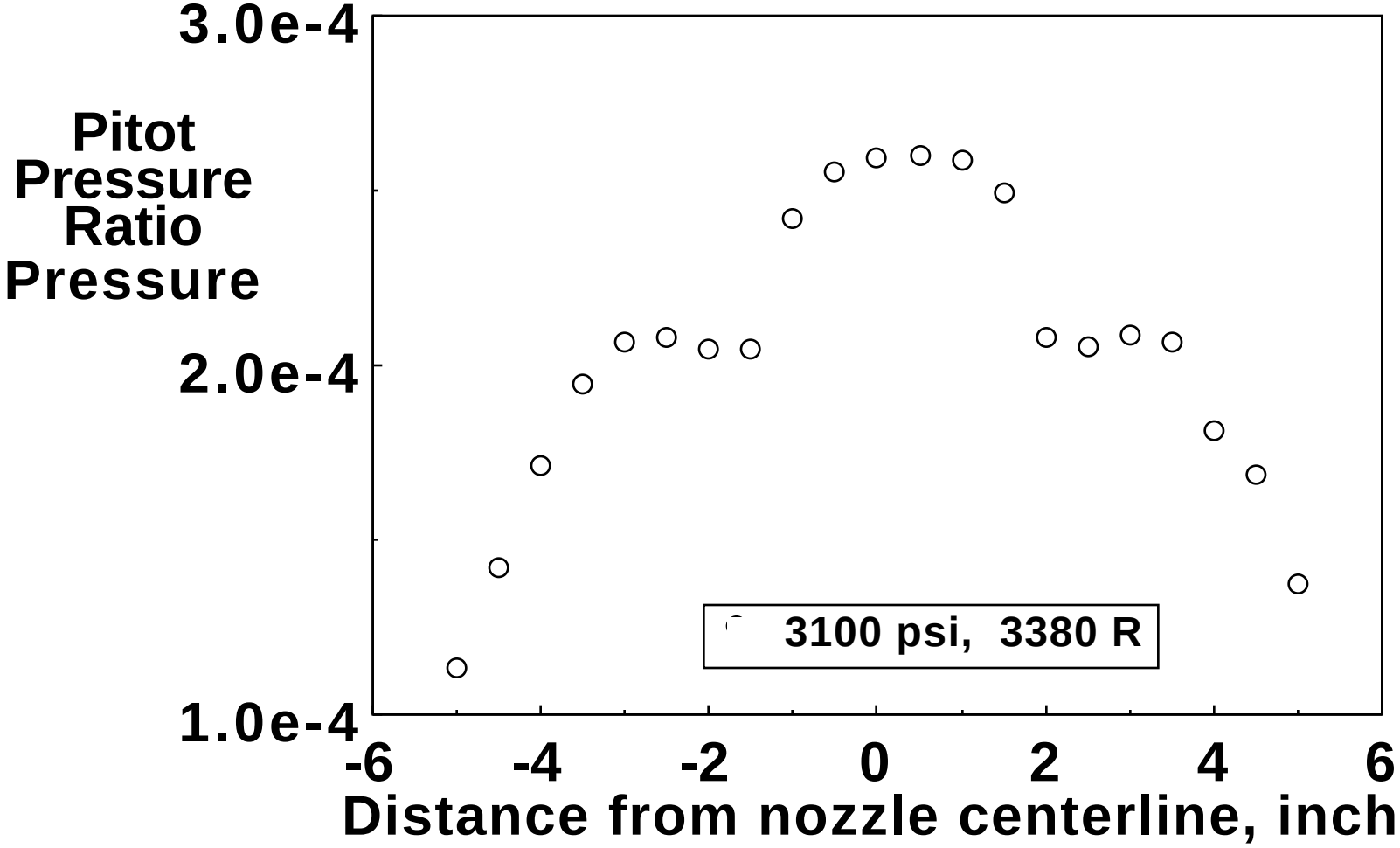
Outline

- Motivation
- Real Gas Design Procedure
- Design Example
- Summary

Motivation

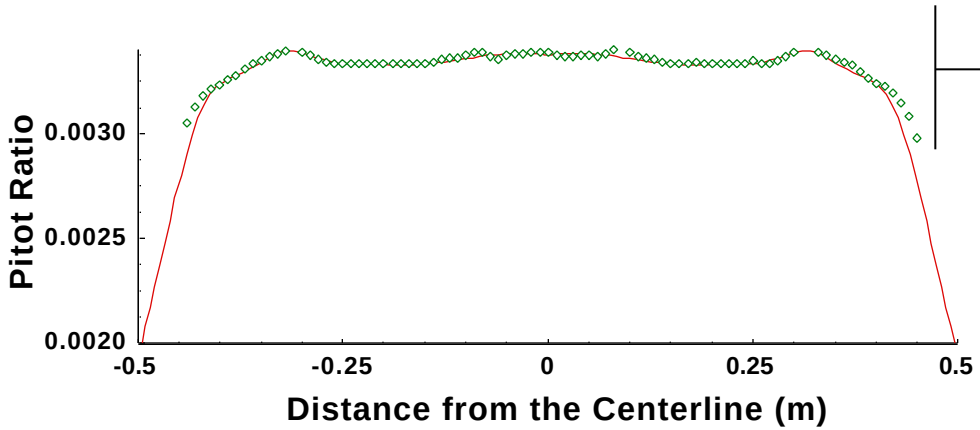
- Many examples of poor flow quality of wind-tunnel nozzles designed for a real gas because
  - Poor aerodynamic design
  - Real gas behavior not considered in the design
  - Thick boundary layers
    - Method-of-characteristics/boundary layer becomes invalid
  - Inaccurate machining and mechanical design
  - Facility constraints

Pitot Pressure Survey for Mach 17, Nitrogen Tunnel



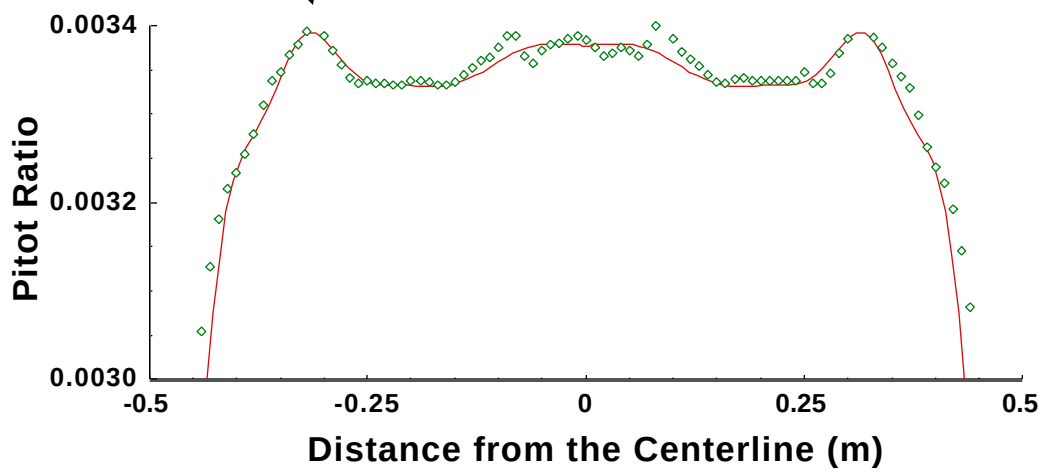
Use CFD to Evaluate Flow Quality

(Comparison with Pitot data for Mach 10, Air)



Computed solution before nozzle construction

Expanded Scale

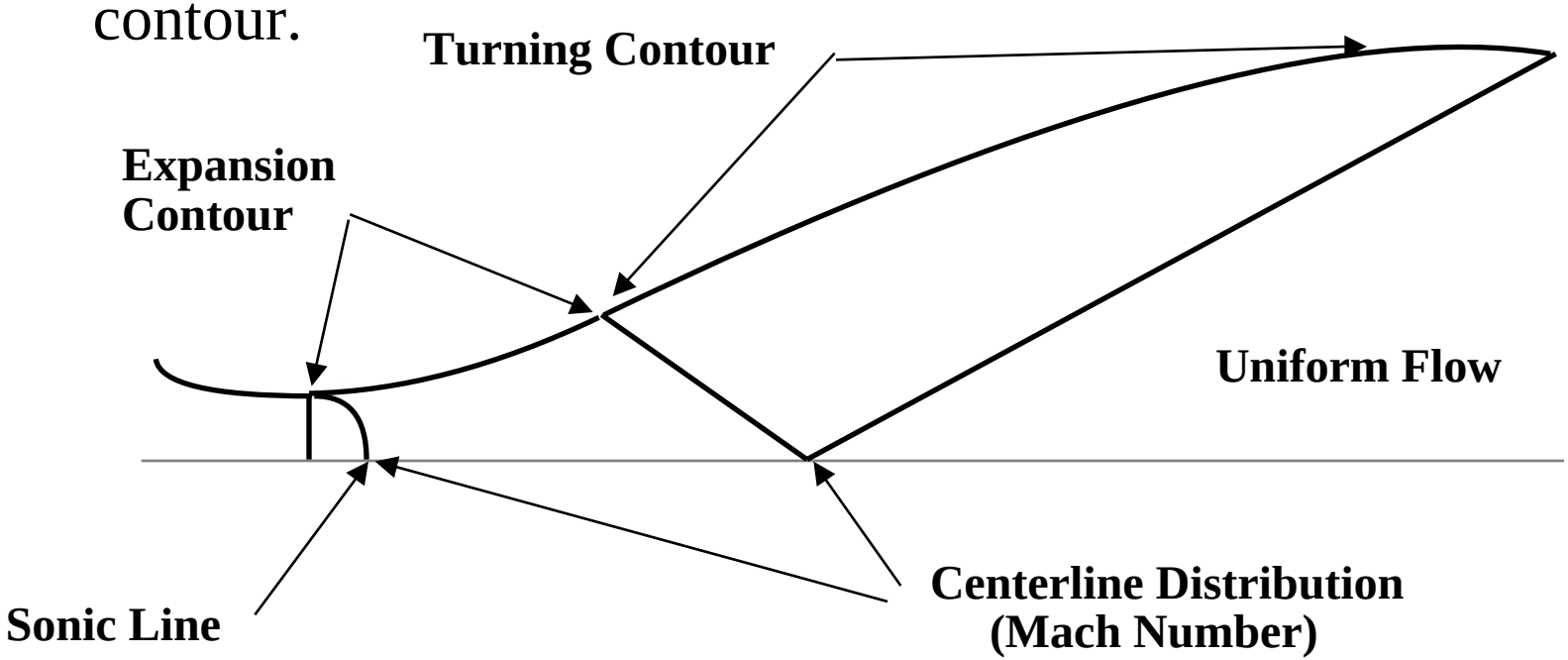


Motivation (concluded)

- Many examples of poor flow quality of wind-tunnel nozzles designed for a real gas because
  - *Poor aerodynamic design*
  - Real gas behavior not considered in the design
  - Thick boundary layers
    - MOC/BL becomes invalid
  - Inaccurate machining and mechanical design
- Typical inviscid contour methods inadequate for a real gas
- Need for quick real gas contour design
  - Classical boundary-layer correction
    - Shock tunnels (have thin BLs)

Wind-Tunnel Nozzle Design

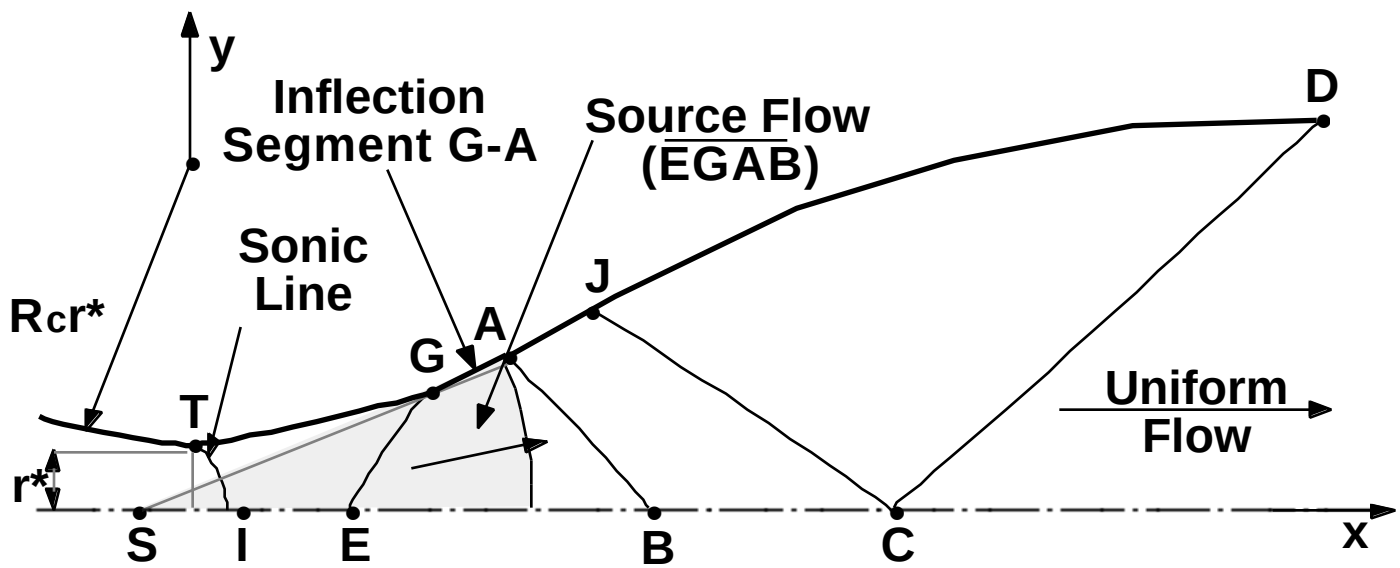
- Design Problem - Given an inflow condition, a centerline Mach number distribution, and uniform outflow, determine the wall contour.



- Additional Items for Real Gas Design -
  - Area Ratio
  - Ratio of specific heats; $\gamma(p,T)$
  - Compressible Effects ($Z=PV/MRT$)

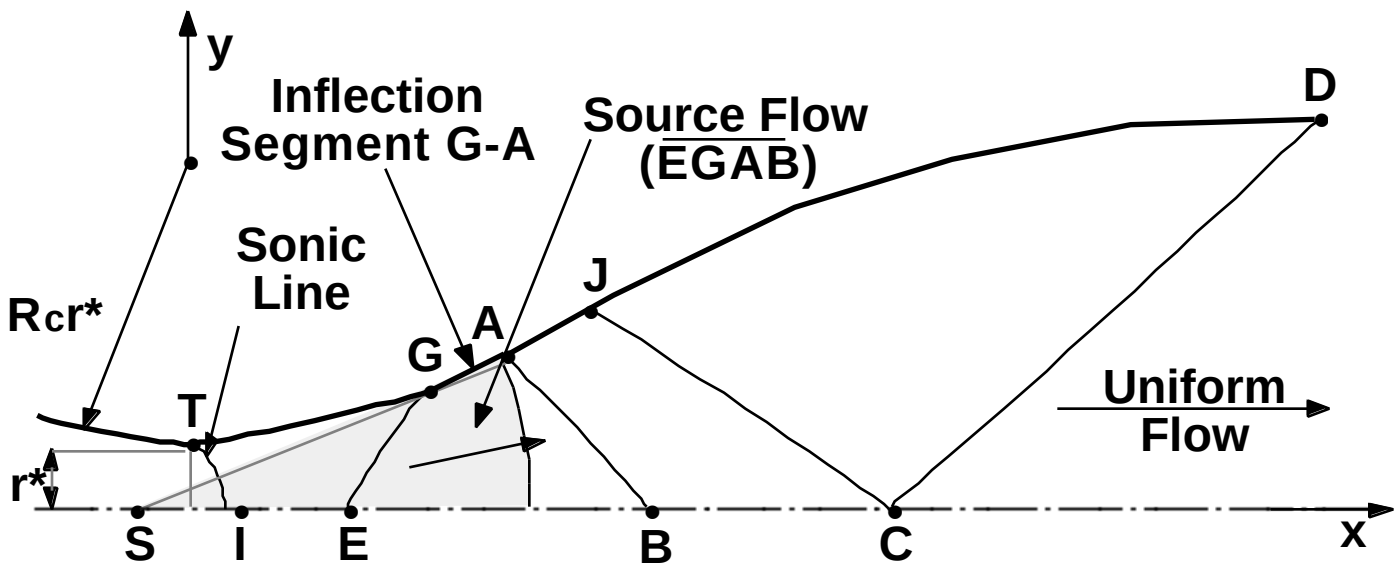
Sivells Design Philosophy (Ideal Gas)

- Continuous Wall Curvature
  - Specify the centerline Mach number distribution such that the MOC design results in a wall with continuous curvature
  - CFD-based optimization procedure based on this principle



Real Gas Design Philosophy

- Continuous Wall Curvature
- Demonstrate using Sivells ideal gas code to design parts of the real gas design
- Key: Use the conical section to adjust for area ratio



Inviscid Wind Tunnel Nozzle Design Procedure for a Real Gas

Step 1: Subsonic Throat Region

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Step 2: Geometric Area Ratio (real gas, contraction effects)

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Step 3: Throat to Conical Section Design (Sivells code)

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Step 4: Turning Contour Design (Sivells code)

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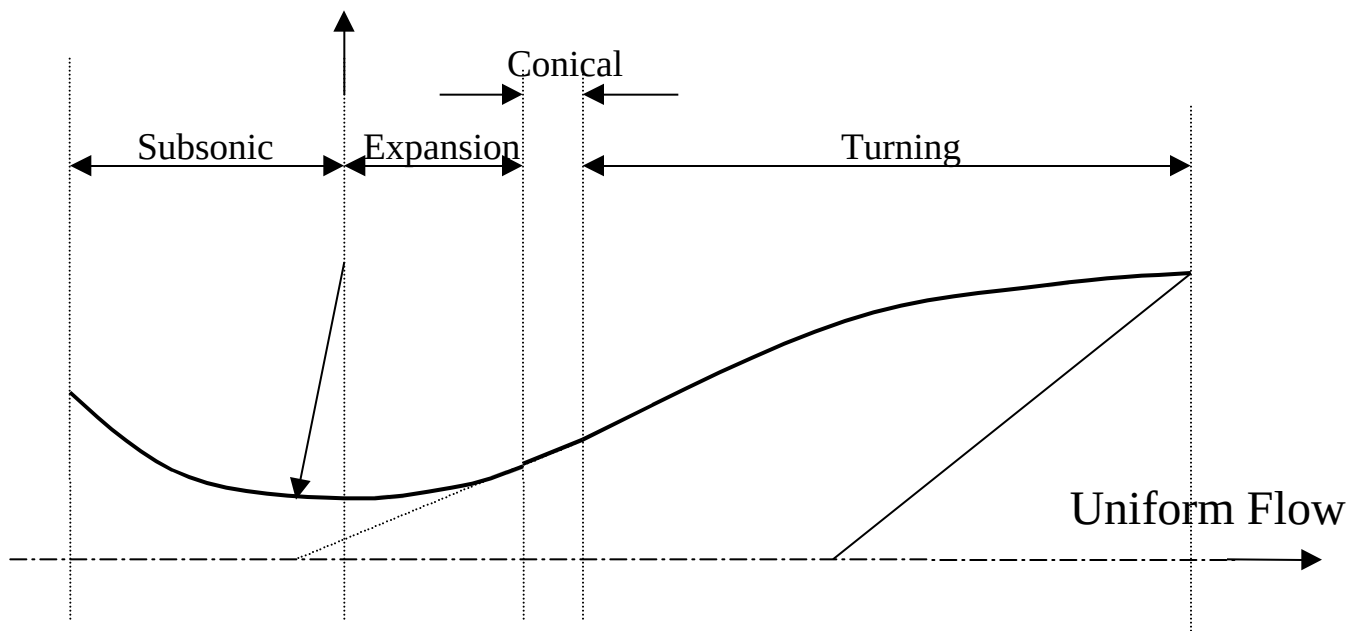
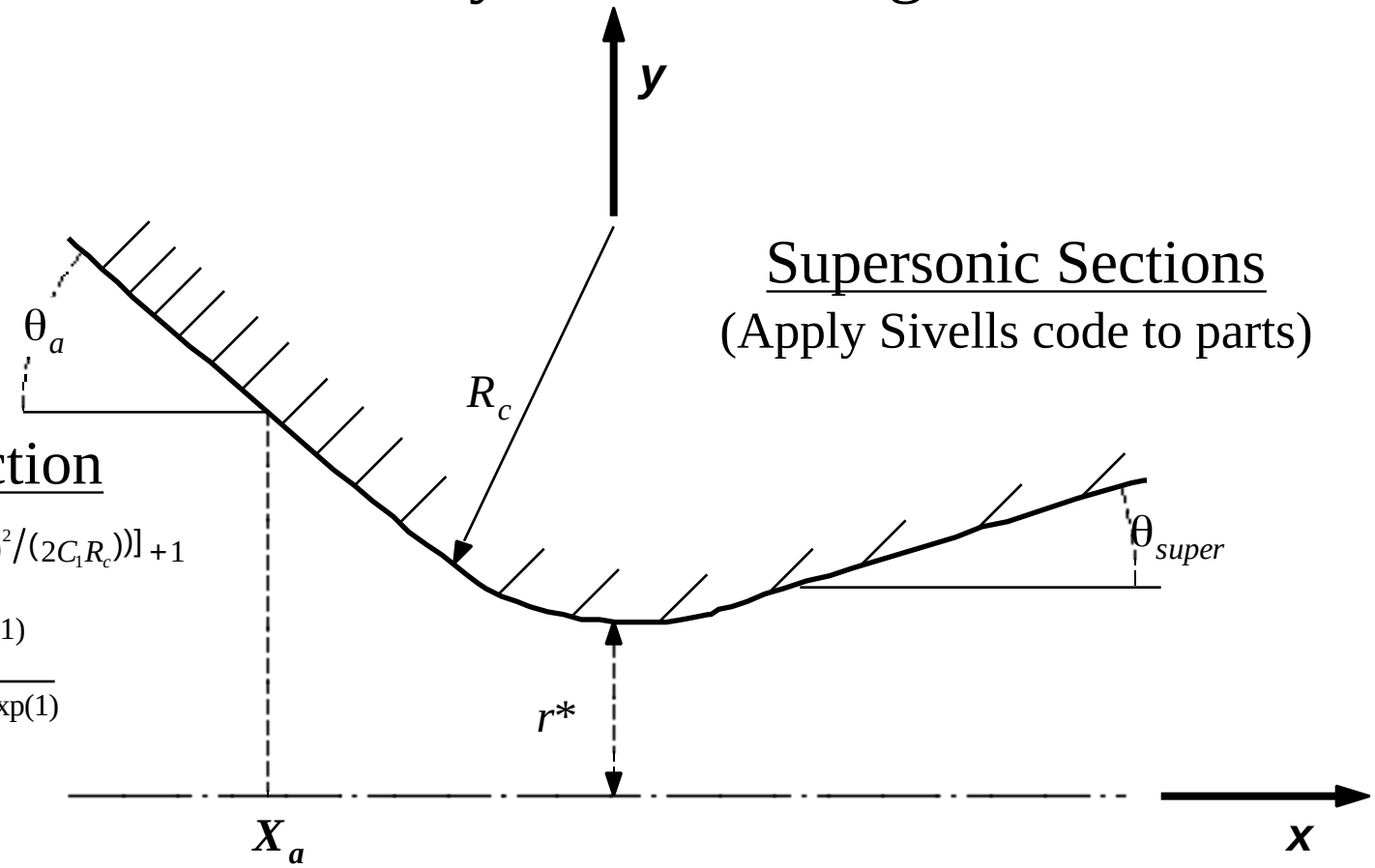
Step 5: Assembling/Scale the Inviscid Design



Geometry in Throat Region



Supersonic Sections

(Apply Sivells code to parts)

Subsonic Section

$$y_w / r^* = C_1\left[1 - \exp\left(-(x / r^*)^2 / (2C_1R_c)\right)\right] + 1$$

$$C_1 = R_c \tan^2(\theta_a)\exp(1)$$

$$X_a / r^* = -R_c \tan(\theta_a)\sqrt{\exp(1)}$$

$$C_D = 1 - \frac{\gamma + 1}{96S^2}\left[1 + \frac{8\gamma - 2}{24S} + \frac{75\gamma^2 - 757\gamma + 3615}{2880S^2} + \ldots\right]$$

Example Problem

Wind Tunnel Nozzle Designs

Case 1: Real Gas Design Using New Procedure

Case 2: Ideal Gas Design, For Comparison

Constraints

All parameters same except γ & Z

Compare CFD computed Mach number and flow angle

Case	1	2
Nozzle Design	Real Gas	Ideal Gas
CFD/Analysis	Real Gas	Ideal Gas

Design Conditions

Design Mach Number: 14

Gas Composition: Nitrogen

Total Pressure: 20,000 psi

Total Temperature: 3,000 ºR

Area Ratio:

- Ideal Gas (γ=1.4) = 2686
- Caloric imperfect gas = 3232.
- Real Gas (Zstag=1.312) = 2396.87 — Case 1
- Ideal Gas(γ=1.4073) = 2396.87 — Case 2

Geometry

- subsonic approach angle = 45º
- ratio of radius of curvature/throat = 3.0
- source flow angle = 12.0º
- throat radius = 1.0
- type = axisymmetric

CFD Validation of Design

- Real Gas Model of Nitrogen (AIAA 92-4010)

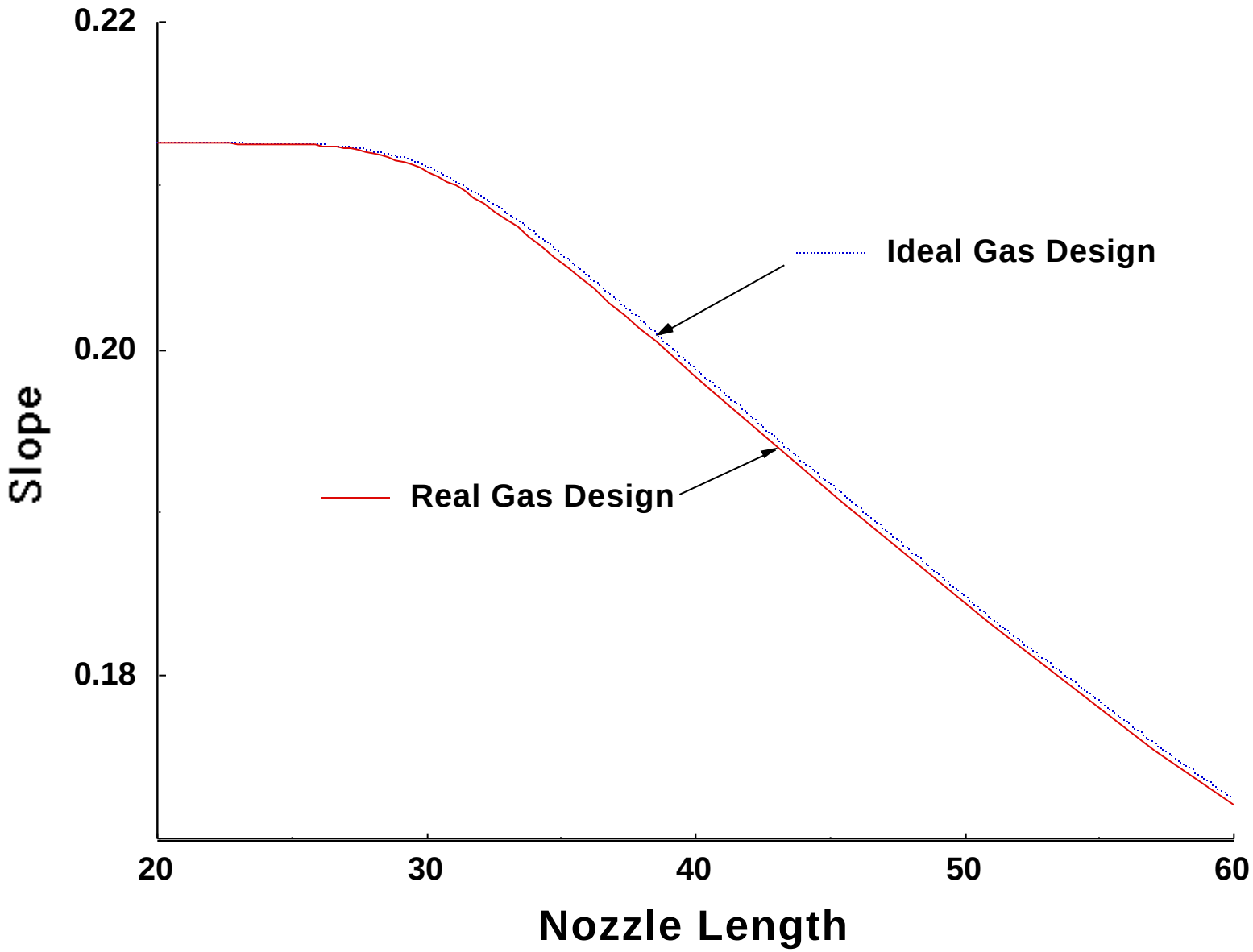
$$p = \rho RT/(1-\rho b)$$

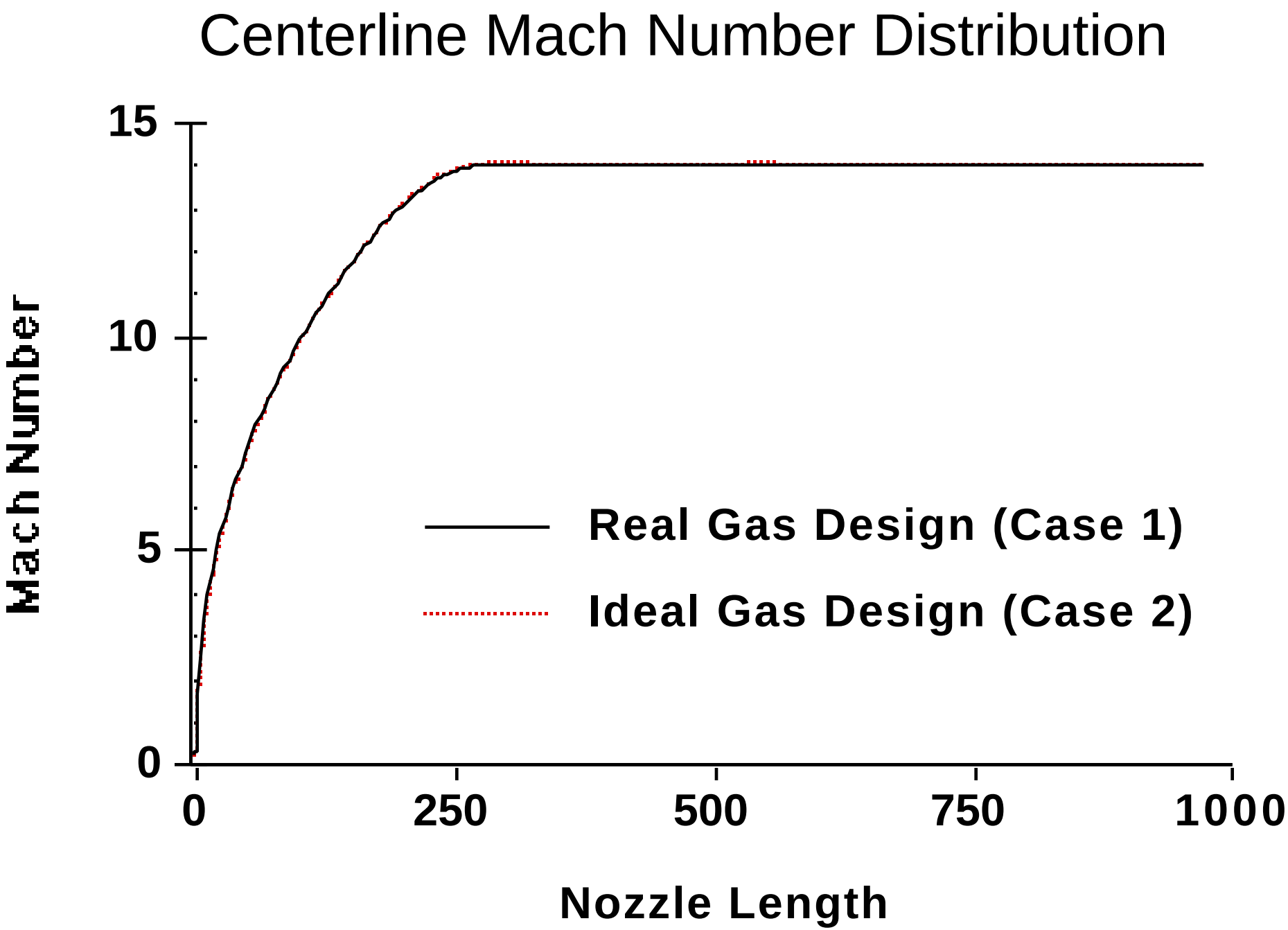
$$e(T) = \int c_v(T)\,dT$$

$$c_v(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5$$

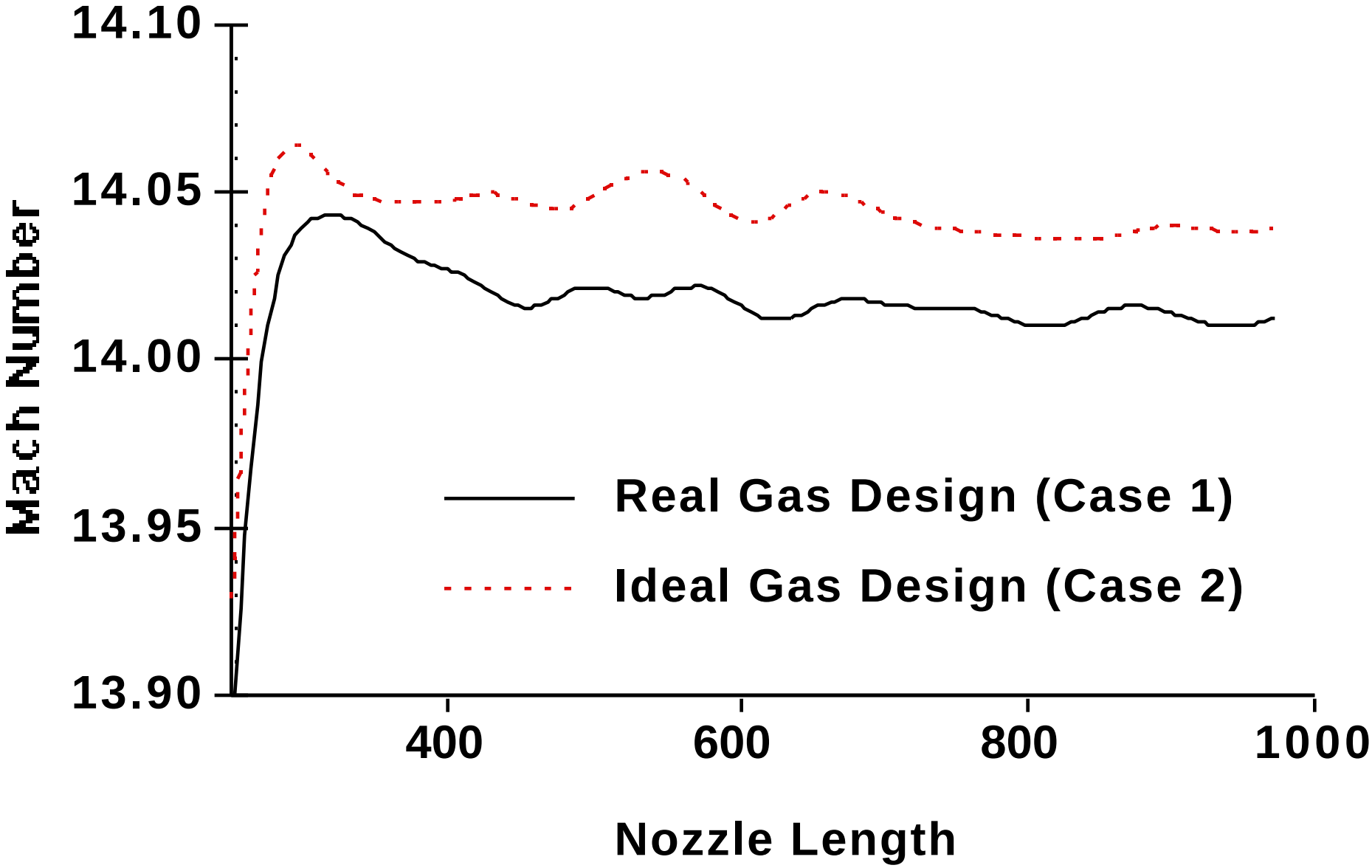
- CFD Solution
  - Unsteady Euler Solution for Subsonic/Transonic Section
  - Marching Euler Solution for Supersonic/Hypersonic Section

Comparison of Nozzle Slopes

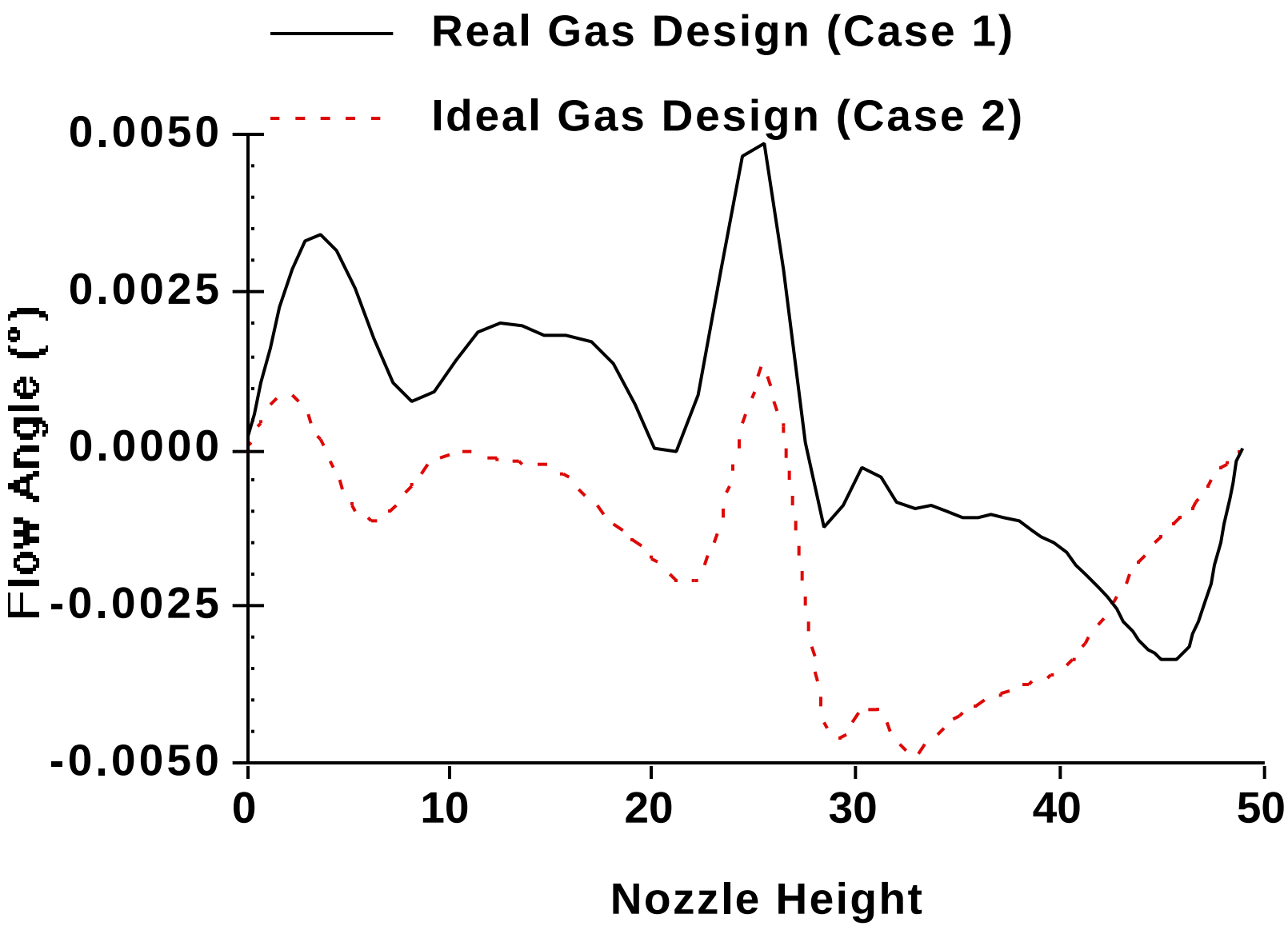


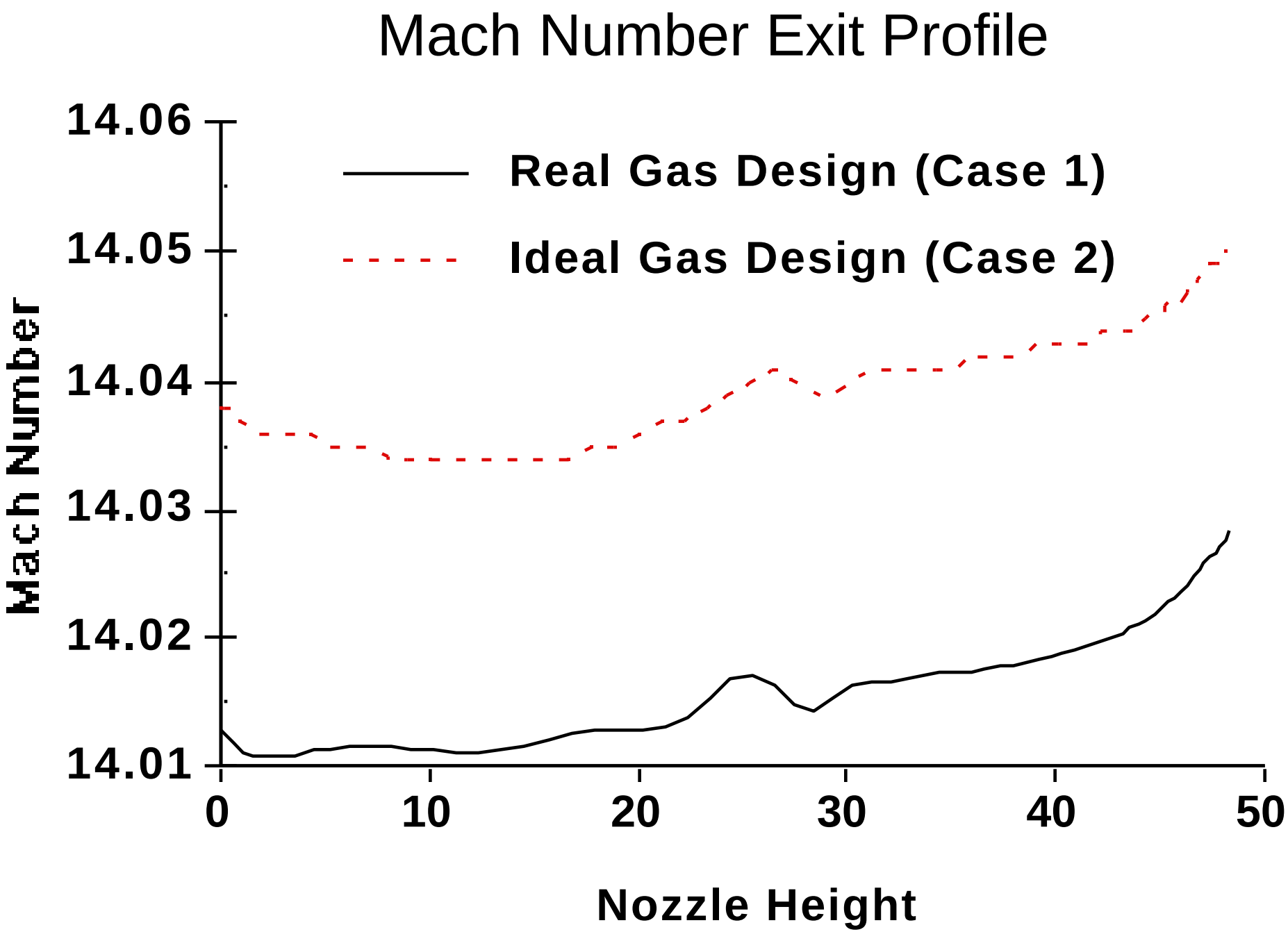

Centerline Mach Number Distribution
Mach Number
15
10
5
0
0
250
500
750
1000
Nozzle Length
Real Gas Design (Case 1)
Ideal Gas Design (Case 2)

Centerline Mach Number Distribution



Flow Angle Exit Profile




Mach Number Exit Profile
Real Gas Design (Case 1)
Ideal Gas Design (Case 2)
Mach Number
14.06
14.05
14.04
14.03
14.02
14.01
0
10
20
30
40
50
Nozzle Height

Nozzle Designed Using Real Gas Procedure

- NASA Langley Research Center
  - HTT pilot facility, Mach 5, products CH4+air
  - Arc-Heated Scramjet Test Facility, Mach 6, air (in process)
- CALSPAN, Buffalo NY
  - LENS, Mach 8, air (AIAA 96-0585)
  - LENS, Mach 4.5, air

Summary

- A procedure for real gas inviscid wind-tunnel nozzle design was presented
- An example design was presented
  - Wall coordinates are given in the paper
- Flow quality of real gas design procedure was evaluated using CFD
  - Real gas design gave excellent flow quality based on CFD analysis
  - Variations in Mach number and flow angle were similar to the variations obtained when designing for an ideal gas, with minor variations in absolute values
- Method has been used at Langley Research Center and elsewhere to design hypersonic wind-tunnel nozzles with good success
- Design should be validated using CFD to ensure nozzle flow quality