Evidence of Standing Waves in Arc Jet Nozzle Flow

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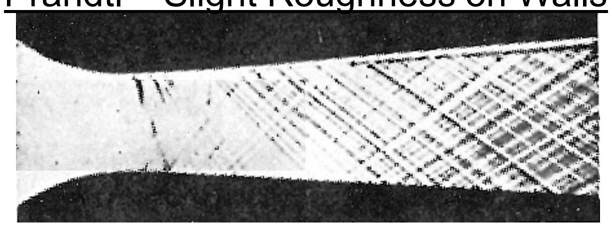
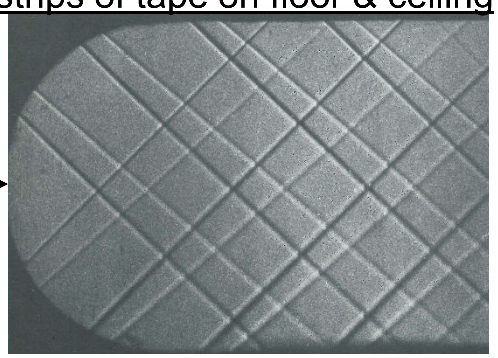
Examples of Waves from small disturbance on nozzle walls (supersonic flow)

Prandtl – Slight Roughness on Walls

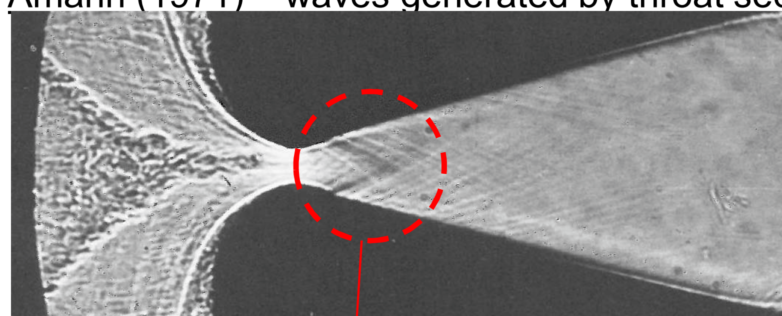


AEDC – strips of tape on floor & ceiling

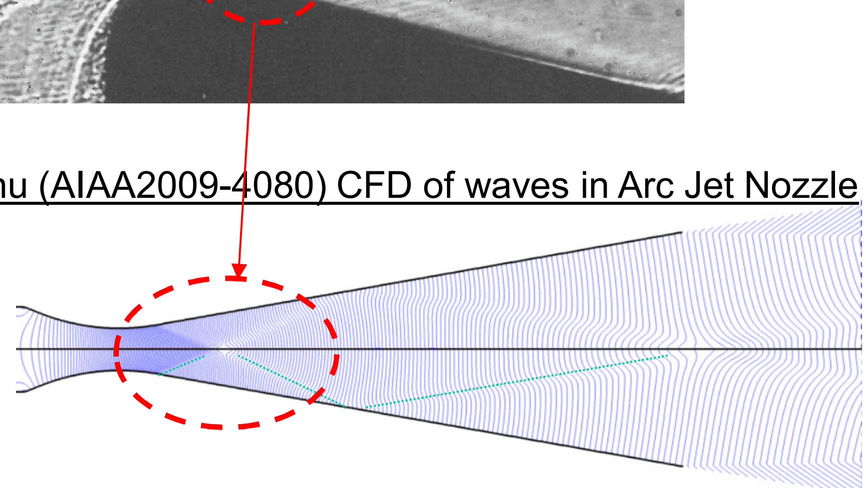
M=1.5



Amann (1971) – waves generated by throat section

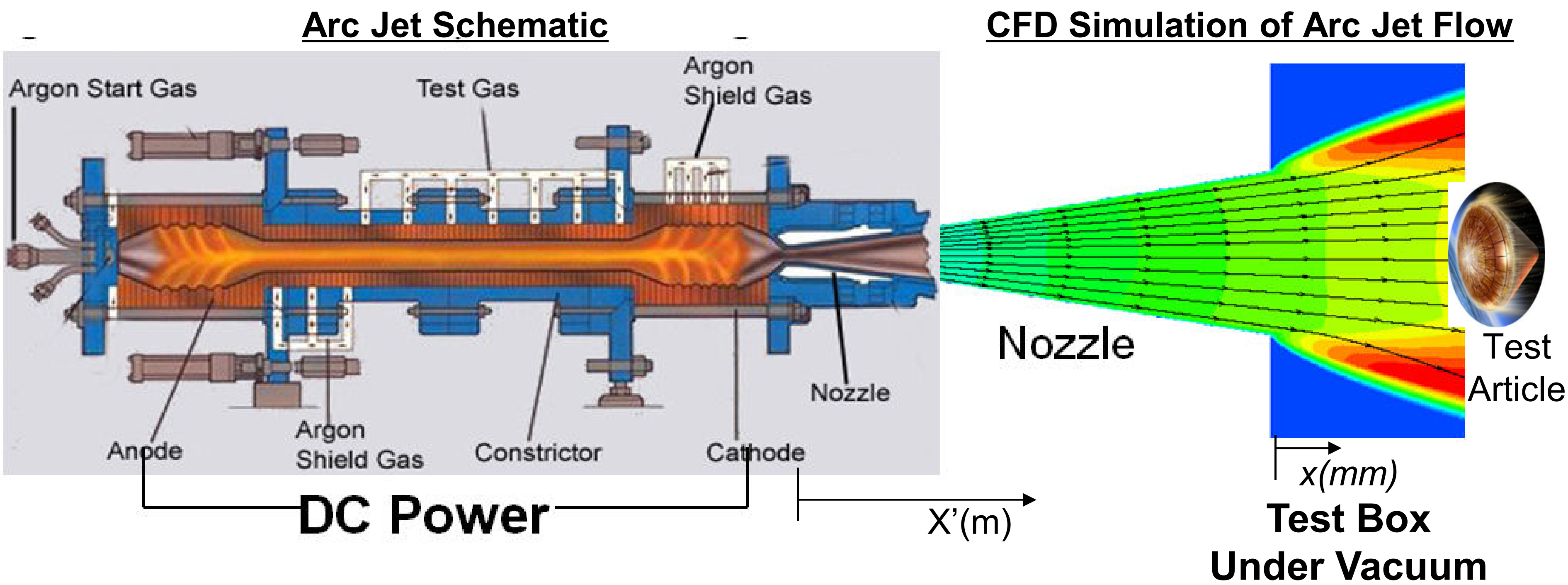


Prabhu (AIAA2009-4080) CFD of waves in Arc Jet Nozzle



NASA Ames Arc Jet Facility

- Flow is heated by an Electrical Arc
- Super heated flow is accelerated through a converging/diverging nozzle to M>4



- Arc jet provides a realistic atmospheric entry environment for testing heat shield material
  - High Enthalpy
  - Aerodynamic and Thermal Loads
- Arc Jet testing is a key part of Thermal Protection Systems development / qualification
- Nozzle exit diameter can be varied from 152 mm to 1041 mm by adding nozzle segments
- The 152 mm (6") and 330mm (13") nozzles are popular – customers wanted a 229mm (9")

Outline

New IHF 9” Nozzle Checkout

- New 9” (229mm) exit diameter nozzle for the Interactive Heating Facility (IHF) intermediate nozzle (between 6” and 13”) designed to facilitate adding radiative heating to a wedge test article (with new 100KW laser)
- Initial checkout of the nozzle using stagnation test articles
- Teflon “Burn” patterns
- Radial Sweeps with Pressure and Heat Flux Probes
- Instrumentation study with spectral emission and Laser Induced Fluorescence

In the process of Checkout

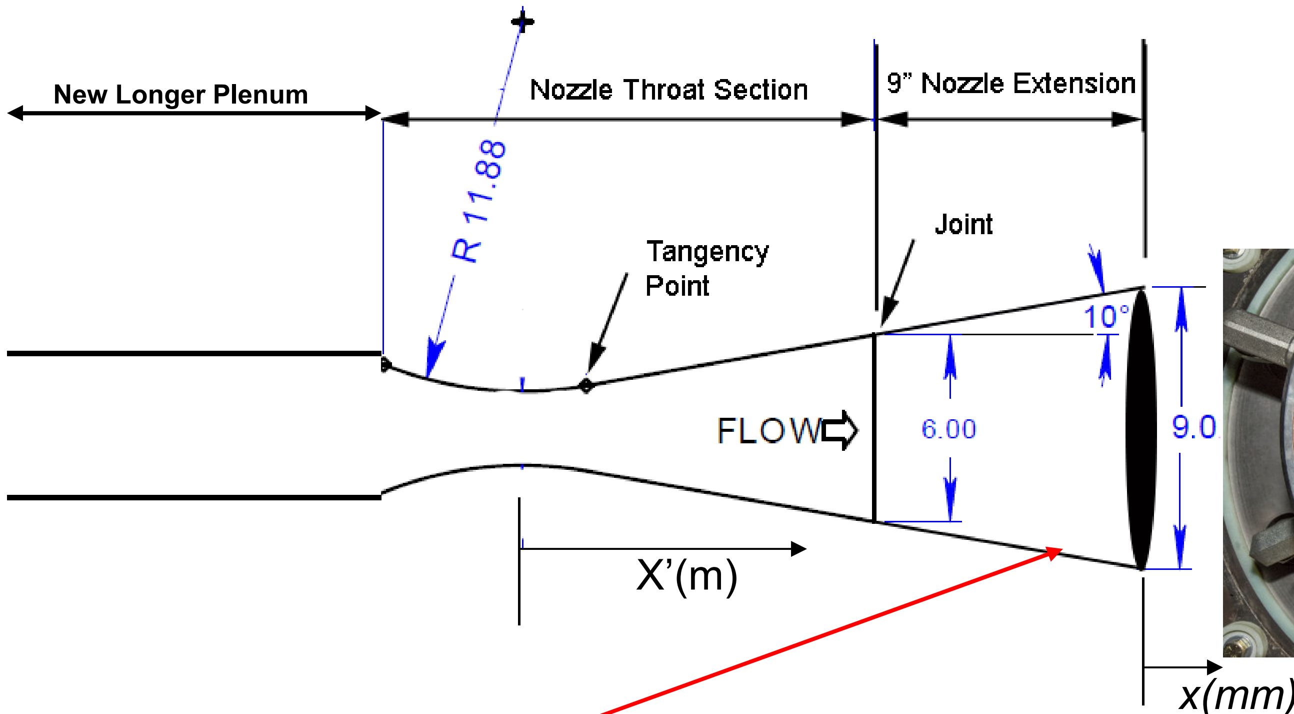
- Non-uniform burn patterns on Teflon test articles (at x=127mm and 178mm)
- Experimentally Observed standing waves in the IHF nozzle
- CFD with real gas effects (follow up to Dinesh Prabhu AIAA 2009-4080)
- Simulation of test articles
- Proposal for Alternate Nozzle Design (wave free)

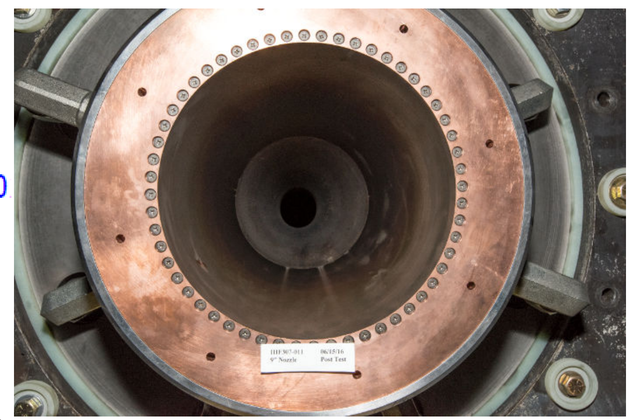
Acknowledgement

This work was partially funded under the NASA Strategic Capabilities Assets Program (SCAP) and the Laser-Enhanced Arc Jet Facilty (LEAF) programs.

New IHF 9” Nozzle Check Out

IHF 9” Nozzle with Long Plenum Chamber





Features

- Extension of IHF 6” (152mm) nozzle throat section
- Special attention to joint between IHF throat section and 9” (229mm) Extension
- Longer Plenum Chamber produces flatter enthalpy distribution (not discussed here)
- Desire better flow quality than was had with the IHF 8” (203mm) nozzle extension

9” Nozzle Check Out Test Plan

Range of Test Condition – spanning the test envelope

Test Conditions							Probe at x=76mm		
Case #	Current amps	Voltage Volts	Main Air gm/s	Add Air gm/s	Argon gm/s	P_{plenum} kPa	P_{stag} kPa	$q_{4\text{"Hemi}}$ W/cm2	H_{sonic} MJ/kg
CEV-a13	3450	2720	105	645	51	350	30.7	92	2.9
MSL-a1	3500	4795	330	551	59	593	52.3	350	7.2
MSL-c1	2000	3430	200	55	21	180	19.8	375	7.8
MSL-c4	3500	5910	546	55	42	555	52.0	706	15.6
MSL-c8	6000	6600	741	55	54	810	75.9	995	24.4

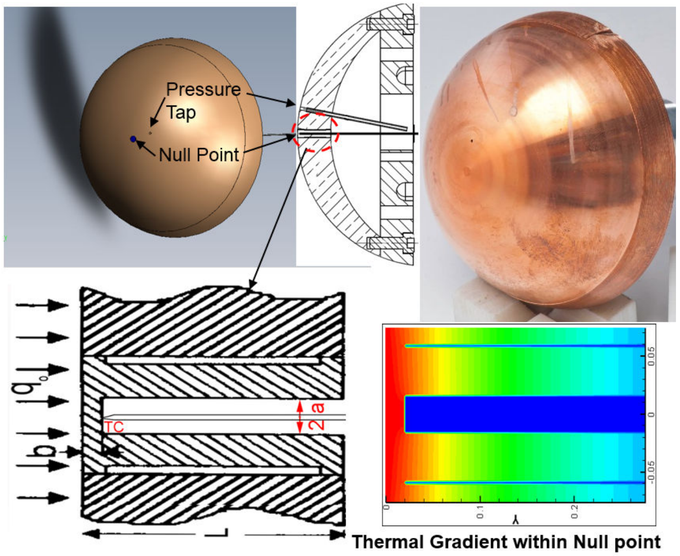
IsoQ Teflon Test Article Recession

Pre-Test

Post Test

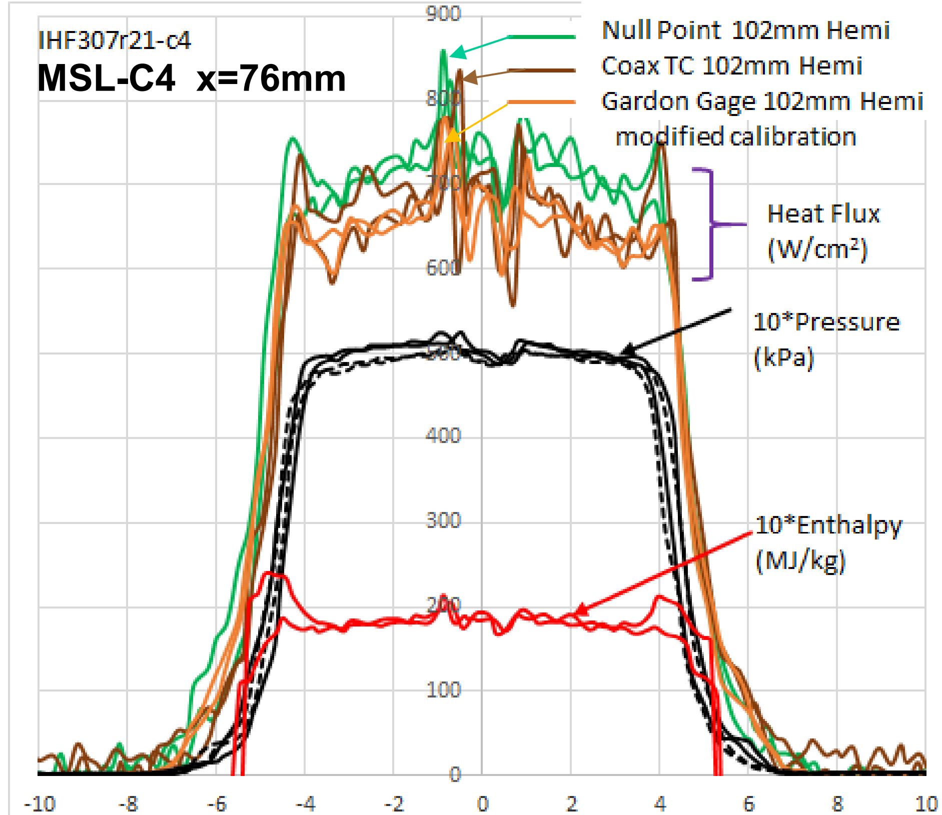
- IsoQ produces uniform heating across its face
- Teflon recession is proportional to heat rate
- Teflon “Burns” give global map of heat flux
- Asses uniformity of heating (aka flow quality)

Fast Response Probes (Null Pt & CoaxTC)



Radial Sweeps of Multiple Types of Heat Flux Sensors

4” Hemi with
Pressure tap



Radial Distance From Jet Centerline (inches)

<u>Fast Response Sensors (Null Point, CoaxTC, Gardon Gage)</u>

- Coax,NullPt & Gardon give similar shaped radial distribution of heat flux
  - Gardon Gage calibration adjusted to match Coax TC measurement
- Pressure measured with same probe as heat flux (orifice slightly off center)
- Relatively uniform distribution of Enthalpy (Enthalpy deduced from Fay-Riddell)

Teflon Burns as a function of Condition

c1 c4 c8 a1 a13

- Teflon Burns done at 76mm (x=3”) downstream of nozzle exit
- All Teflon was initially 4” IsoQ
- IsoQ shape preserved in most cases.
- C8 condition produced a little flatness in the center of the face
- Flow quality deemed to be good at x= 76mm
- However problems were discovered at downstream locations

Teflon Burns as a function of distance from the nozzle exit plane (at condition c4)

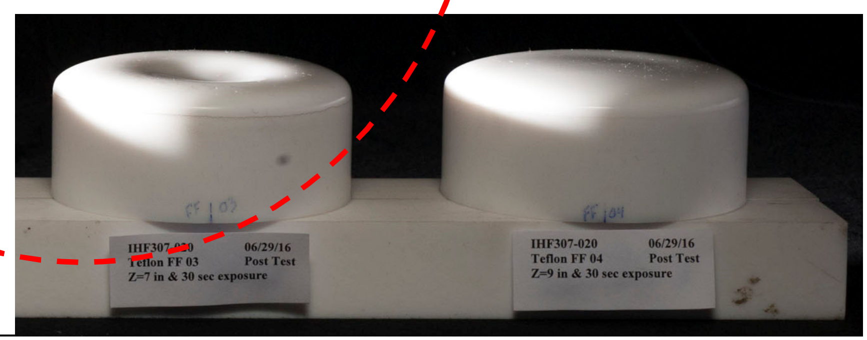
Initial Shape IsoQ

x=25mm x=76mm x=127mm x=178mm

Initial Shape Flat Face

x=25mm

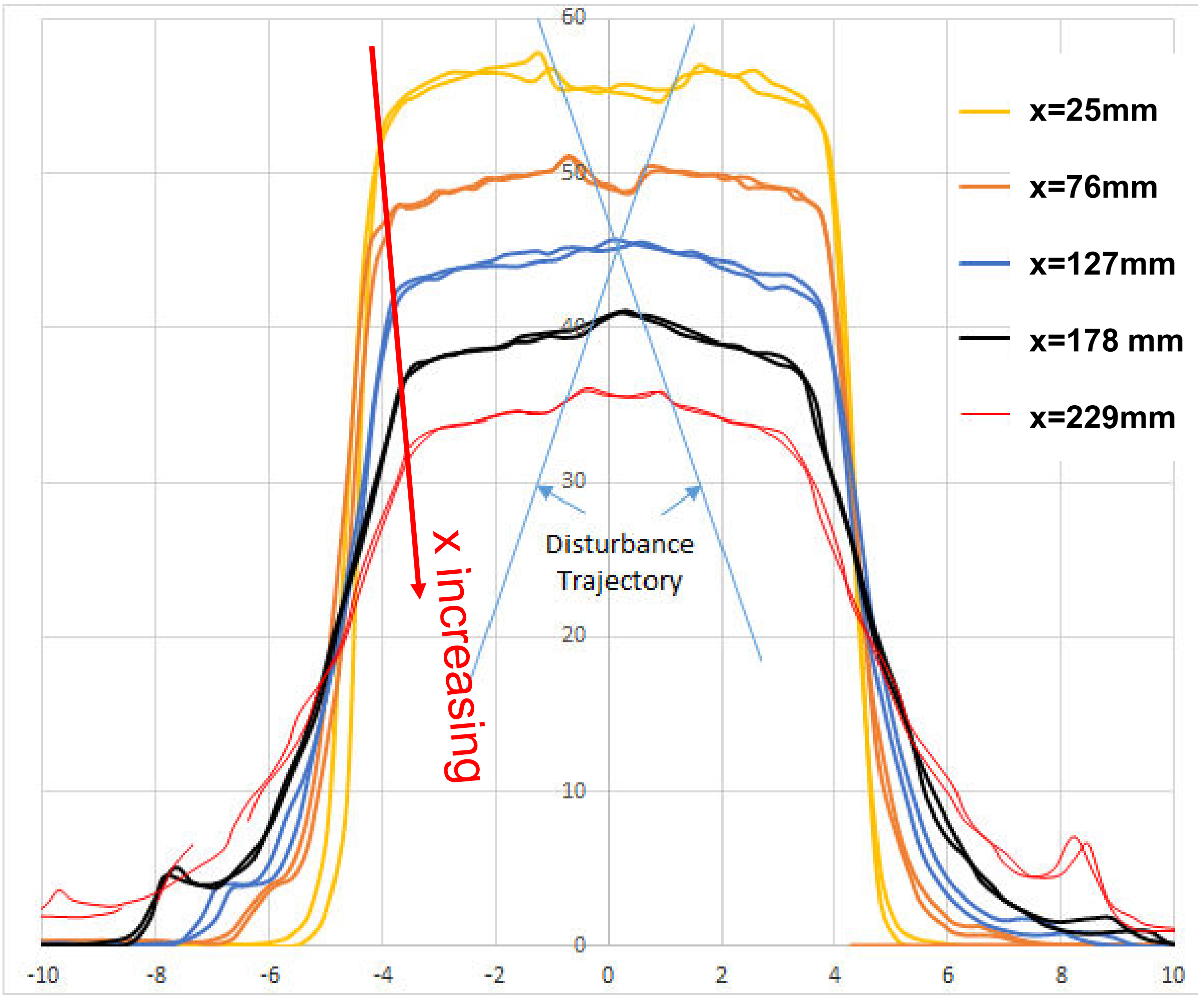
x=178mm x=229mm



Non-Uniform Burn patterns at x=127mm and 178m – why?

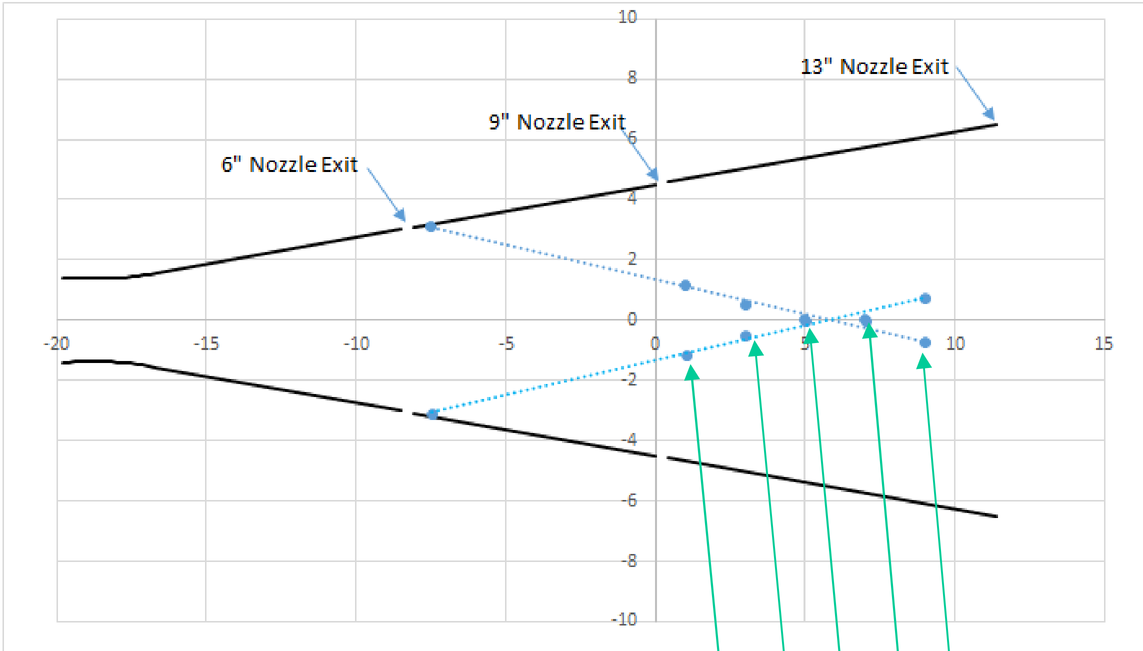
Radial Distribution of Stagnation Pressure at various x

At MSL-c4 → *i=3500amps, $m_{main}/m_{add}/m_{Ar}$ = 546, 55, 54 gm/s*



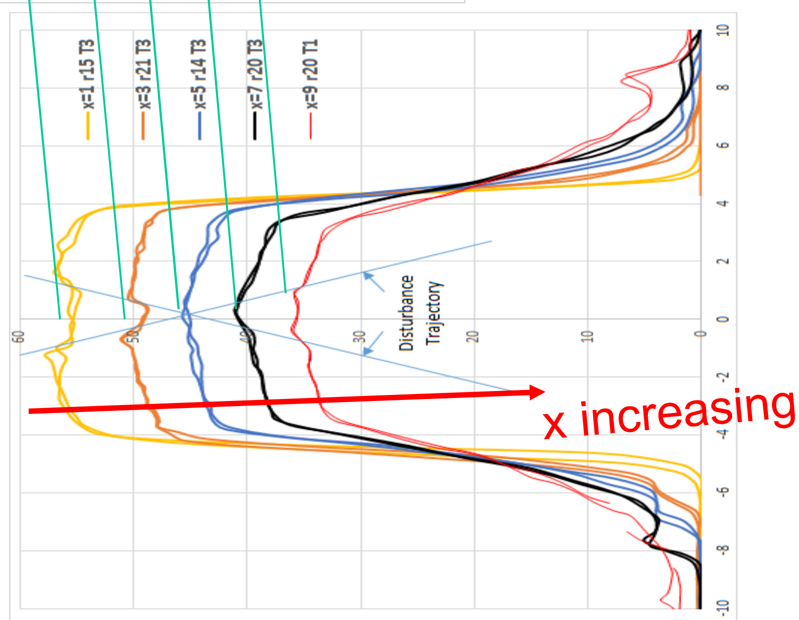
Local minimum in pressure seen upstream of x=127mm
Local maximum in pressure seen downstream of x=127mm

Width of Pressure Disturbance vs Axial Position

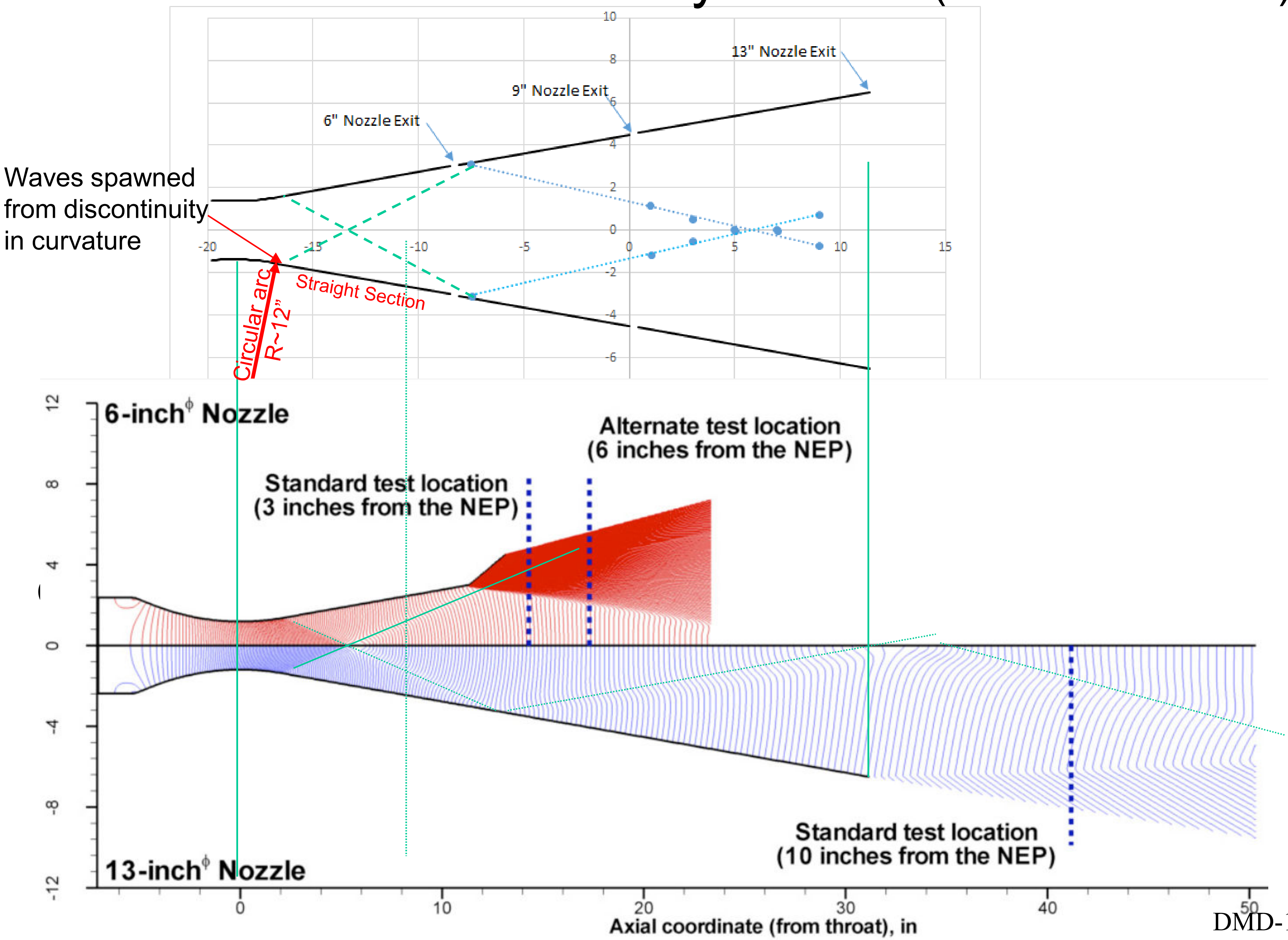


There appears to be a conical wave converging at x ~ 127mm

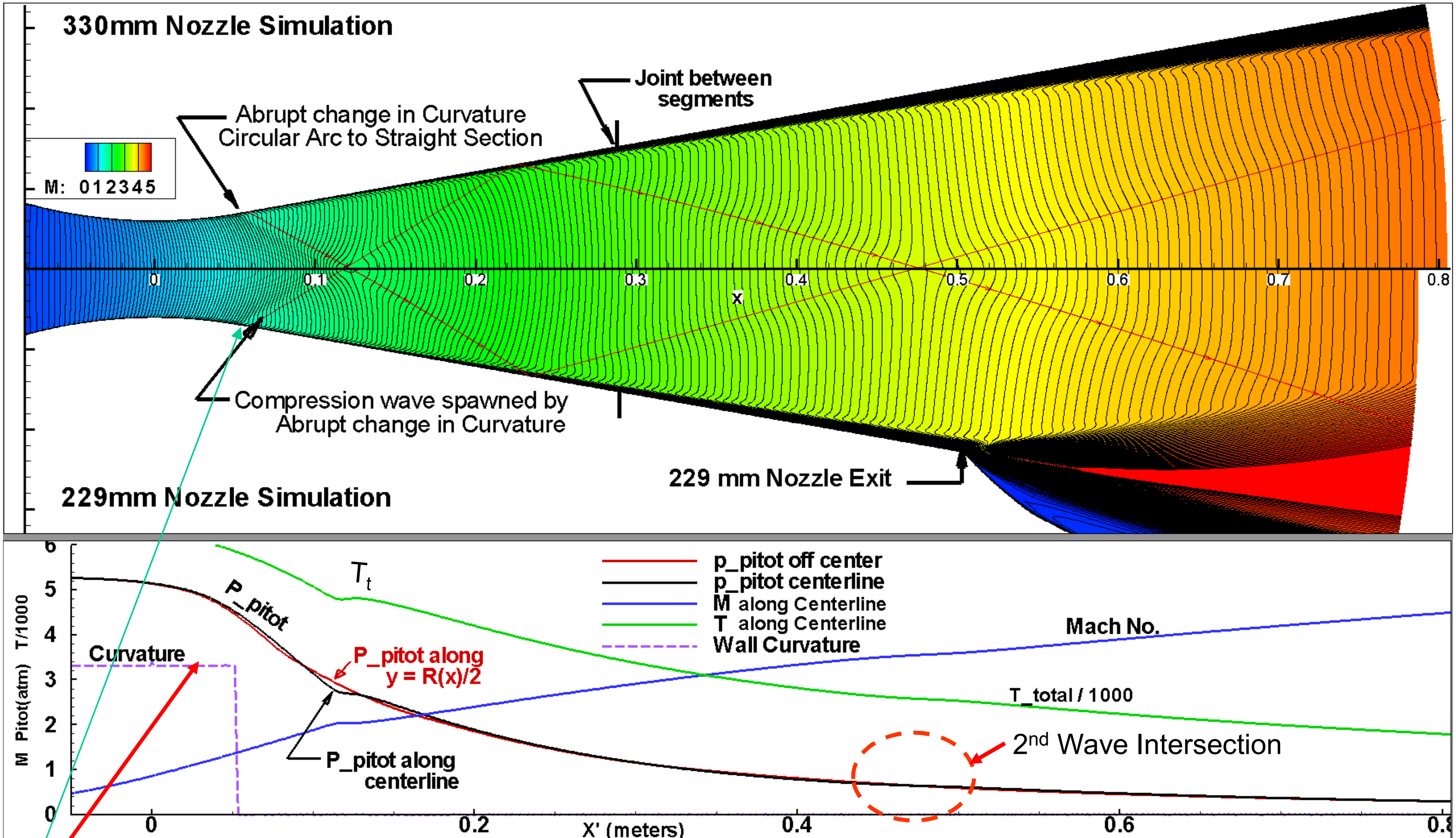
What is the source of the wave?



Waves Seen in CFD done by Prabhu (AIAA 2009-4080)



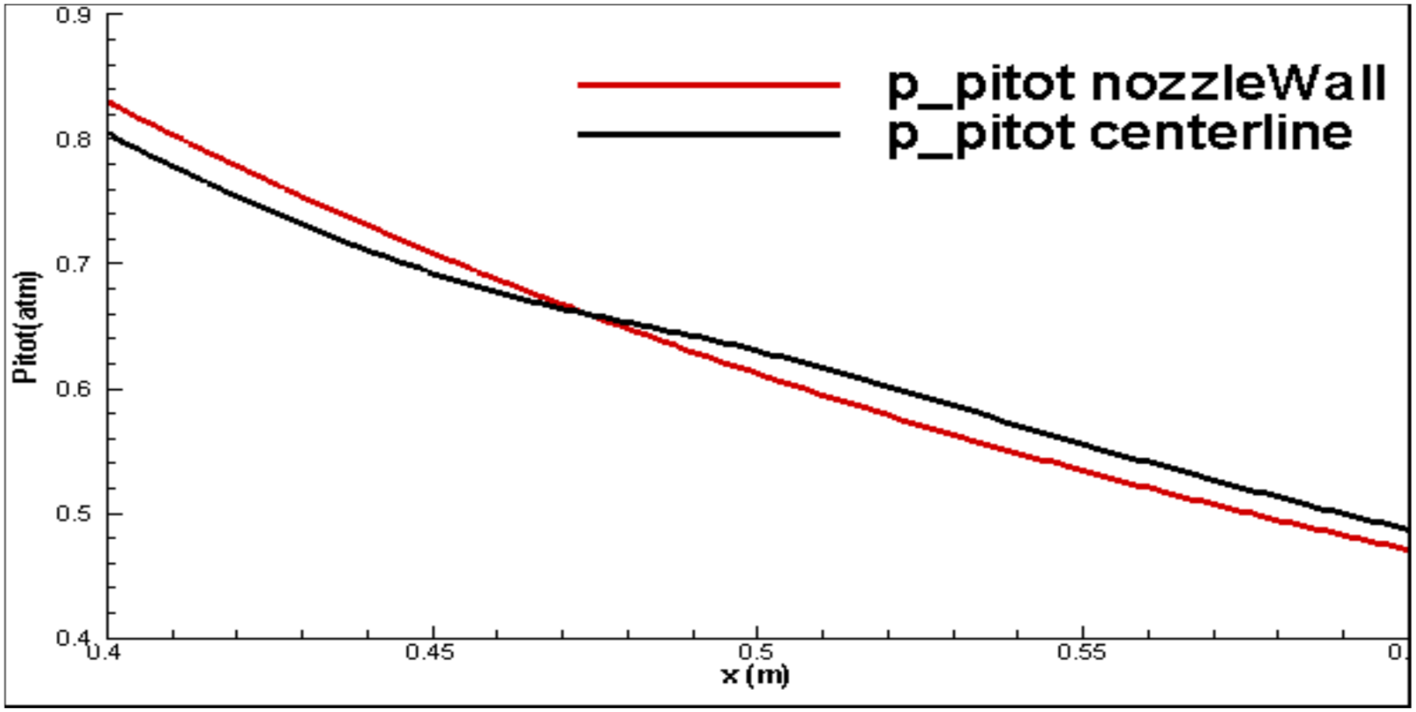
Nozzle Simulation of Existing IHF Throat



Constant Curvature followed by Abrupt change to zero Curvature

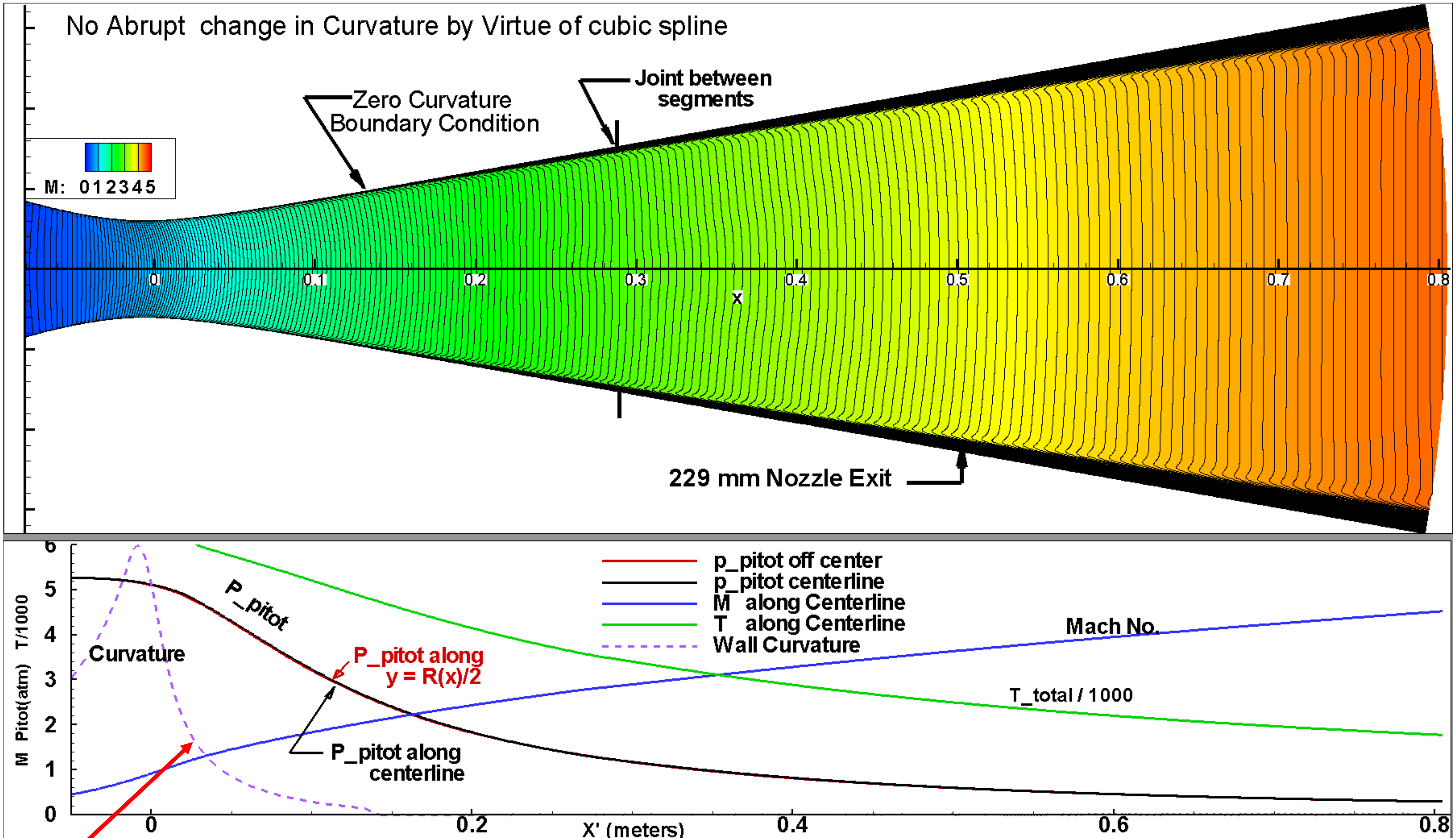
Compression waves spawned from Abrupt change in curvature

2nd Wave Intersection – Effect on Pressure



- There is a local minimum in pressure on the centerline of the flow ahead of the wave intersection point and a local maximum downstream
  – similar to what is seen in experimentally.
- What can be done to eliminate this wave?
  - ➢ Eliminate the discontinuity in curvature at the nozzle throat

Eric Noyes Proposed IHF Throat (cubic spline)

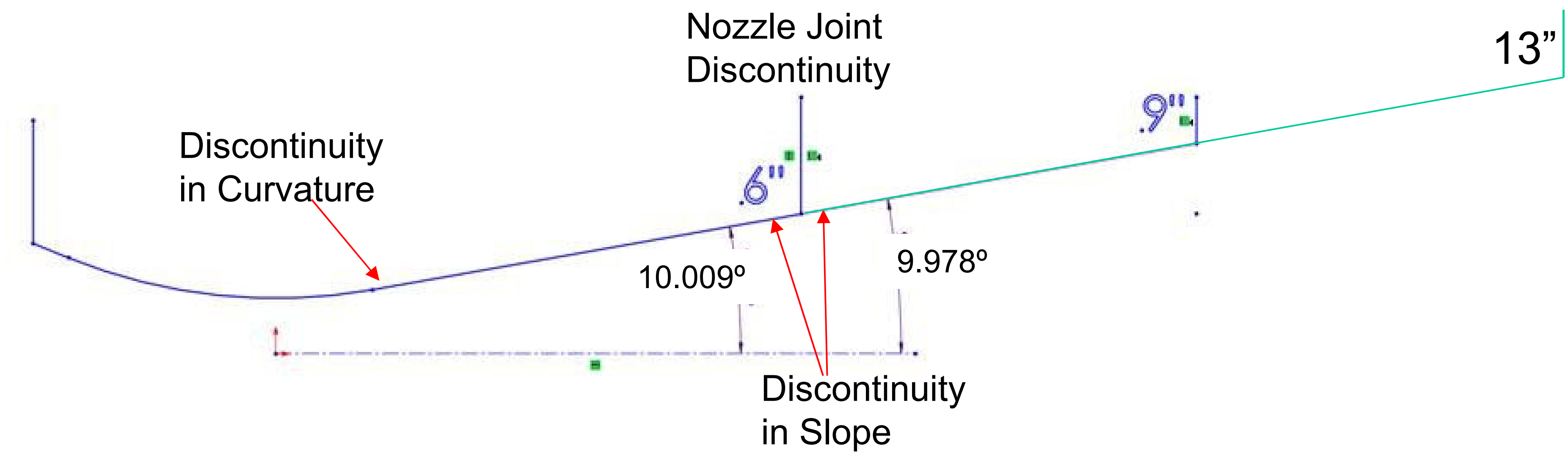


Smooth Decrease in Curvature down to zero

Absence of Compression waves – no local minimum in Pitot Pressure

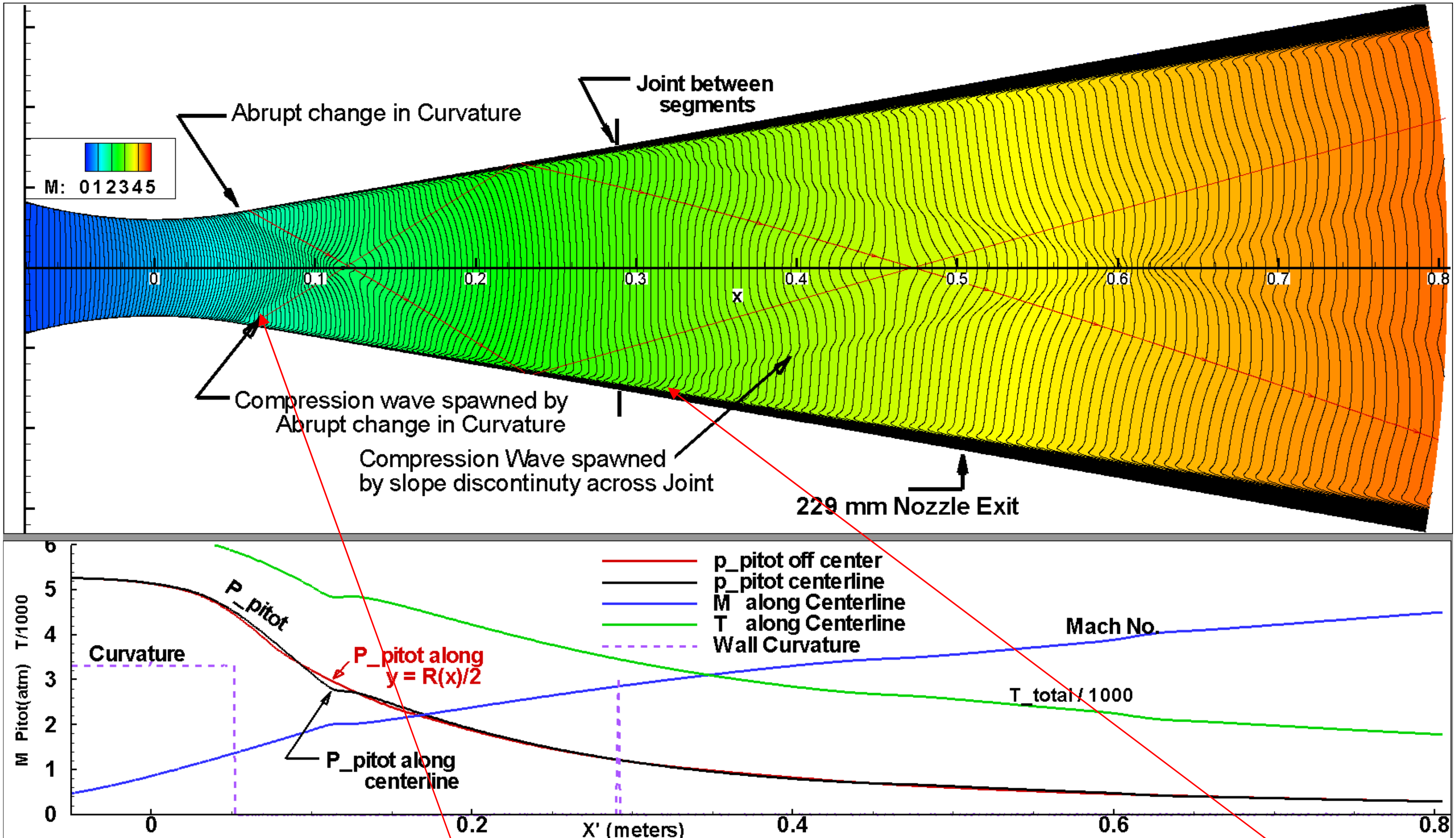
Other Possible Source of Waves – Joint

Hypothetical Case (sensitivity to slope discontinuity)



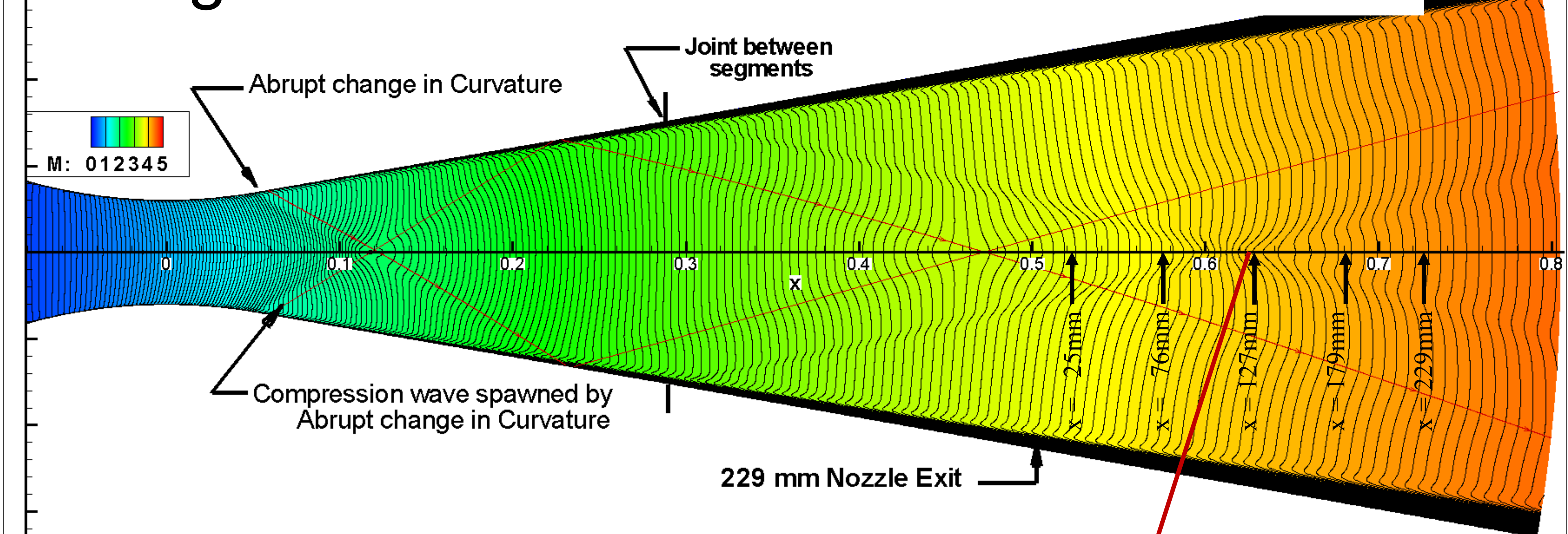
- Nozzle Joint discontinuity due to slope difference associated with tolerance stack up (+/- 0.03^{o}) a hypothetical scenario
- Is this significant enough to cause waves

Discontinuity in Slope at Joint

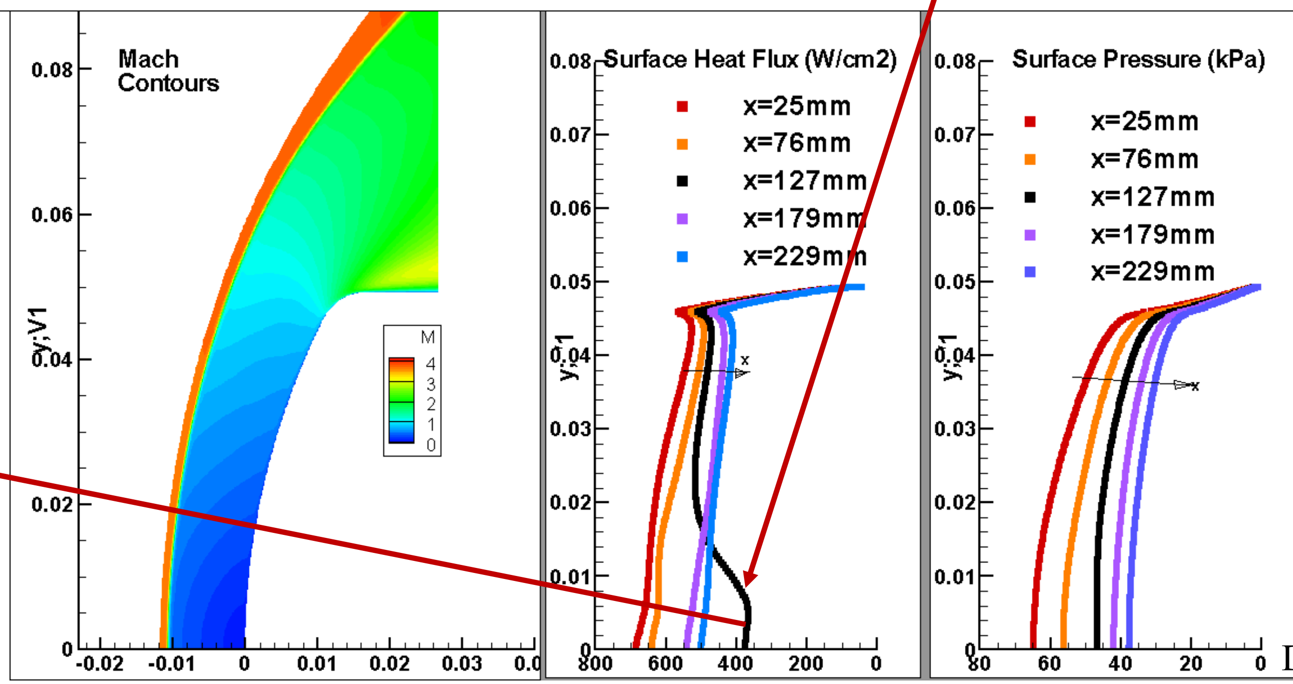


•.Waves from both Curvature discontinuity and difference in slope at joint

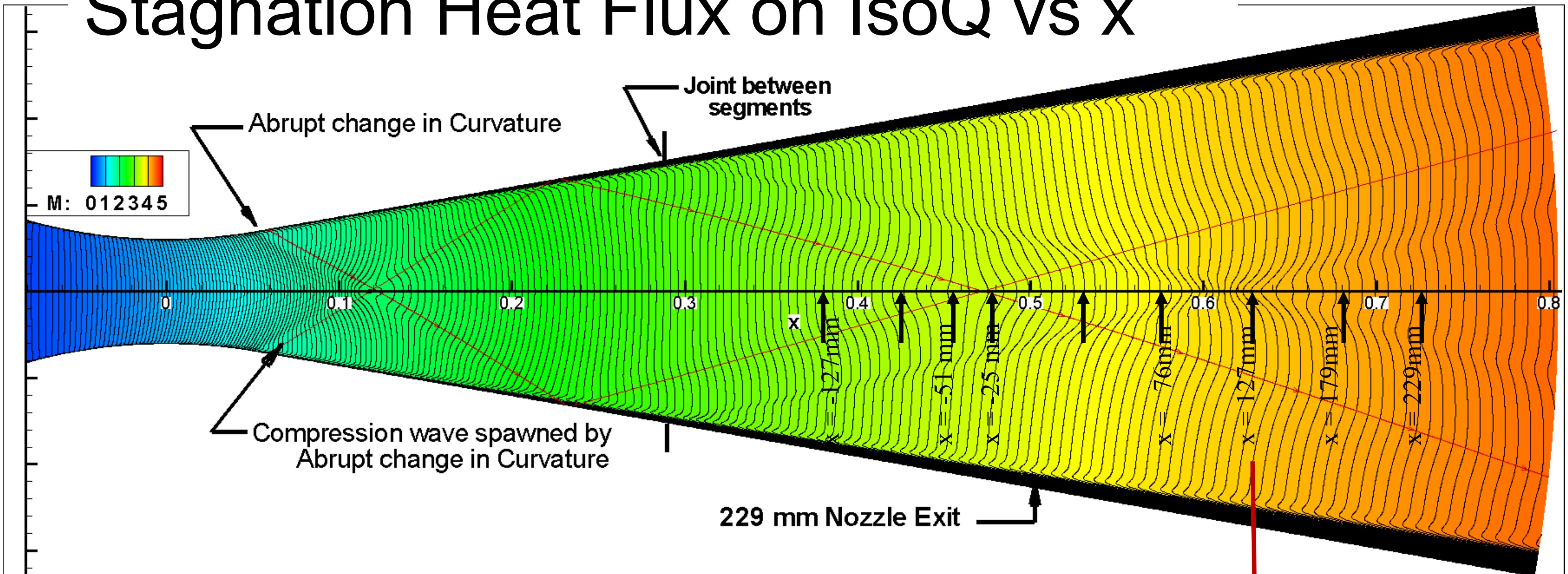
Stagnation Heat Flux on IsoQ Test Articles



Local Minimum in heating when model is at the x=127mm location. Consistent with Teflon Burn



Stagnation Heat Flux on IsoQ vs x



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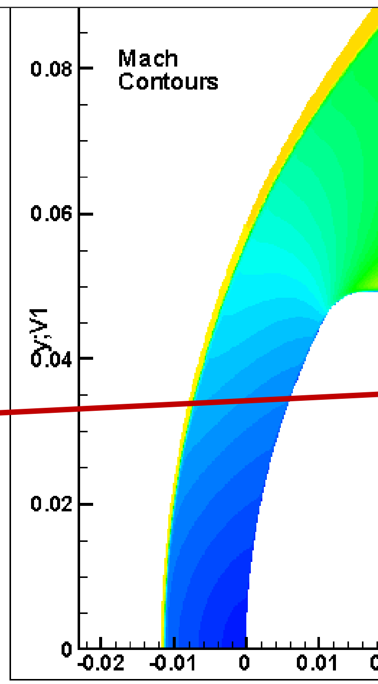
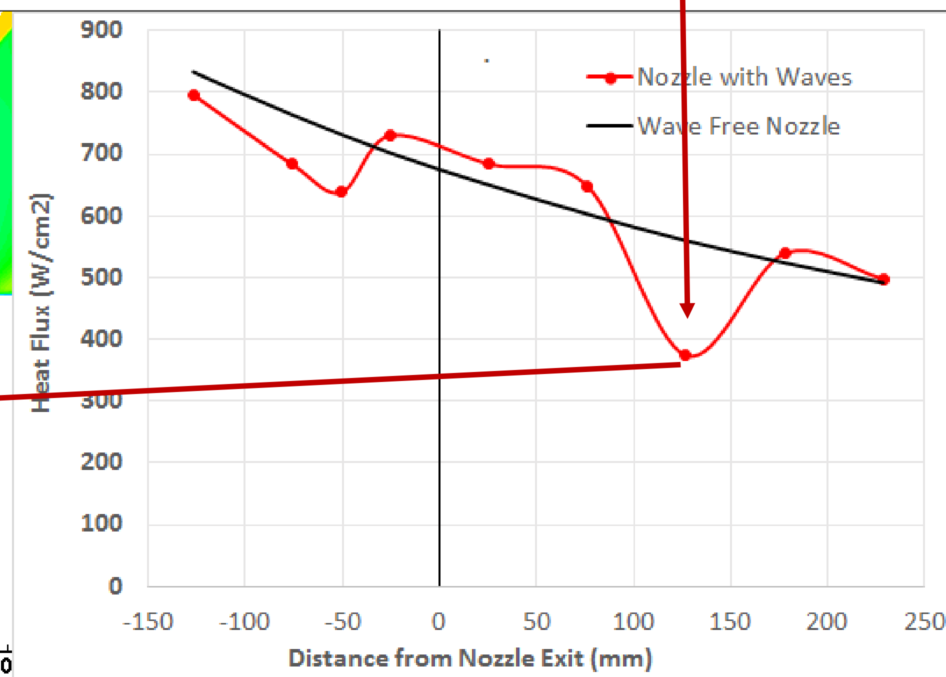
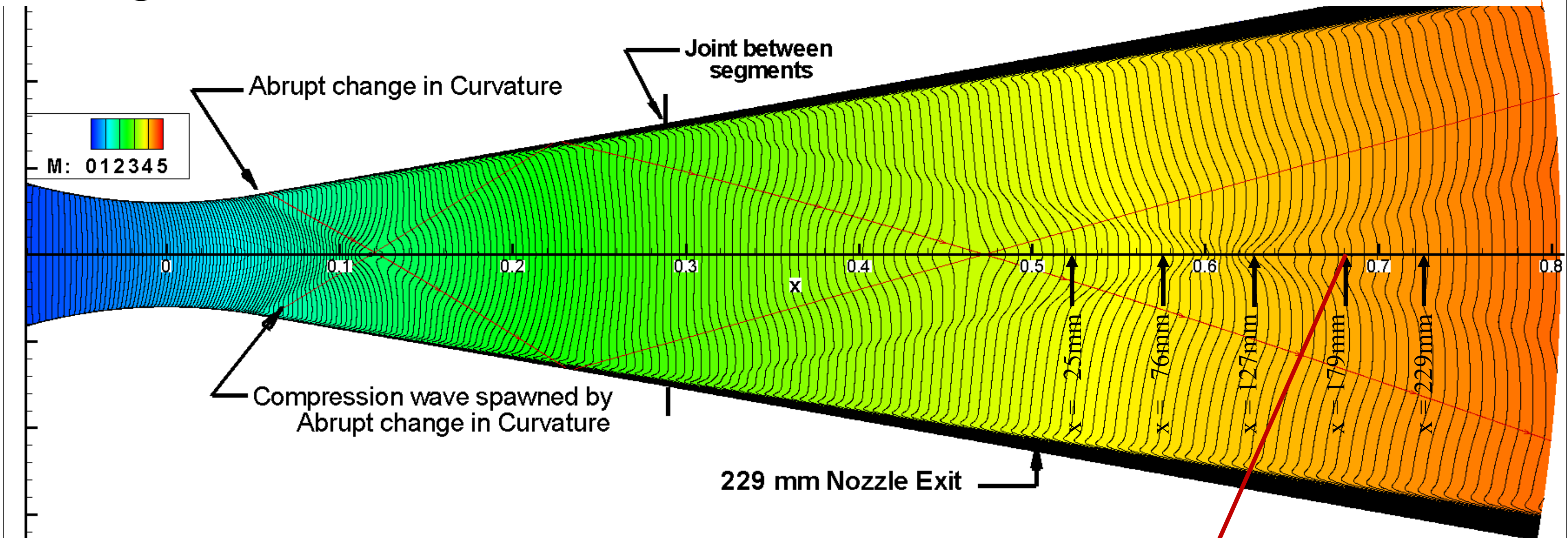
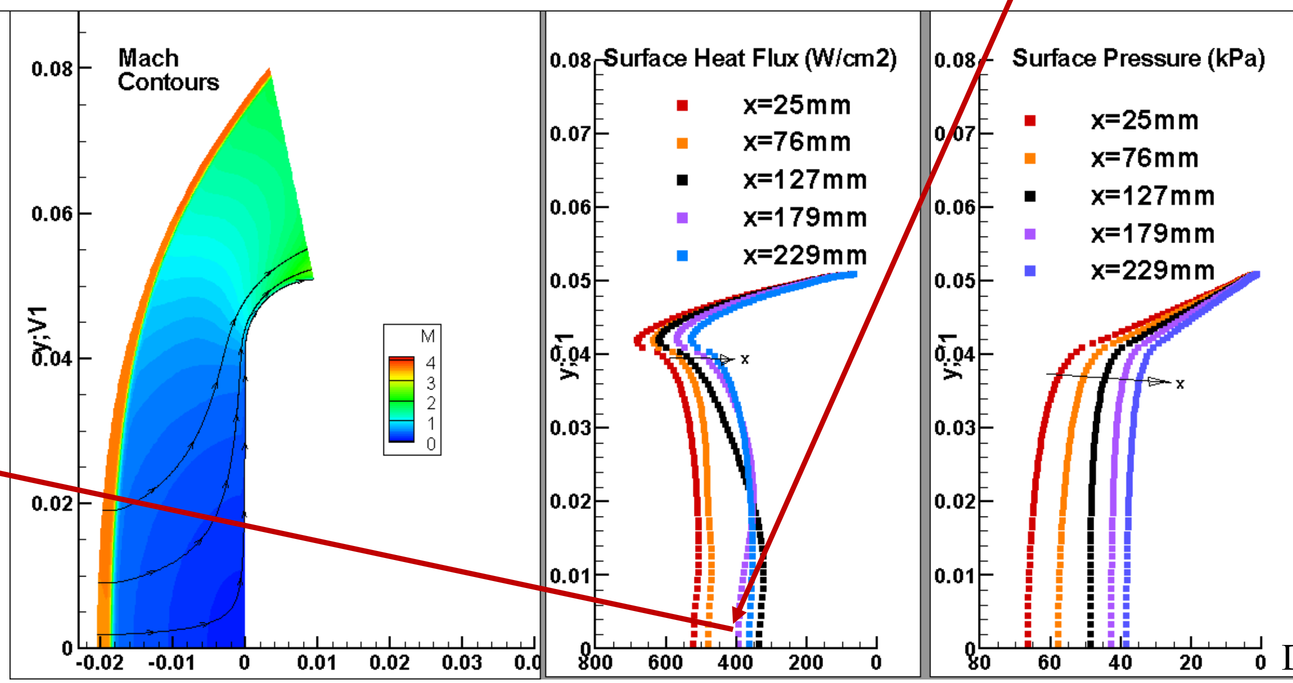




Stagnation Heat Flux on Flat Faced Test Articles



Local Maximum in heating when model is at the x=179mm location. Consistent with Teflon Burn.



Summary

•Waves are seen experimentally in radial pressure distributions (waves intersect at x=127mm).

•Teflon test articles show non-uniform recession when test articles are placed near x=127mm.

•CFD indicates that waves can be expected from a discontinuity in curvature at the throat.
(although relatively week)

•CFD shows that small discontinuities in nozzle slope (across a joint) can cause significant waves

•CFD predicts a non-uniformity in heating on test articles placed near x=127mm.

•Waves can be an issue for the new 229mm nozzle, and it is best to test upstream of x=76mm.

•Waves are a relative non-issue for the 152mm and 330mm nozzles, as their focal point is far from where models are tested

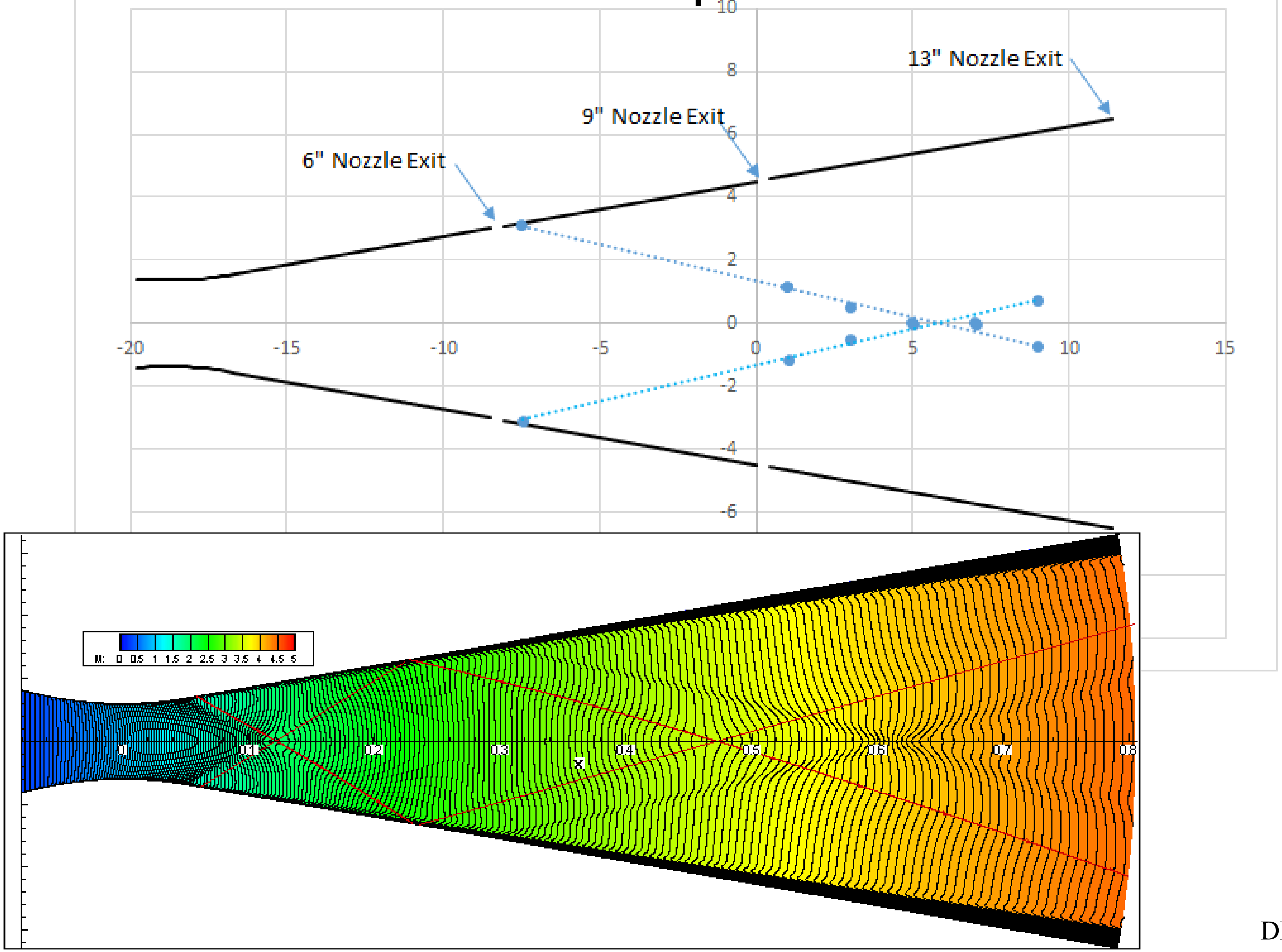
<u>Future Nozzle design</u>

•There is a plan to build a new throat section in which the discontinuity in curvature is eliminated.

•The as built nozzle segments will be measured and CFD performed on them.

•If a wave free 229mm nozzle is required, then it may be necessary to make it a single piece.

Backup

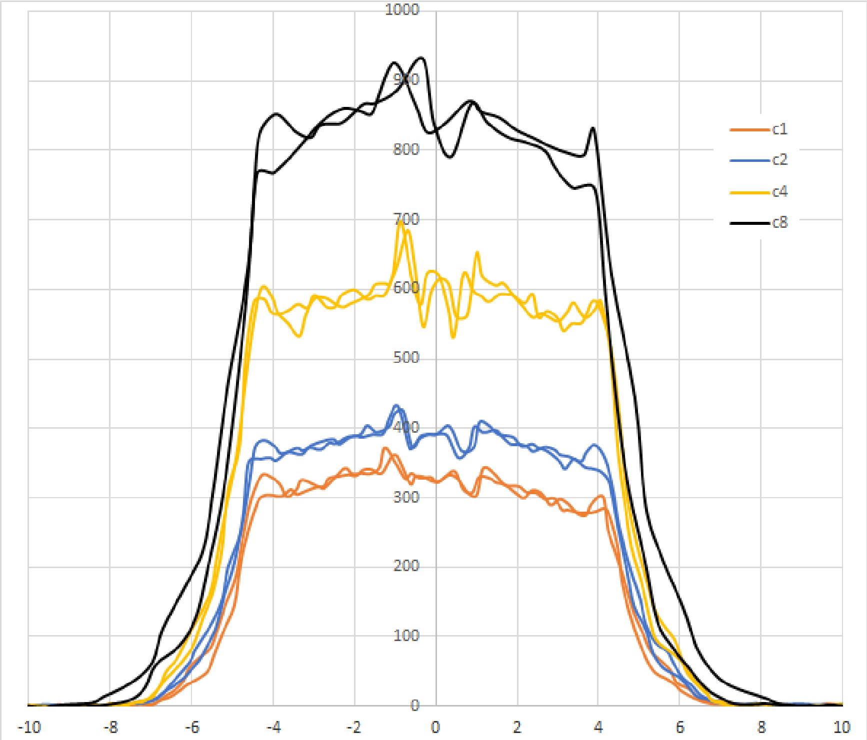


13" Nozzle Exit
9" Nozzle Exit
6" Nozzle Exit
10
8
6
4
2
0
-2
-4
-6
-20
-15
-10
-5
0
5
10
15
M: 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

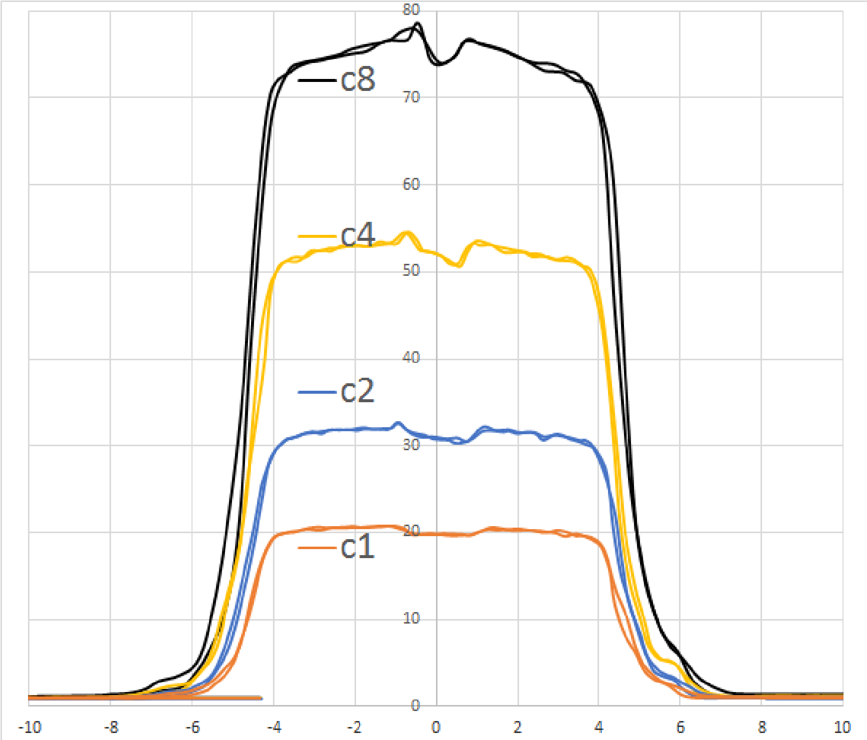
Radial Distributions for various conditions at x=76mm

Condition MSL-c1,"c2", c4, c8

Heat Flux Distribution (Gardon Gage)



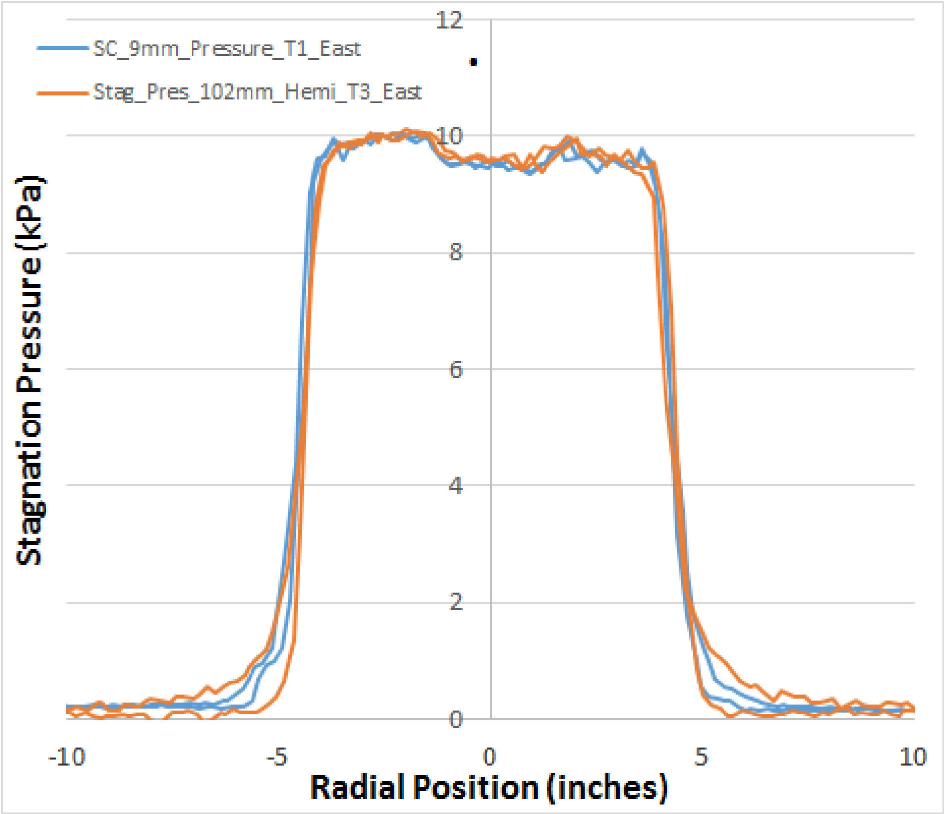
Pressure Distribution



- Local disturbance seen in pressure and heat flux near centerline (at x=76mm location) for most conditions
- Recall Teflon looked reasonably good at x=76mm
- Disturbance broadening with reduction in flow enthalpy

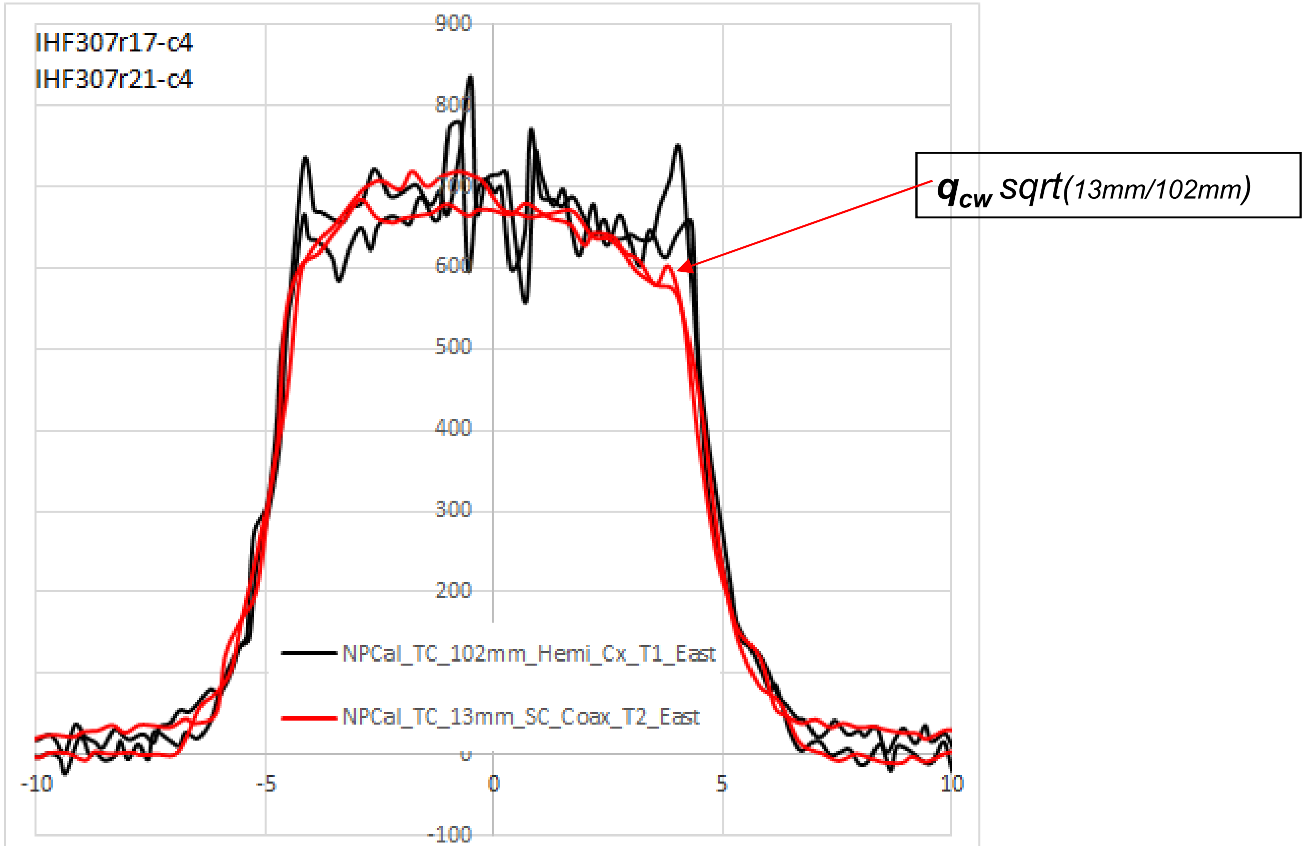
  i.e., wave intersection point moving downstream as flow approaches ideal gas

Pressure measured by Probes of Different Size



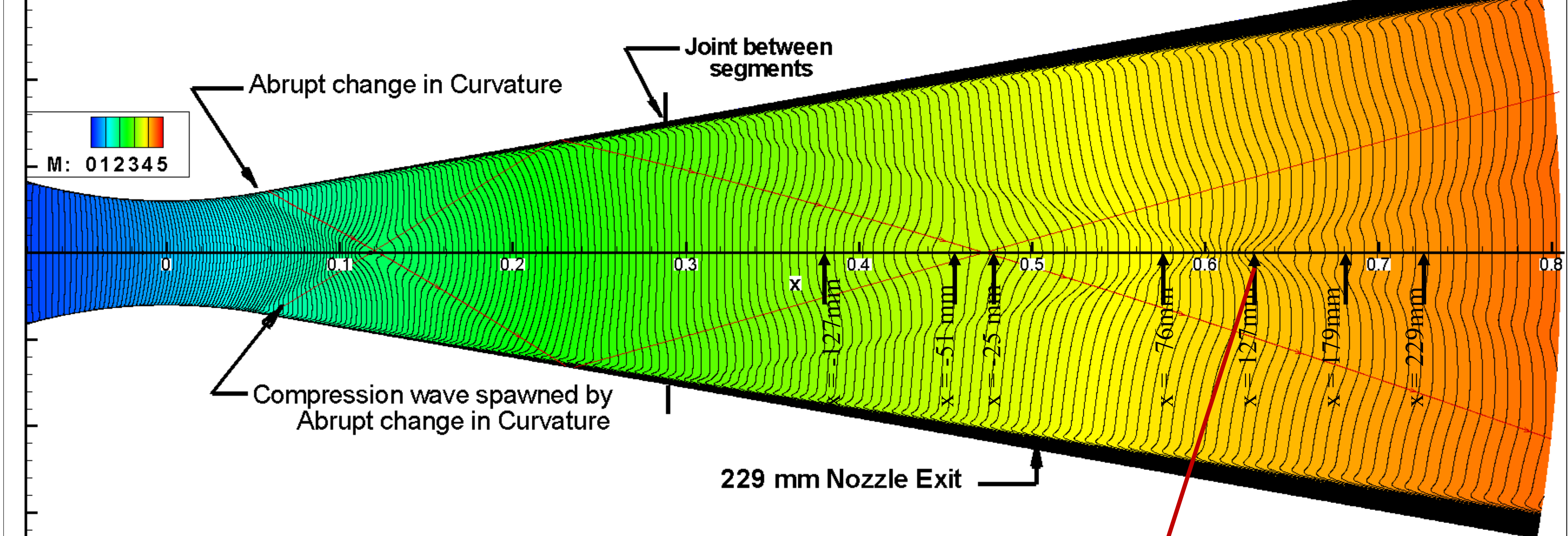
- Pressure measured by 102mm Hemi and 9 mm Sphere Cone agree

Heat Flux Measured by Probes of Different Size



- Magnitude of q_{cw} *sqrt(R)* measured by 102mm Hemi and 13mm Sphere Cone agree
- But the smaller probe does not measure local extrems in heating

Effect on Teflon IsoQ Test Articles



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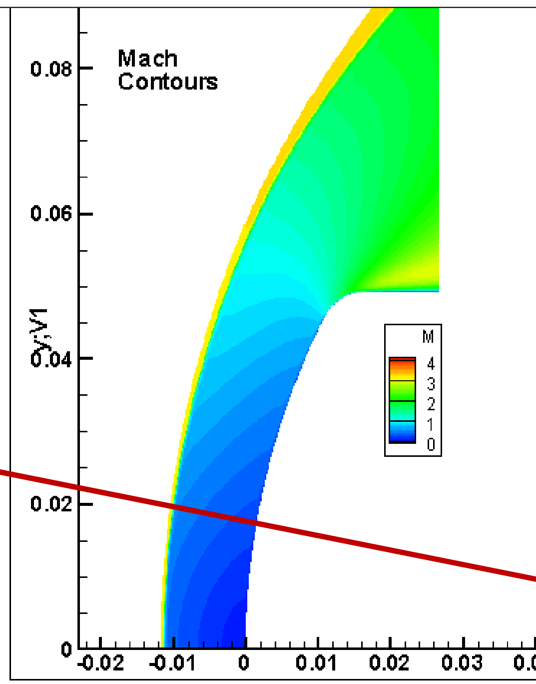
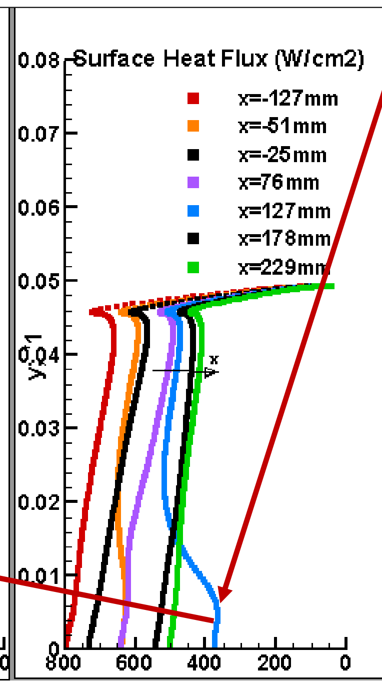
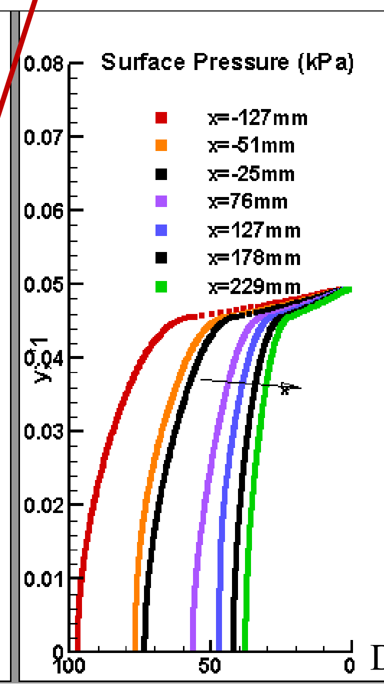
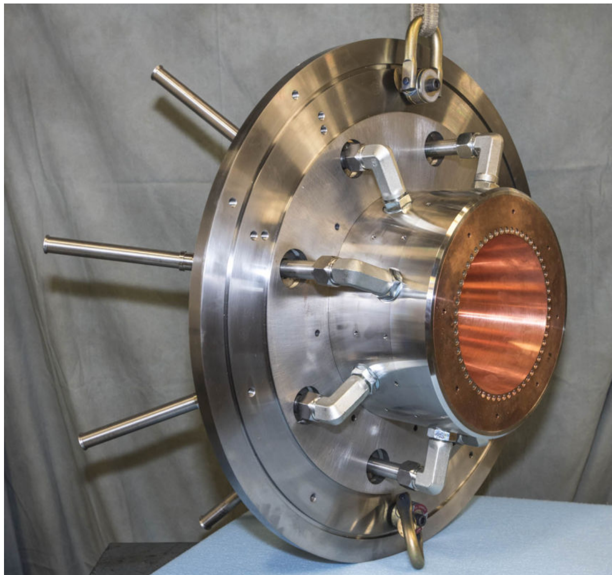
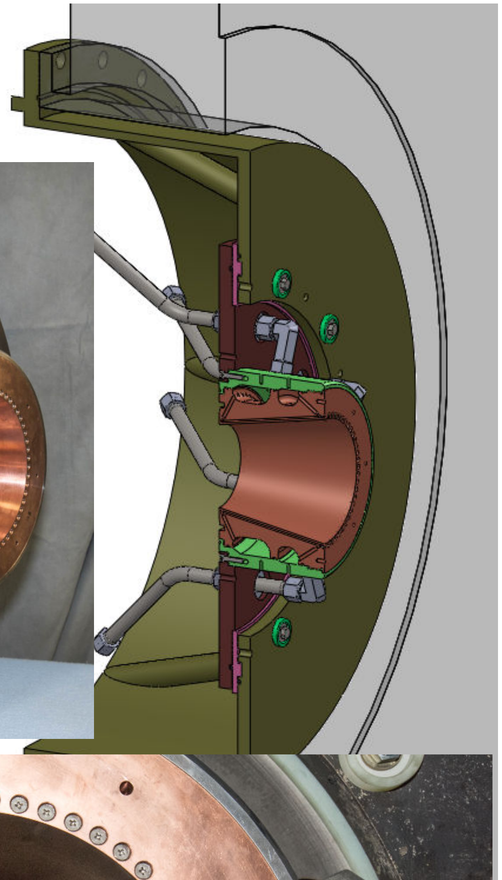


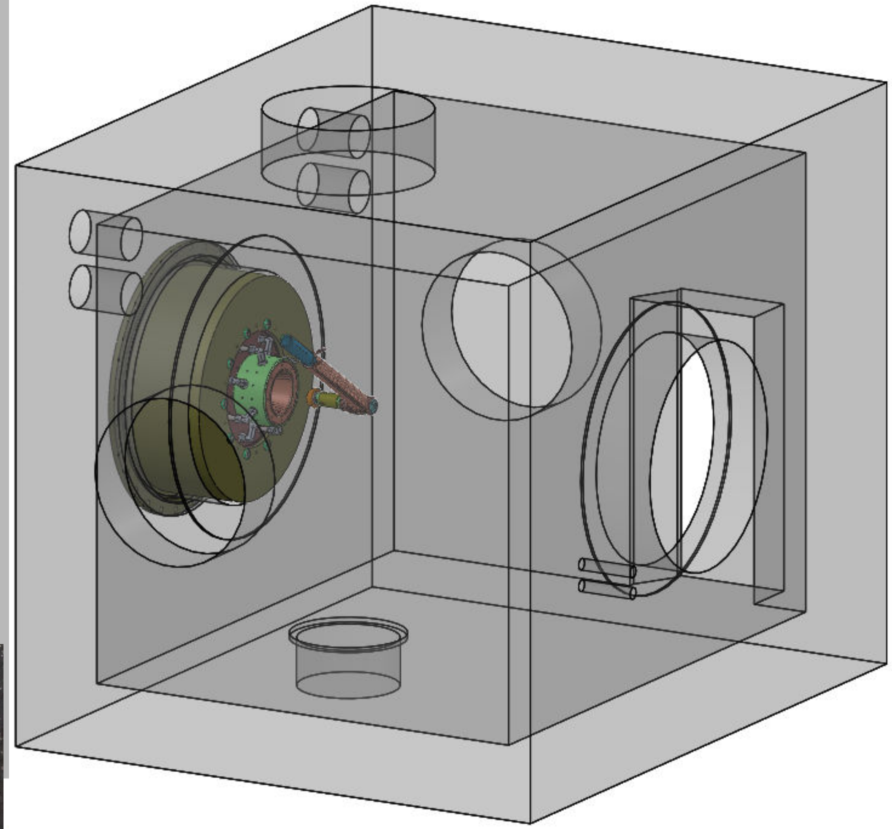


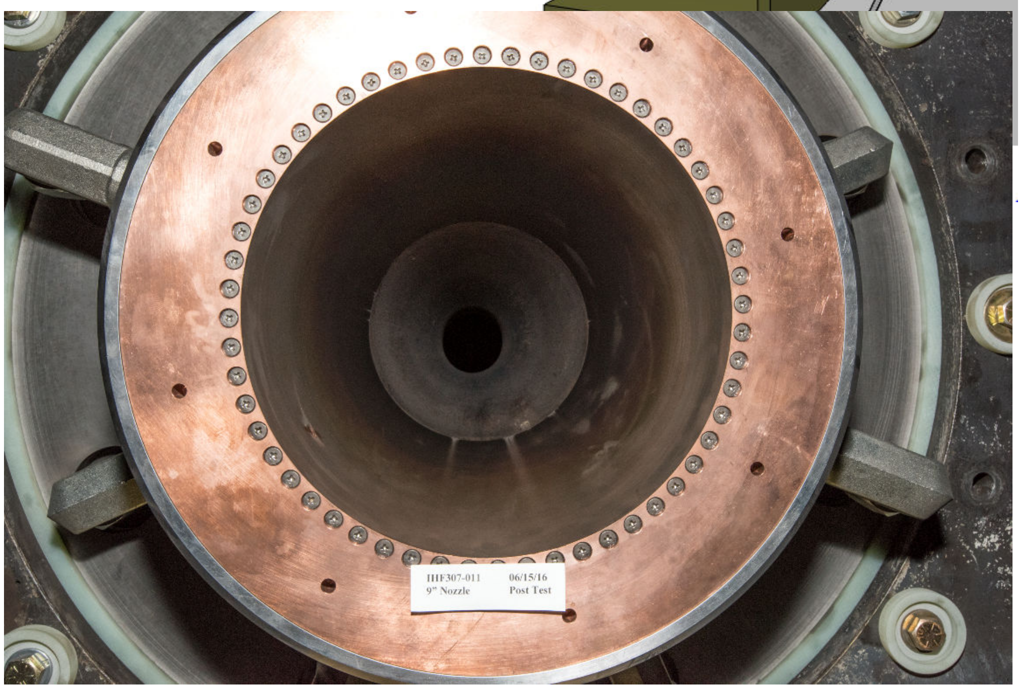


9” Nozzle









<u>Photo of 9” nozzle after testing</u>

No gap between throat and 9” extension
  8” Nozzle extension had a gap (step?)

A couple of small streaks at 6 o’clock position
  Associated with small steps