

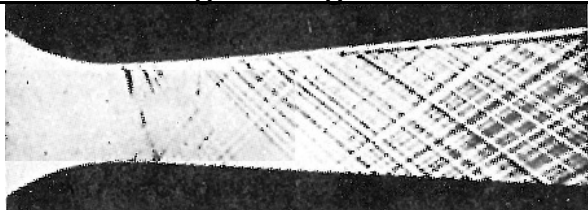
Evidence of Standing Waves in Arc Jet Nozzle Flow

Dave Driver, Joe Hartman, Daniel Philippidis, Eric Noyes, Frank Hui, Imelda Terrazas-Salinas

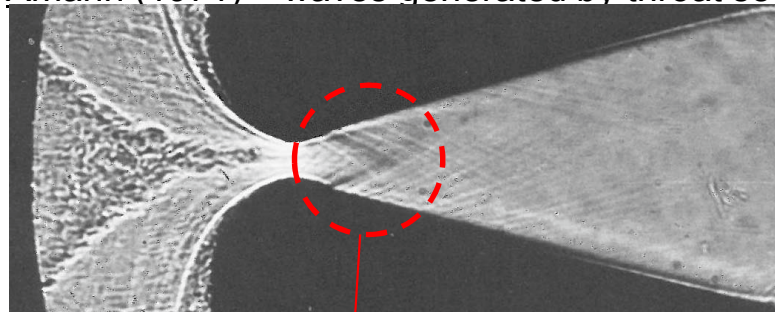
*NASA Ames Research Center – Entry Systems Technology Division
Moffett Field, CA*

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

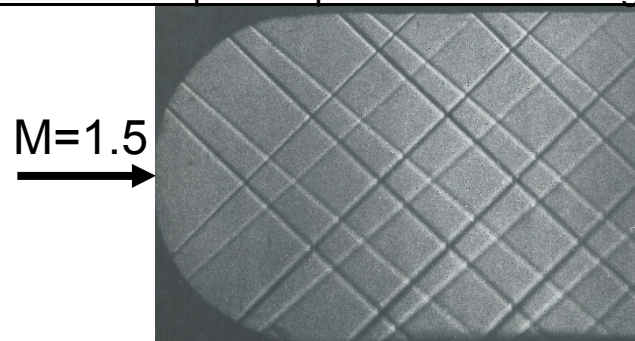
Prandtl – Slight Roughness on Walls



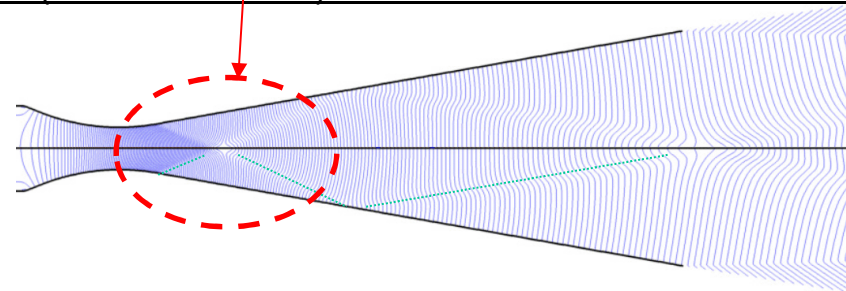
Amann (1971) – waves generated by throat section



AEDC – strips of tape on floor & ceiling



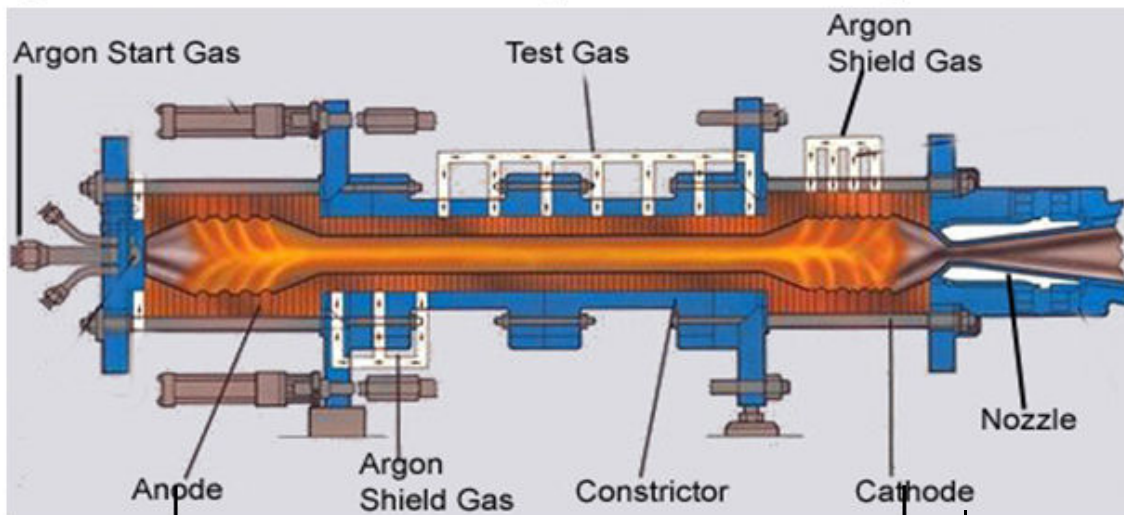
Prabhu (AIAA2009-4080) CFD of waves in Arc Jet Nozzle



NASA Ames Arc Jet Facility

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

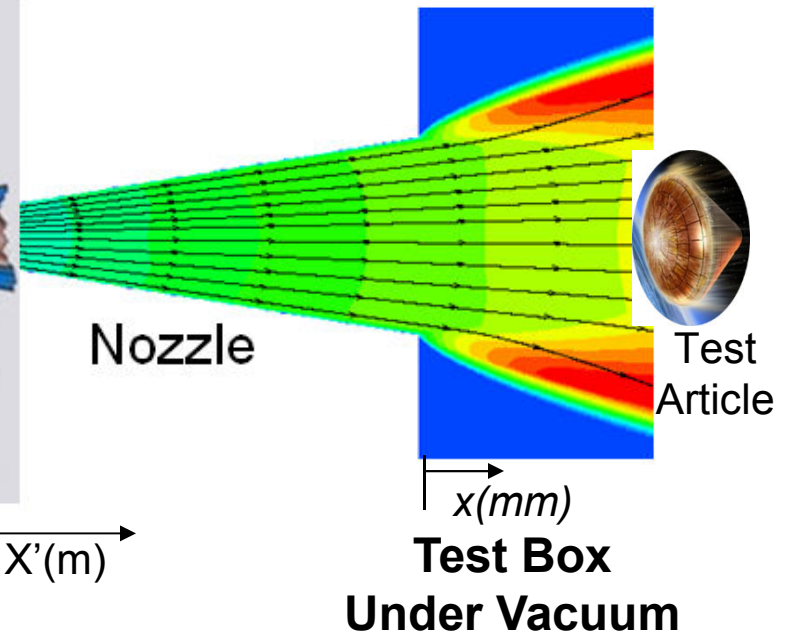
Arc Jet Schematic



DC Power

$X'(m)$

CFD Simulation of Arc Jet Flow



- 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

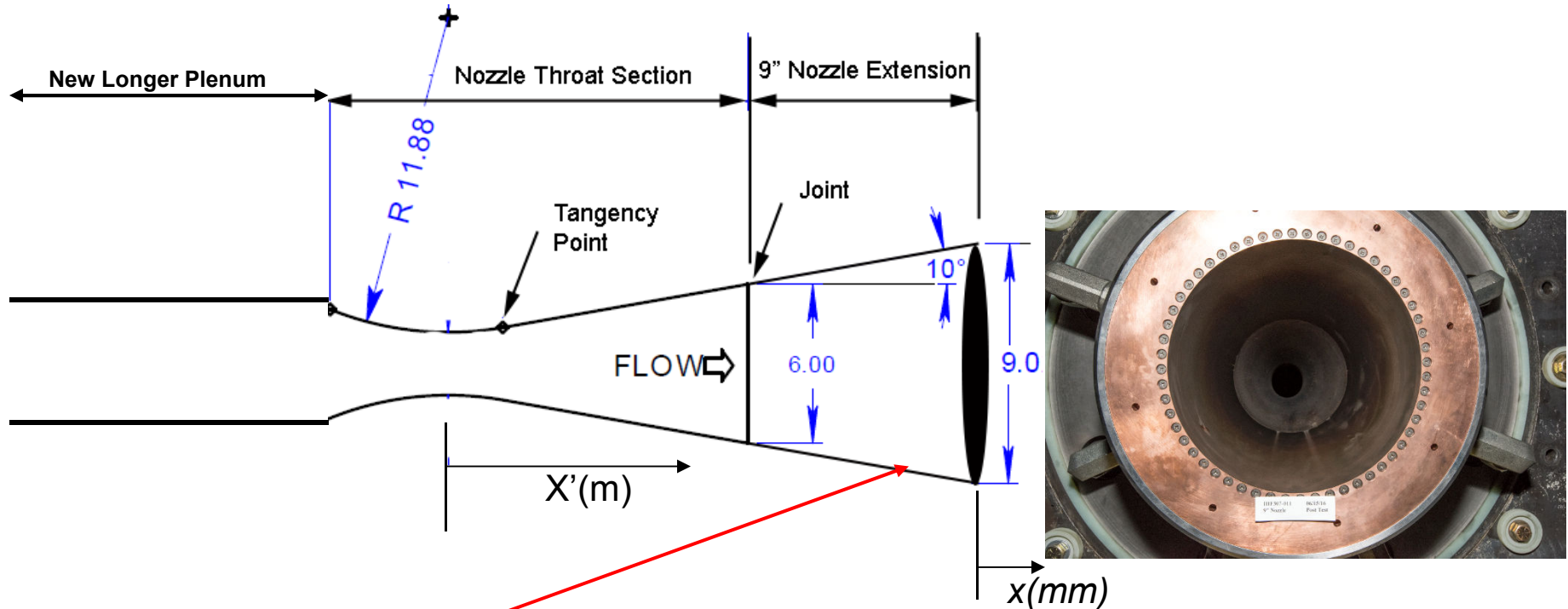
- Non-uniform burn patterns on Teflon test articles (at $x=127\text{mm}$ and 178mm)
- Experimentally Observed standing waves in the IHF nozzle
- CFD with real gas effects (follow up to Dinesh Prabhu AIAA 2009-4080)
- Simulation of test articles
- Proposal for Alternate Nozzle Design (wave free)

Acknowledgement

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

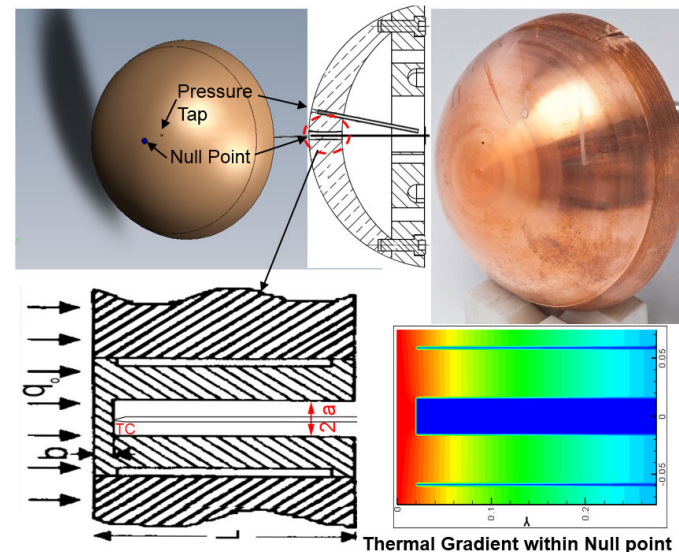
<u>Test Conditions</u>						<u>Probe at x=76mm</u>			
<u>Case #</u>	<u>Current amps</u>	<u>Voltage Volts</u>	<u>Main Air gm/s</u>	<u>Add Air gm/s</u>	<u>Argon gm/s</u>	<u>P_{plenum} kPa</u>	<u>P_{stag} kPa</u>	<u>q_{4"Hemi} W/cm2</u>	<u>H_{sonic} MJ/kg</u>
CEV-a13	3450	2720	105	645	51	350	30.7	92	2.9
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

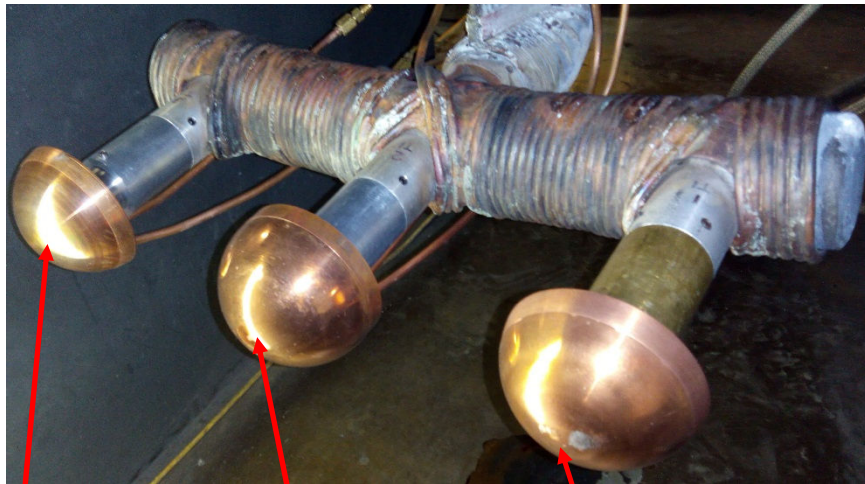


- IsoQ produces uniform heating across its face
- Teflon recession is proportional to heat rate
- Teflon “Burns” give global map of heat flux
- Asses uniformity of heating (aka flow quality)

Fast Response Probes (Null Pt & CoaxTC)

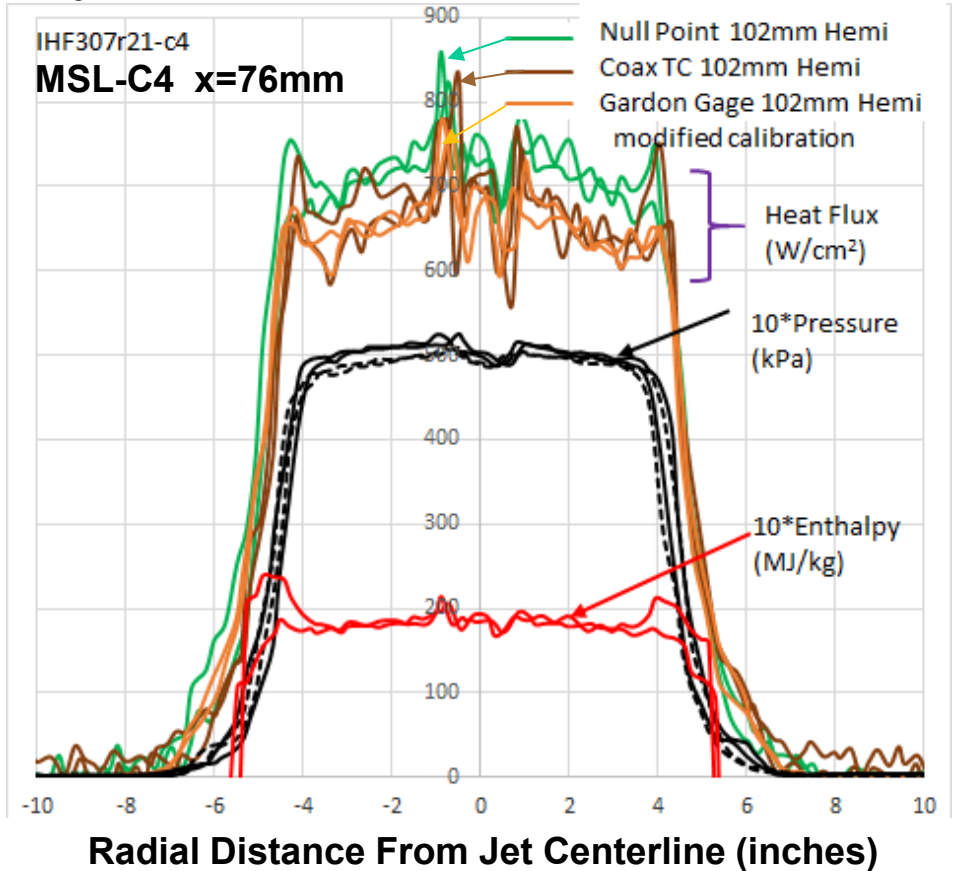


Radial Sweeps of Multiple Types of Heat Flux Sensors



Null Point Gardon Gage Coax TC

4" Hemi with Pressure tap



Fast Response Sensors (Null Point, CoaxTC, Gardon Gage)

- 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 $x=76\text{mm}$
- **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

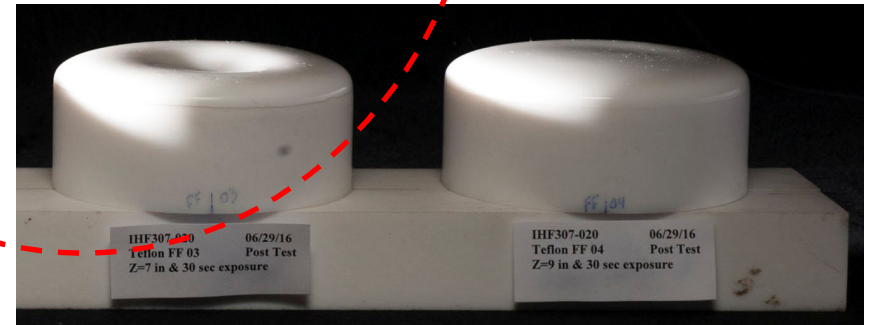


Initial Shape Flat Face

x=25mm

x=178mm

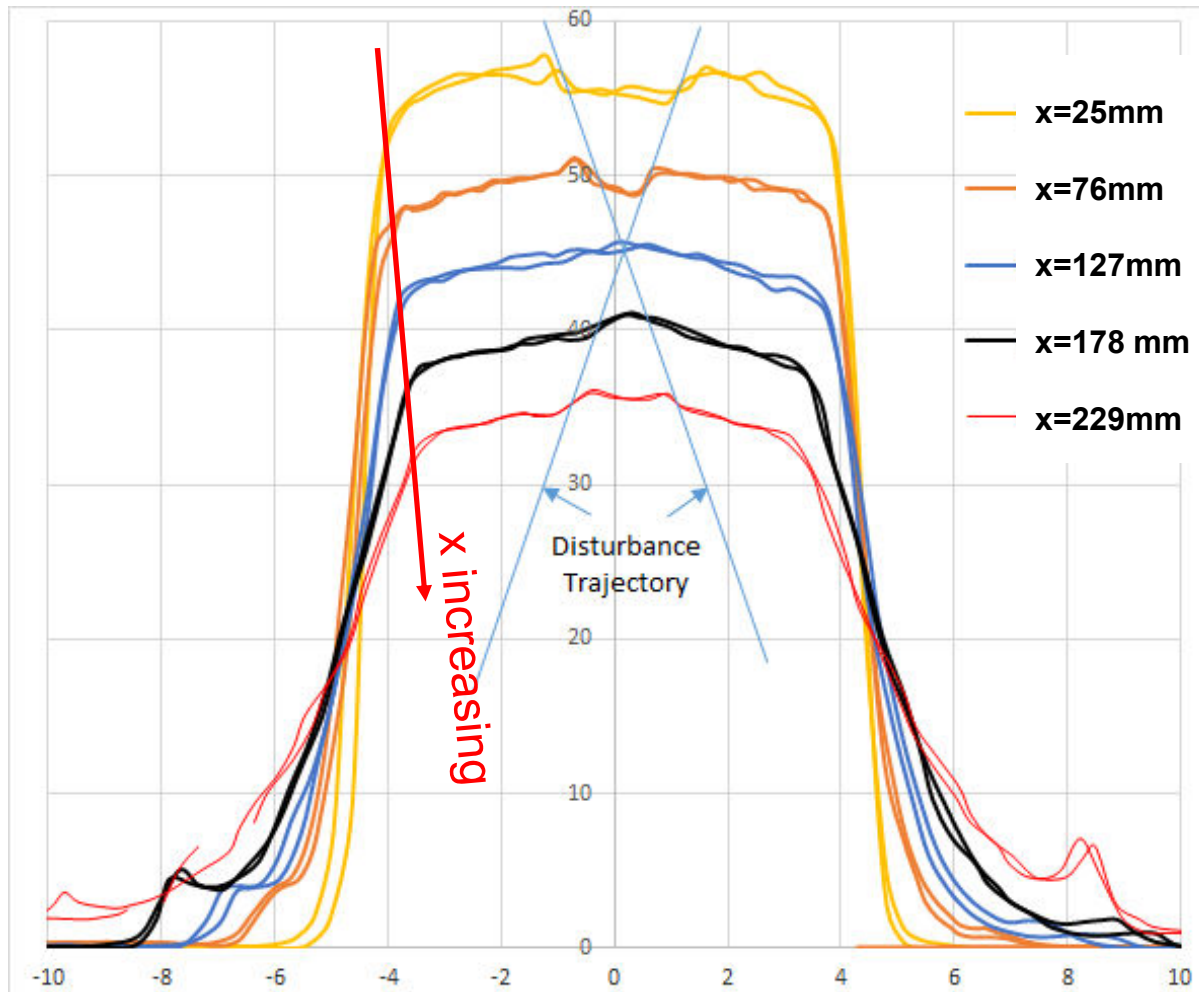
x=229mm



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

Radial Distribution of Stagnation Pressure at various x

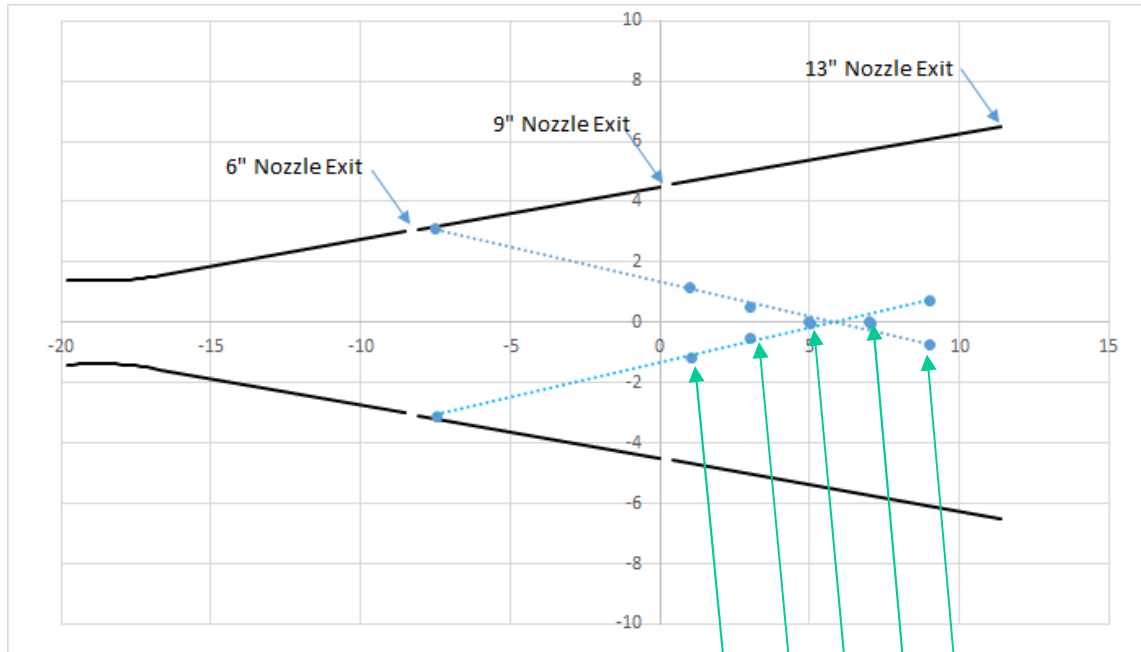
At MSL-c4 $\rightarrow i=3500\text{amps}$, $m_{\text{main}}/m_{\text{add}}/m_{\text{Ar}} = 546, 55, 54 \text{ gm/s}$



Local minimum in pressure seen upstream of x=127mm

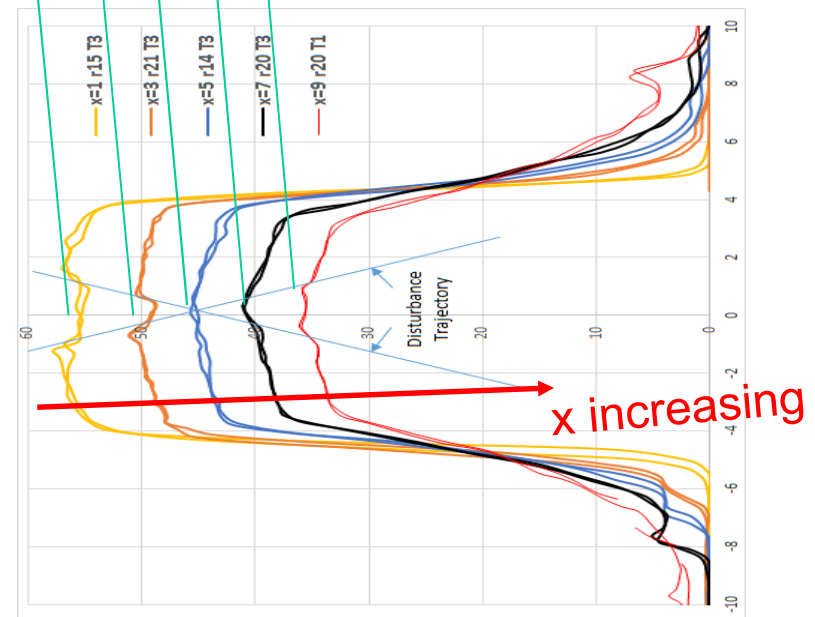
Local maximum in pressure seen downstream of x=127mm

Width of Pressure Disturbance vs Axial Position

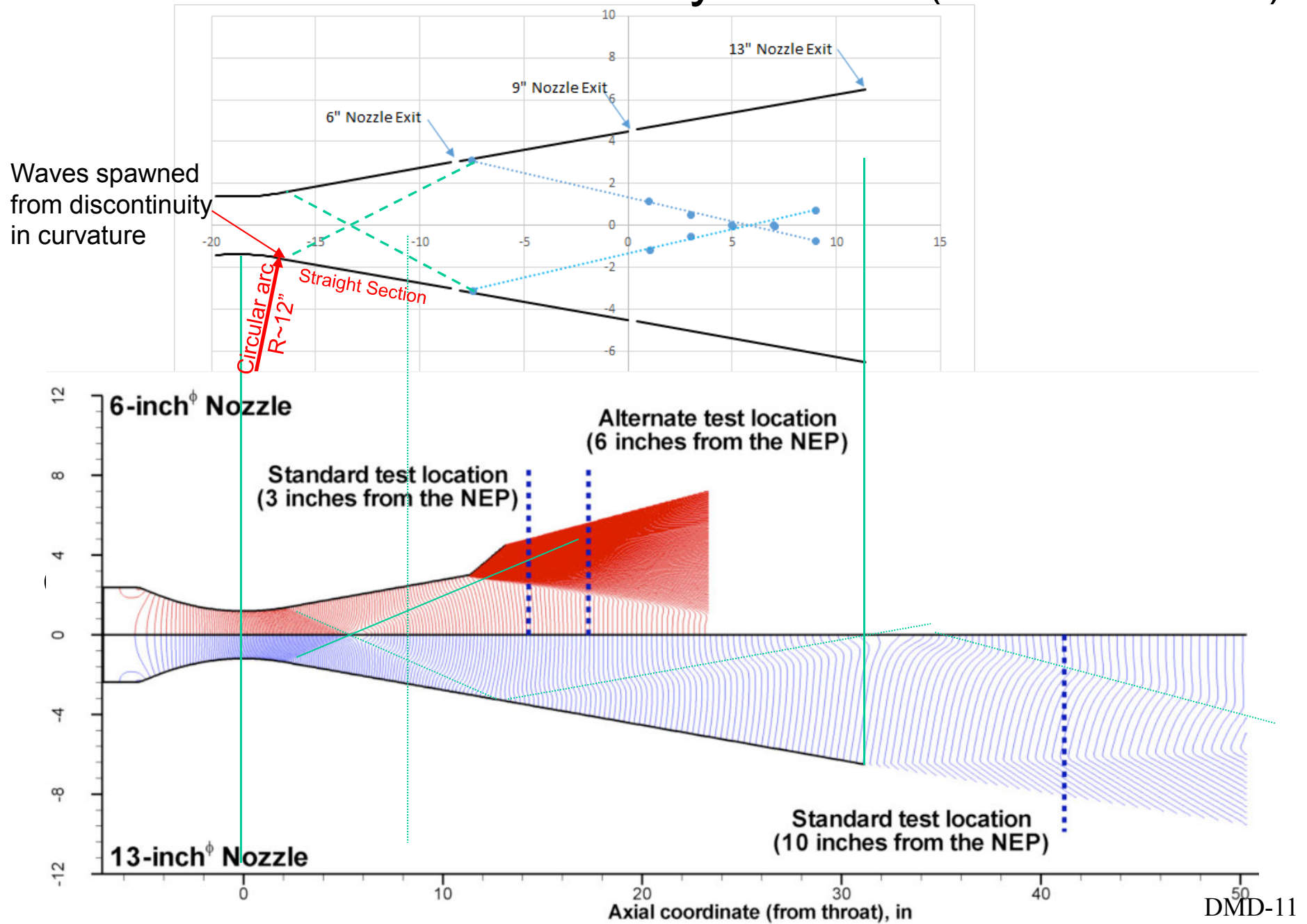


There appears to be a conical wave converging at $x \sim 127\text{mm}$

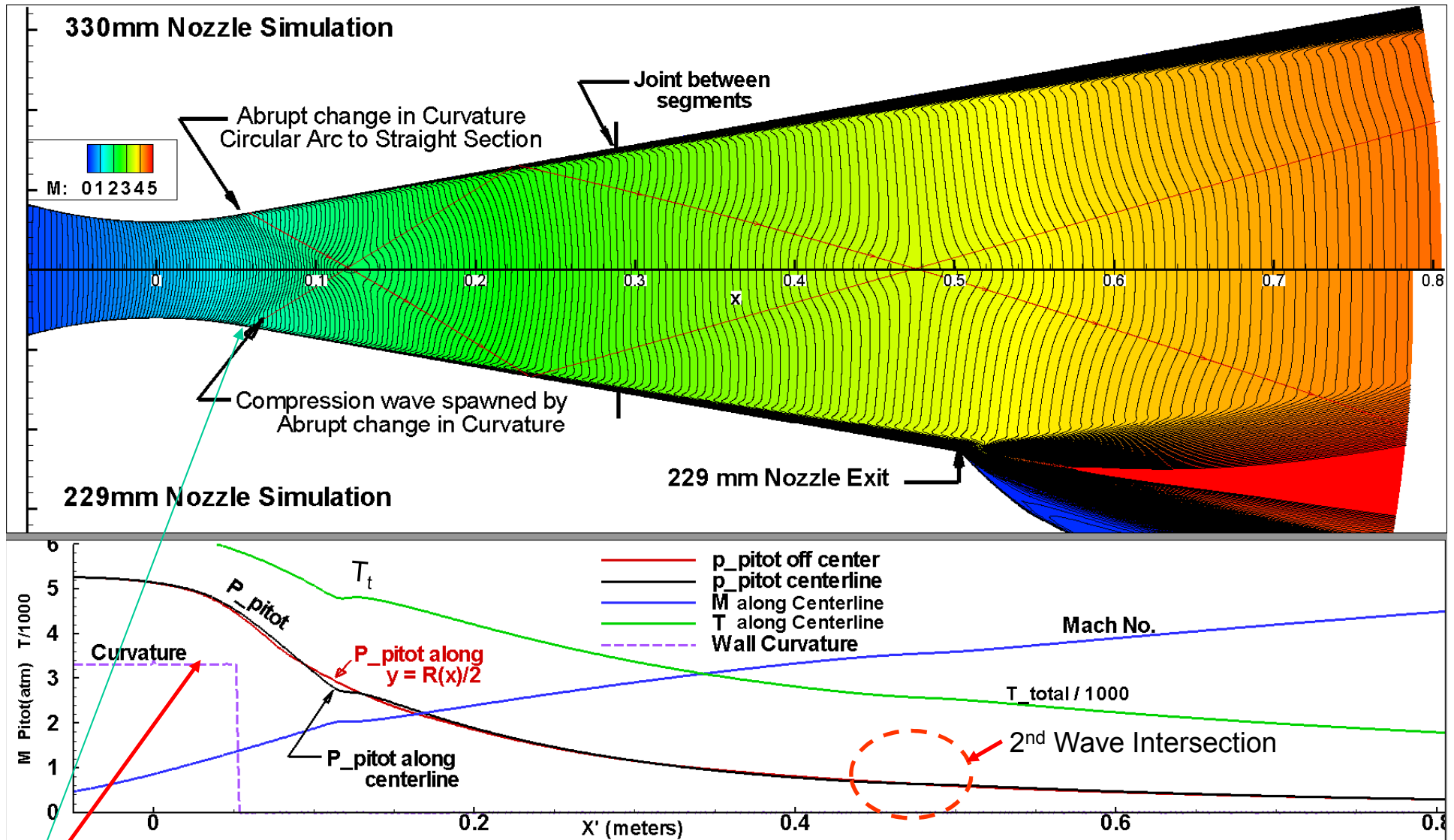
What is the source of the wave?



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

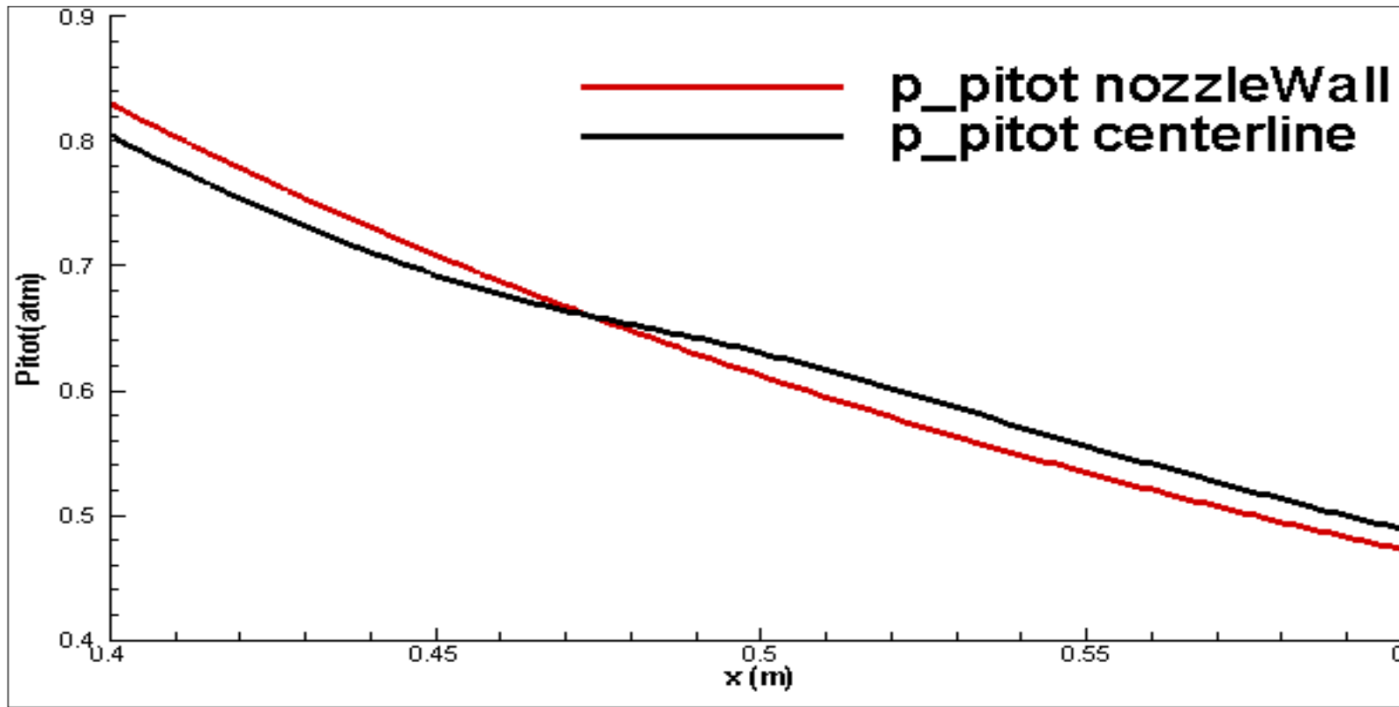


Nozzle Simulation of Existing IHF Throat



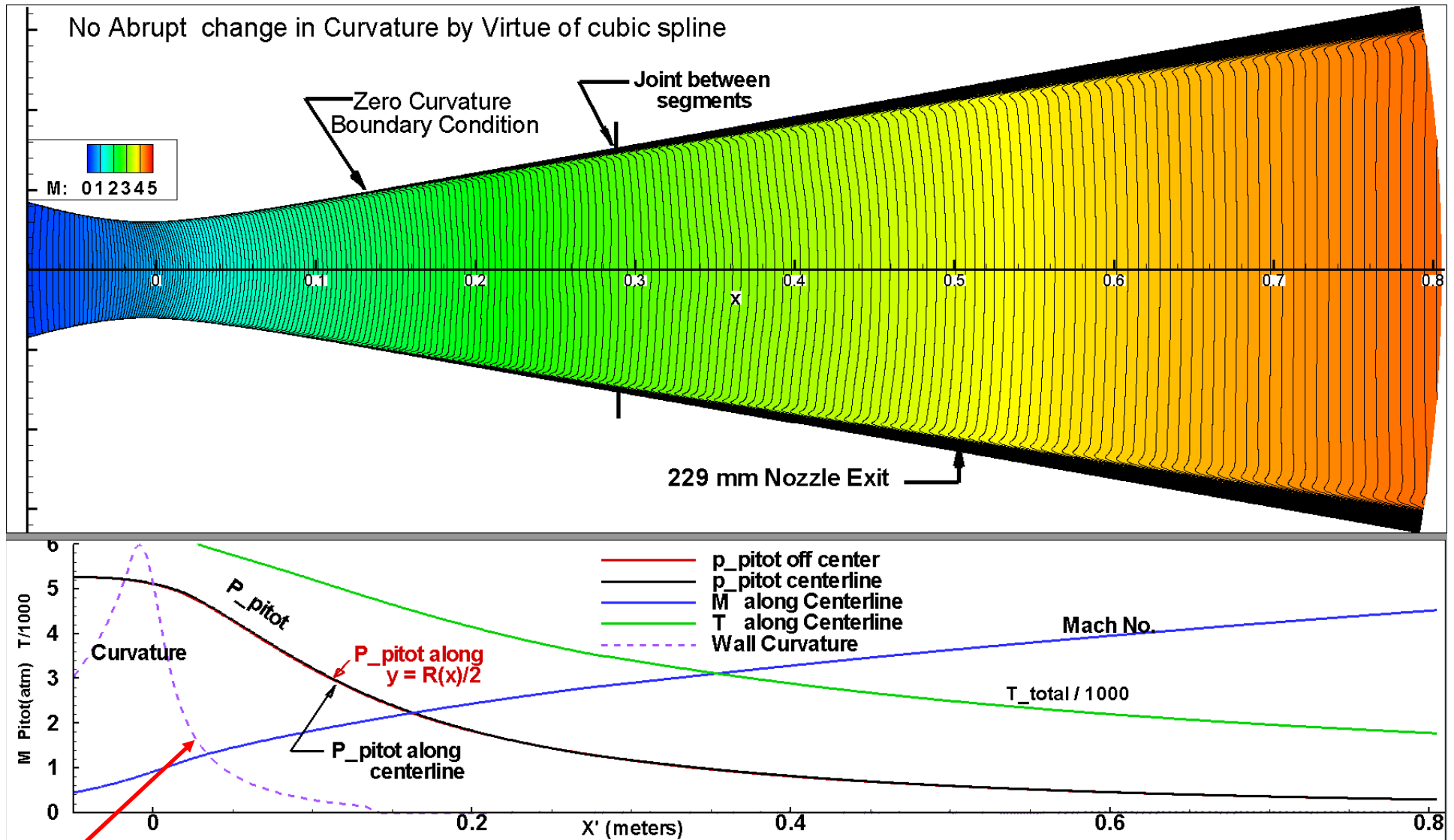
Constant Curvature followed by Abrupt change to zero Curvature
 Compression waves spawned from Abrupt change in curvature

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)

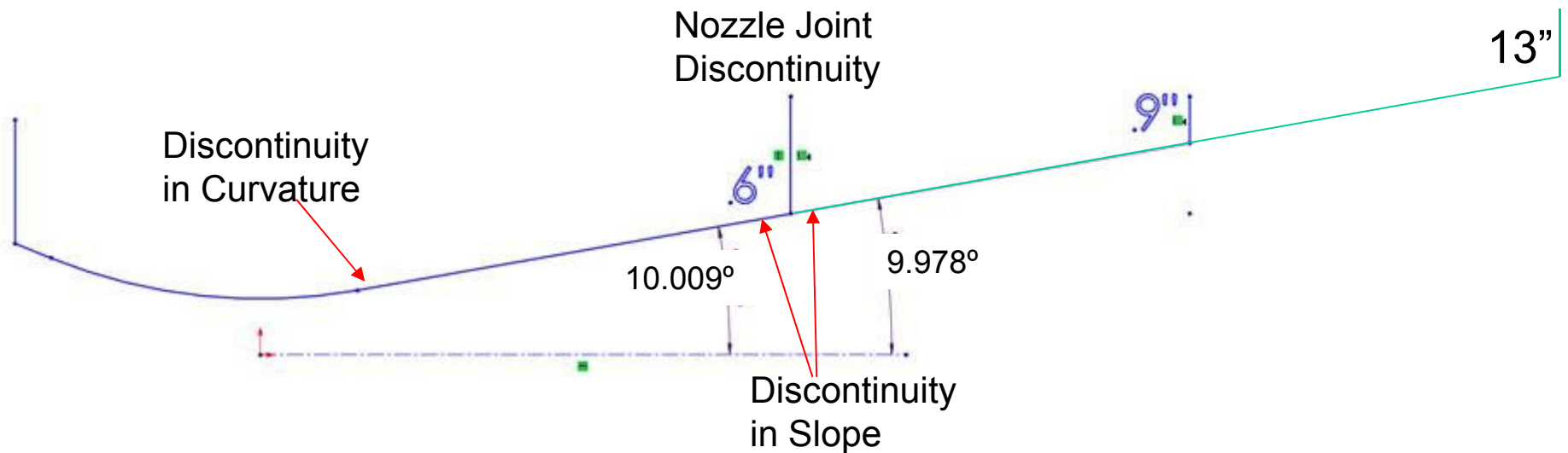


Smooth Decrease in Curvature down to zero

Absence of Compression waves – no local minimum in Pitot Pressure

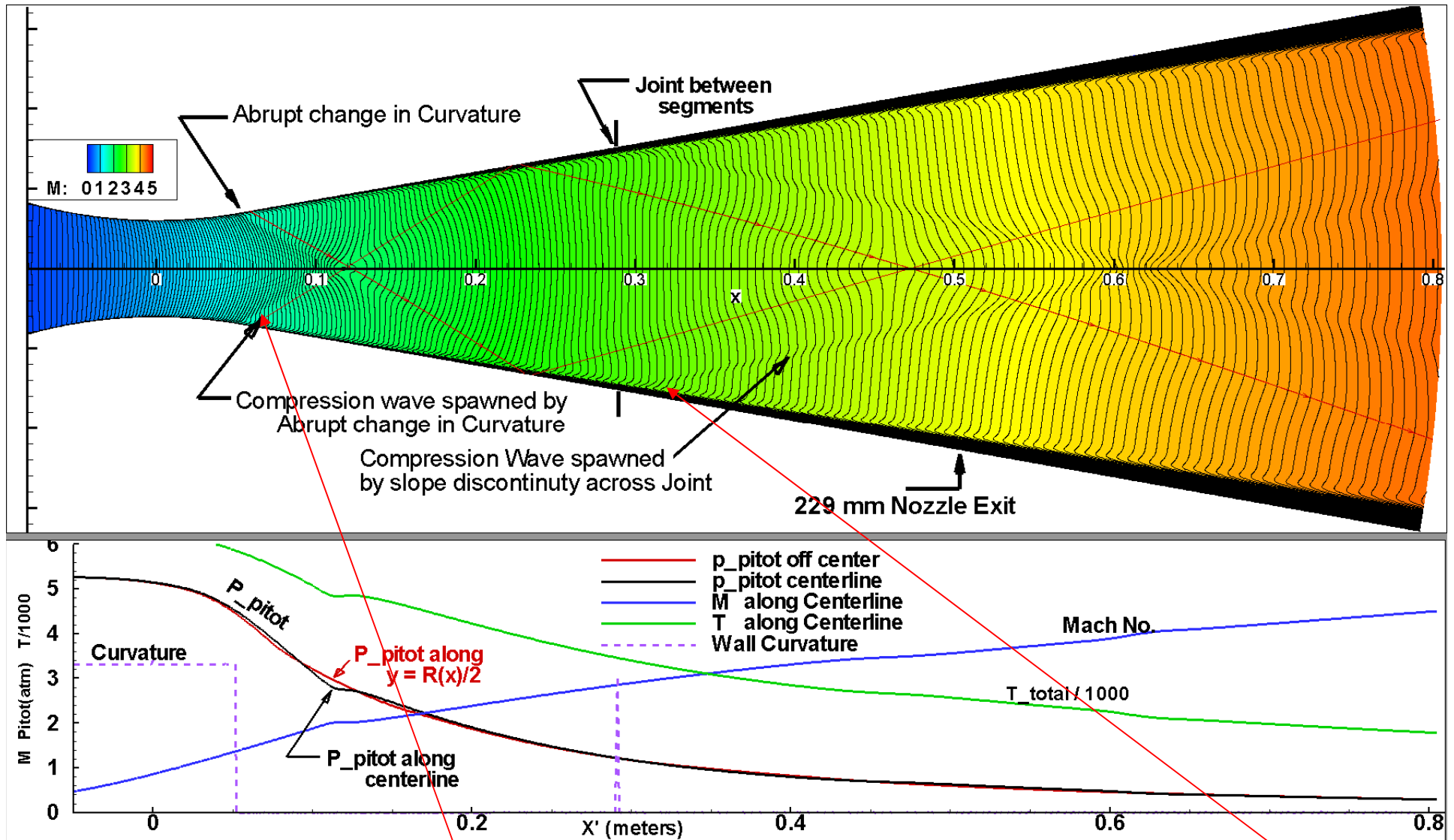
Other Possible Source of Waves – Joint

Hypothetical Case (sensitivity to slope discontinuity)



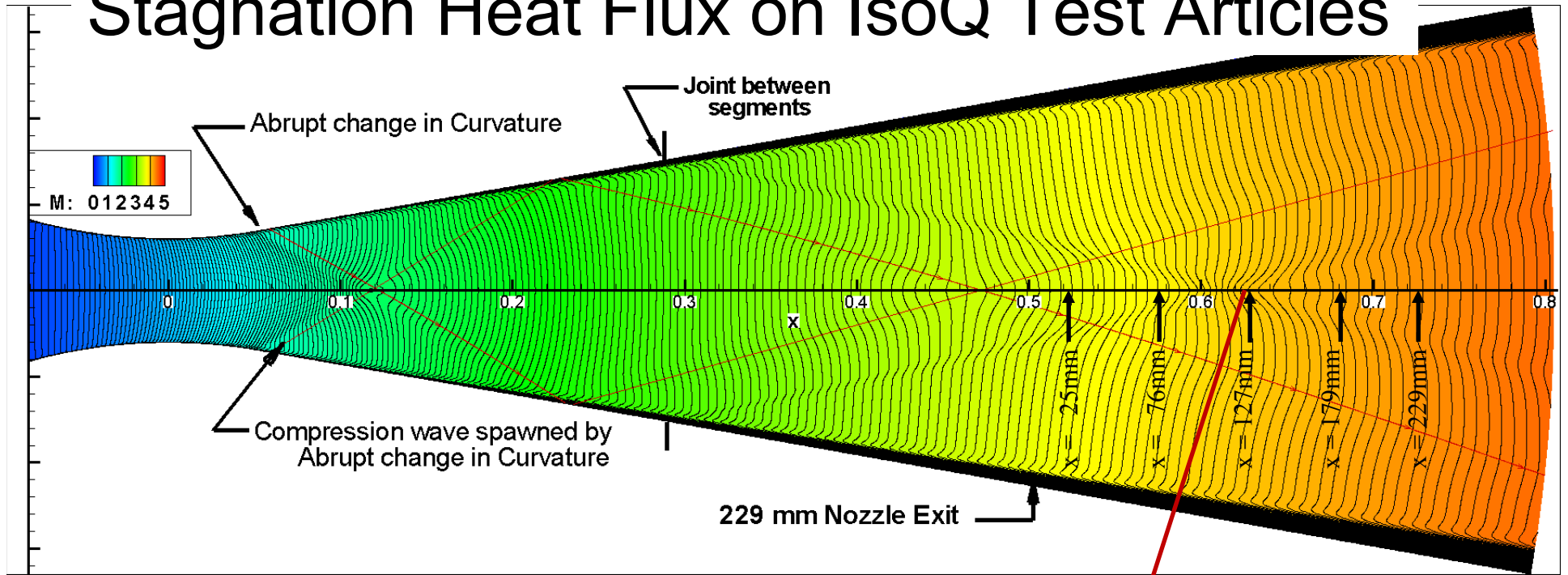
- Nozzle Joint discontinuity due to slope difference associated with tolerance stack up ($\pm 0.03^\circ$) a hypothetical scenario
- **Is this significant enough to cause waves**

Discontinuity in Slope at Joint

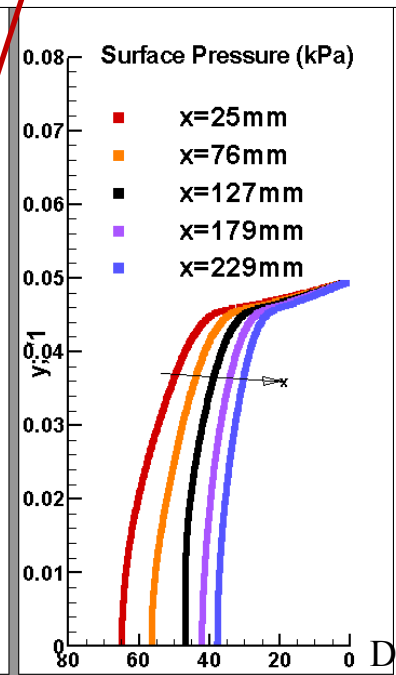
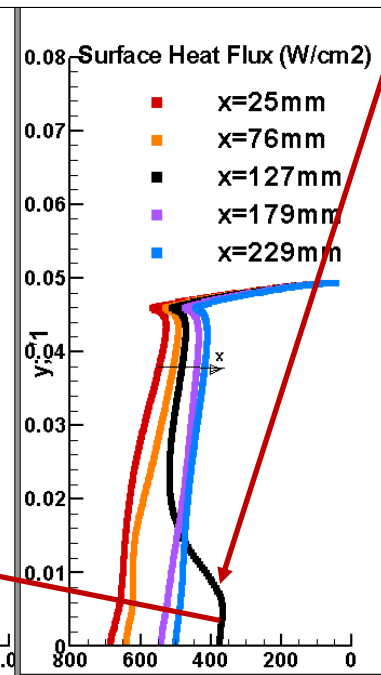
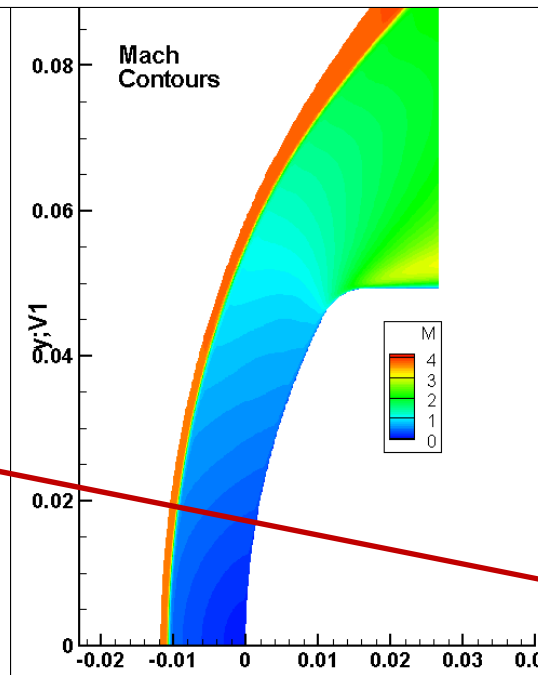


- Waves from both Curvature discontinuity and difference in slope at joint

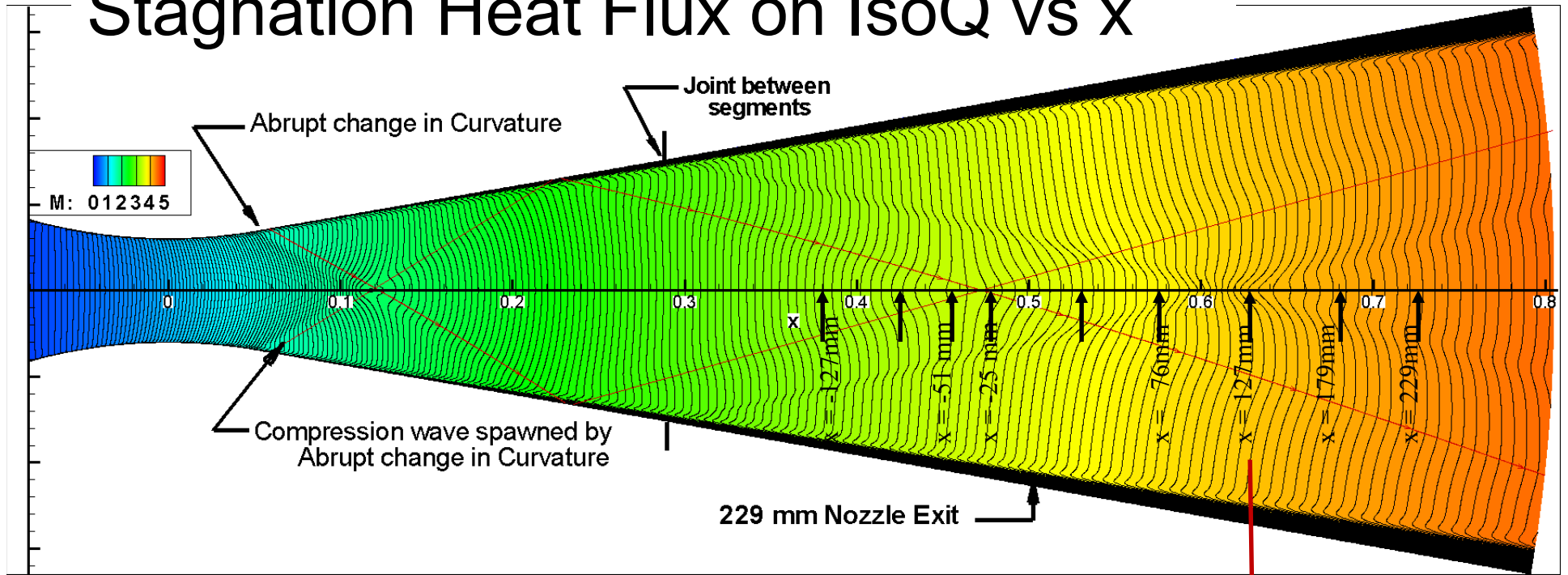
Stagnation Heat Flux on IsoQ Test Articles



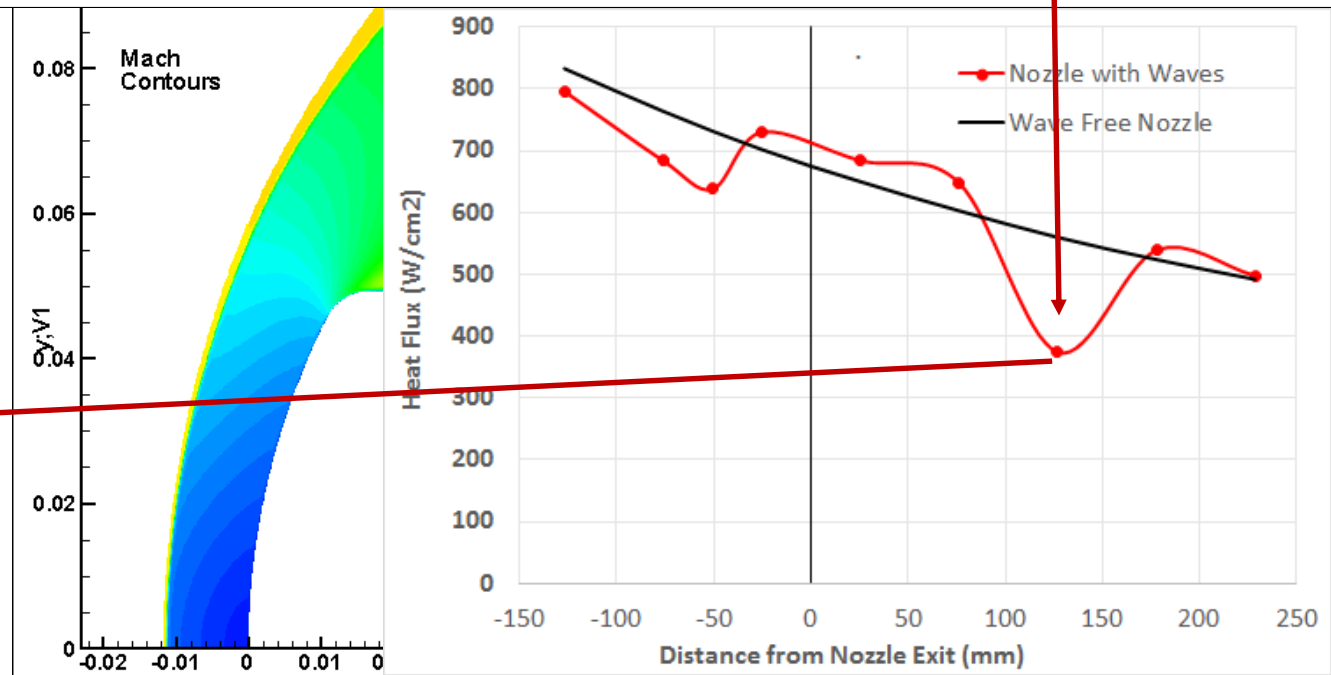
Local Minimum in heating when model is at the $x=127\text{mm}$ location. Consistent with Teflon Burn



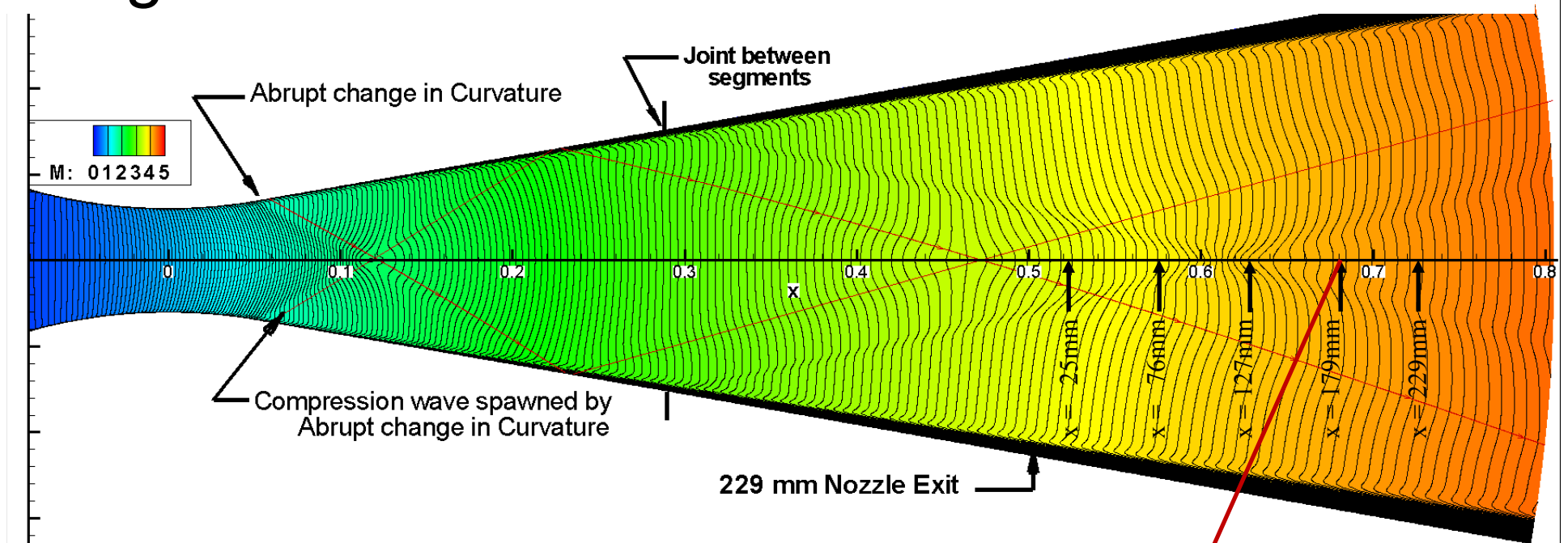
Stagnation Heat Flux on IsoQ vs x



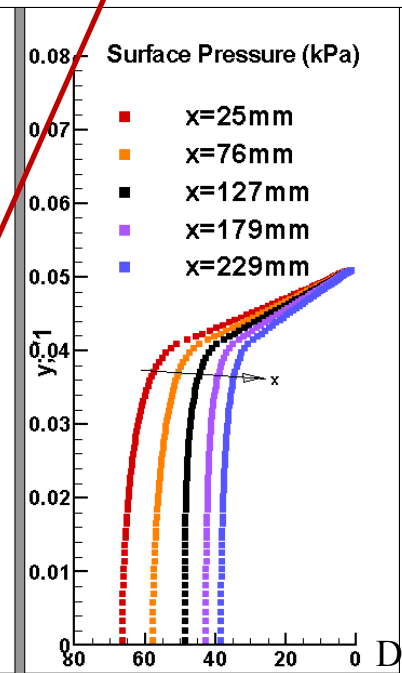
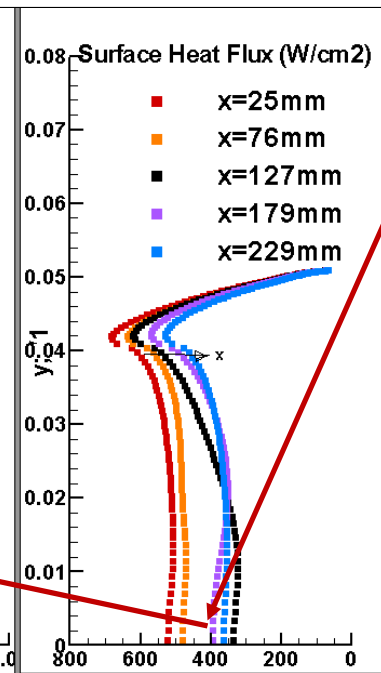
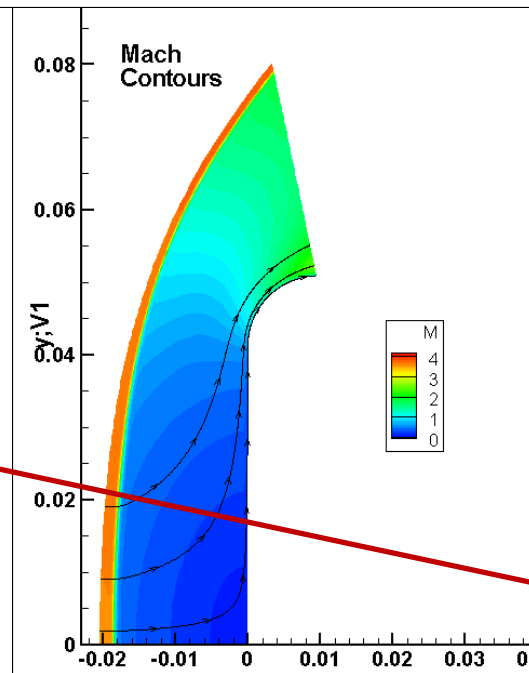
Local Minimum in heating when model is at the x=127mm location. Consistent with Teflon Burn



Stagnation Heat Flux on Flat Faced Test Articles



Local Maximum in heating when model is at the $x=179\text{mm}$ location. Consistent with Teflon Burn.



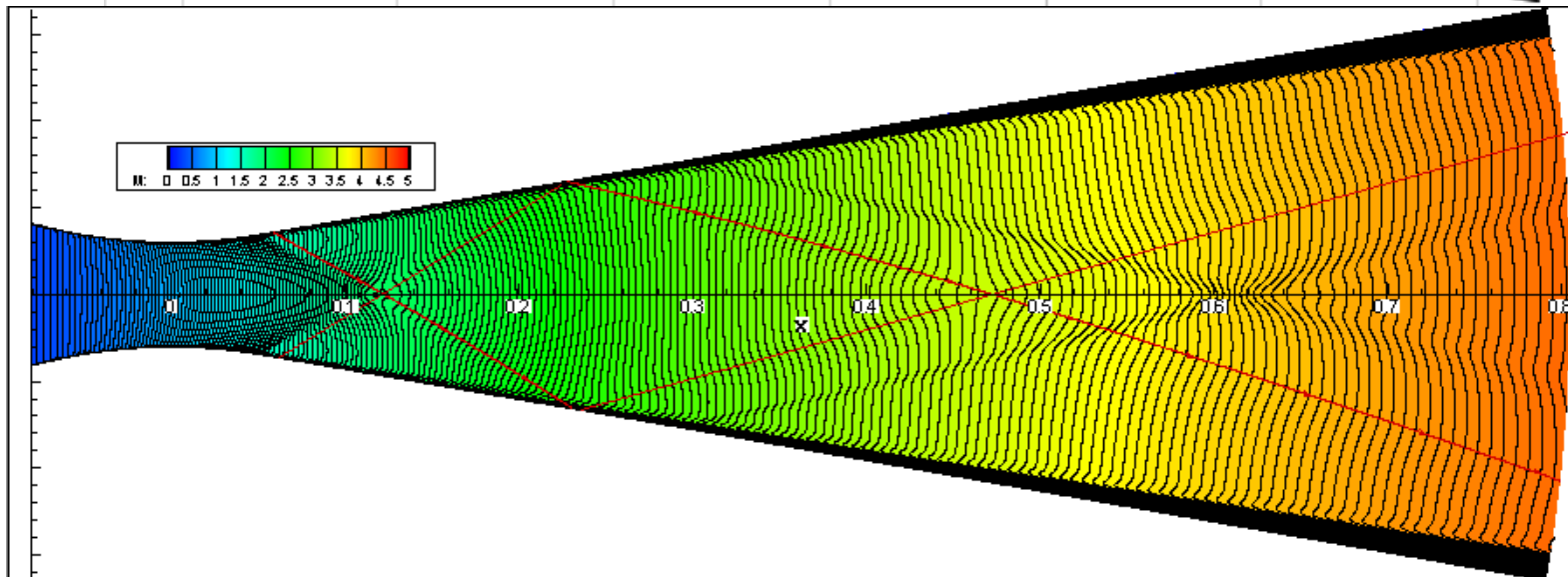
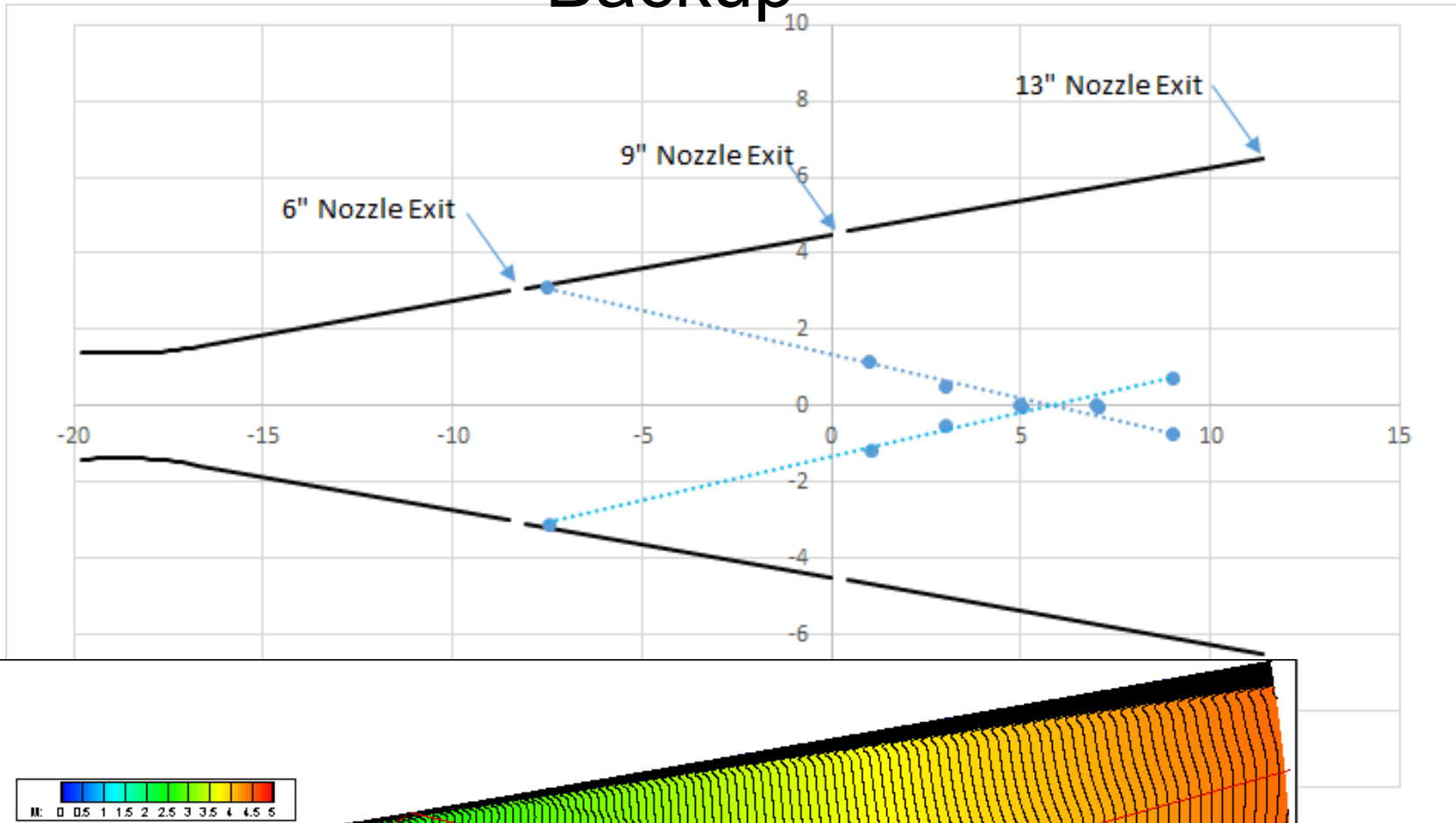
Summary

- Waves are seen experimentally in radial pressure distributions (waves intersect at $x=127\text{mm}$).
- Teflon test articles show non-uniform recession when test articles are placed near $x=127\text{mm}$.
- CFD indicates that waves can be expected from a discontinuity in curvature at the throat.
(although relatively weak)
- 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 $x=127\text{mm}$.
- Waves can be an issue for the new 229mm nozzle, and it is best to test upstream of $x=76\text{mm}$.
- Waves are a relative non-issue for the 152mm and 330mm nozzles, as their focal point is far from where models are tested

Future Nozzle design

- 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.

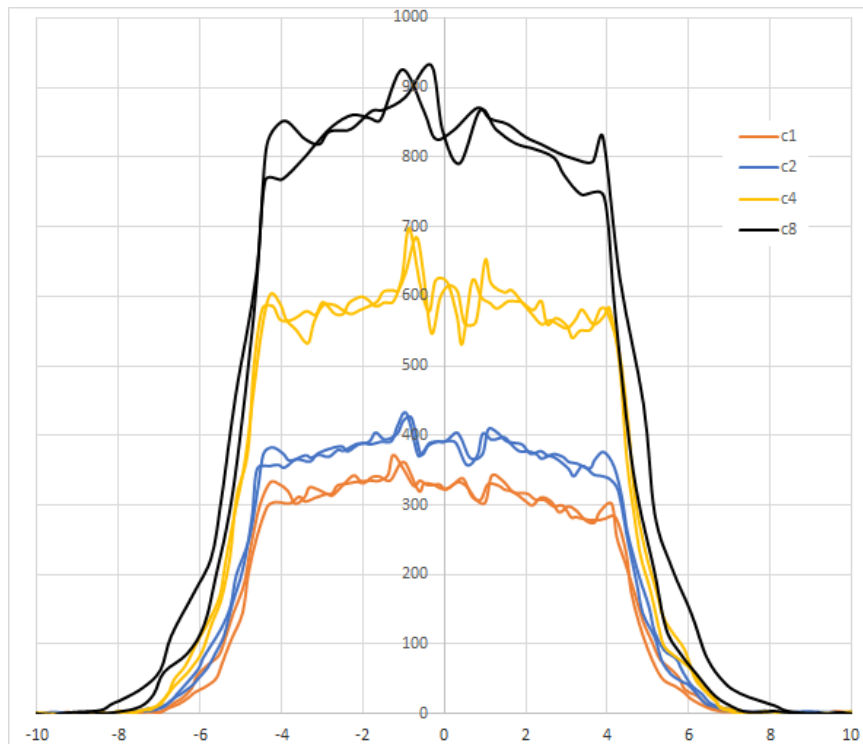
Backup



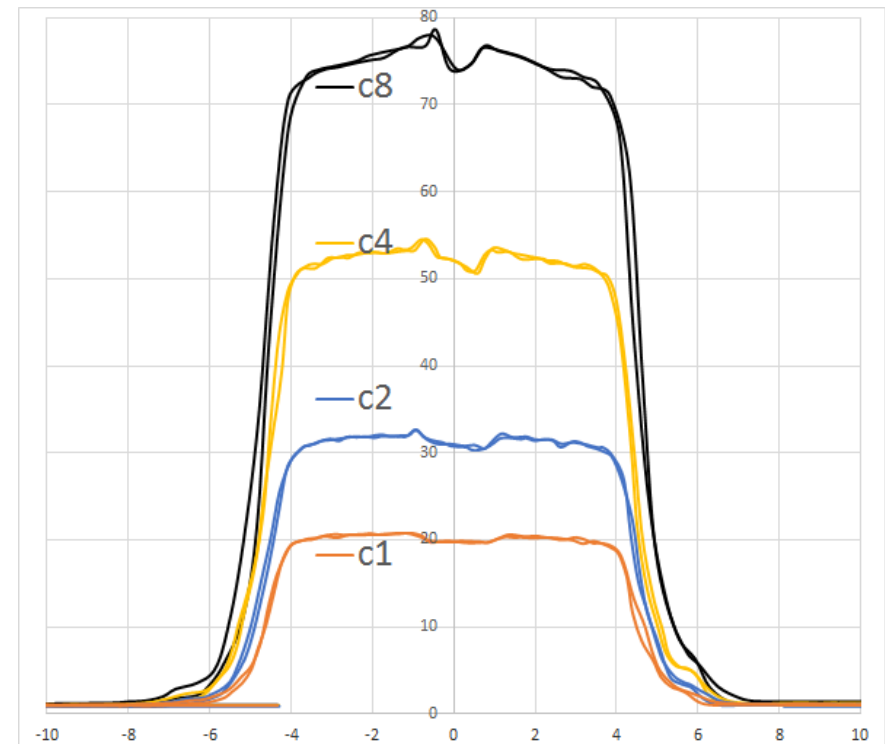
Radial Distributions for various conditions at x=76mm

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

Heat Flux Distribution (Gardon Gage)

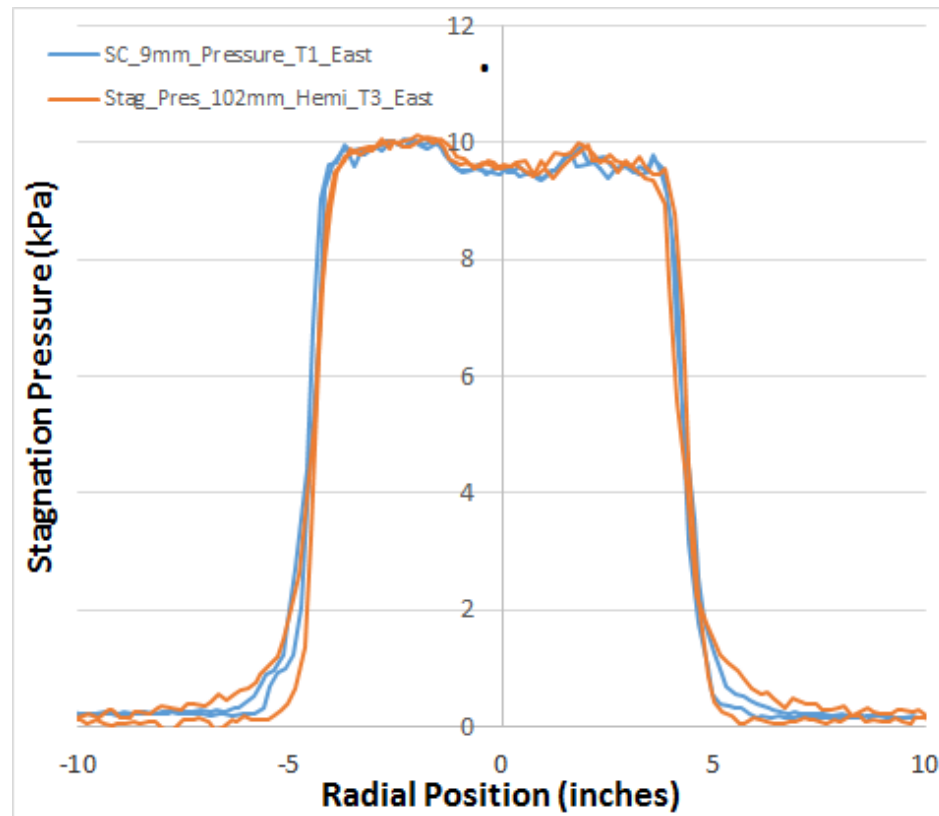


Pressure Distribution



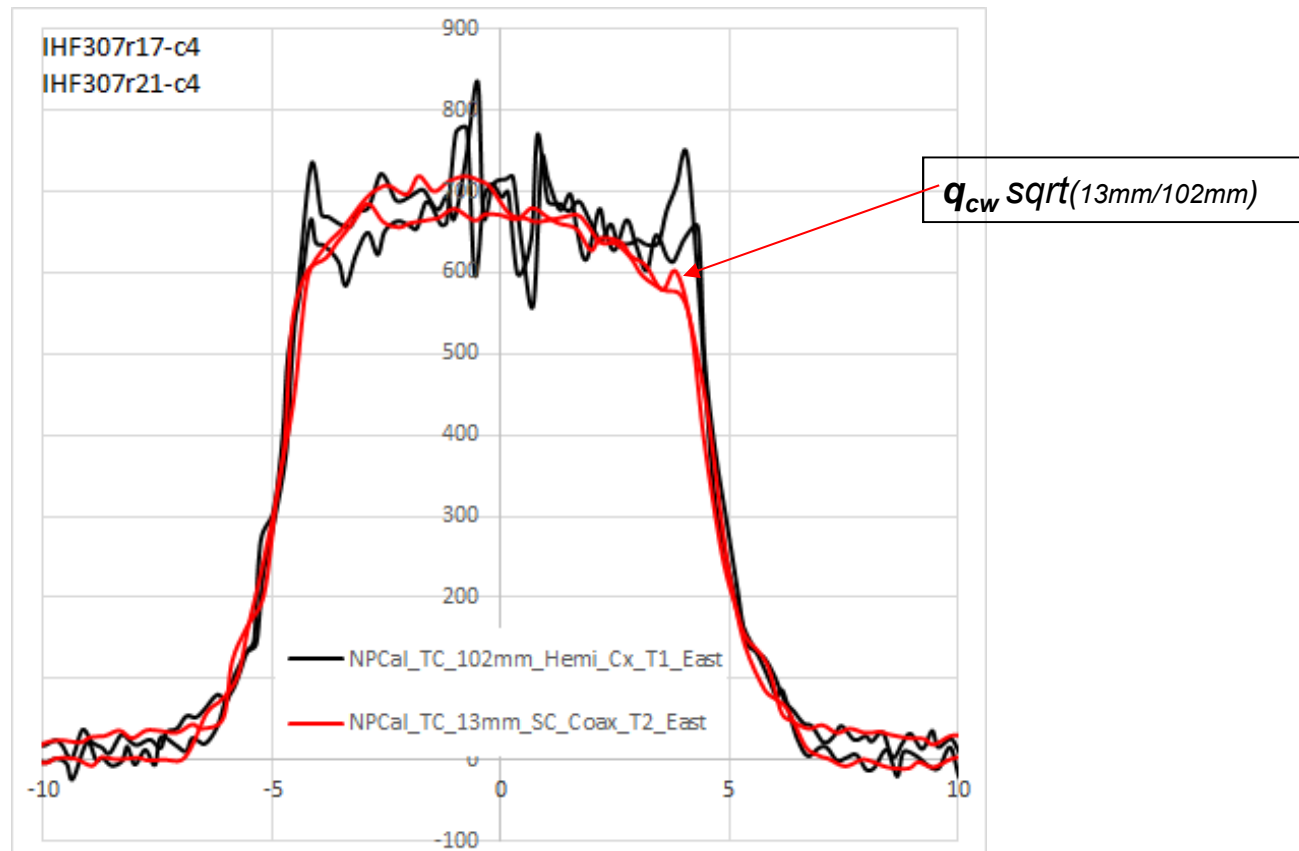
- Local disturbance seen in pressure and heat flux near centerline (at x=76mm location) for most conditions
- Recall Teflon looked reasonably good at x=76mm
- Disturbance broadening with reduction in flow enthalpy
i.e., wave intersection point moving downstream as flow approaches ideal gas

Pressure measured by Probes of Different Size



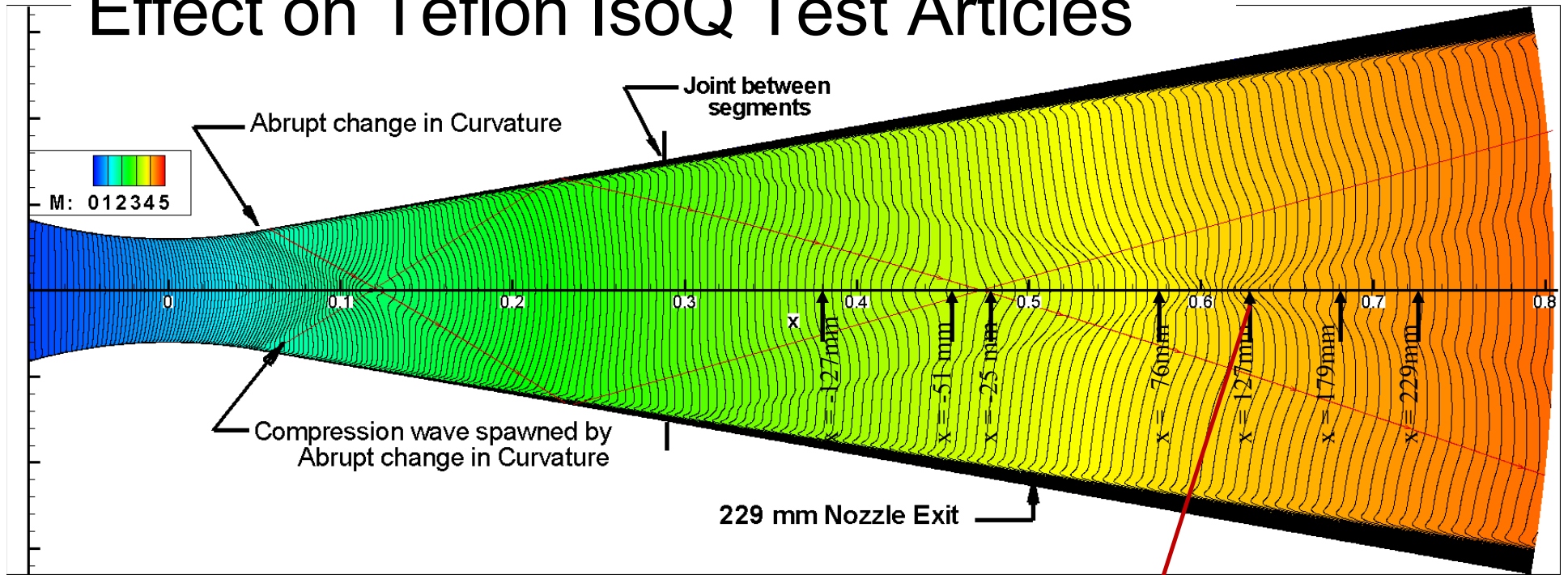
- Pressure measured by 102mm Hemi and 9 mm Sphere Cone agree

Heat Flux Measured by Probes of Different Size

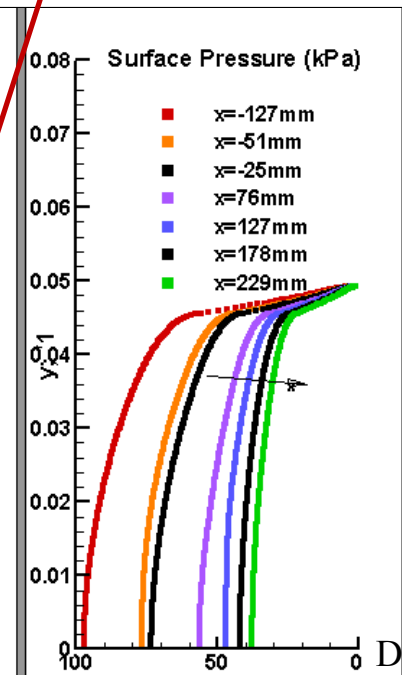
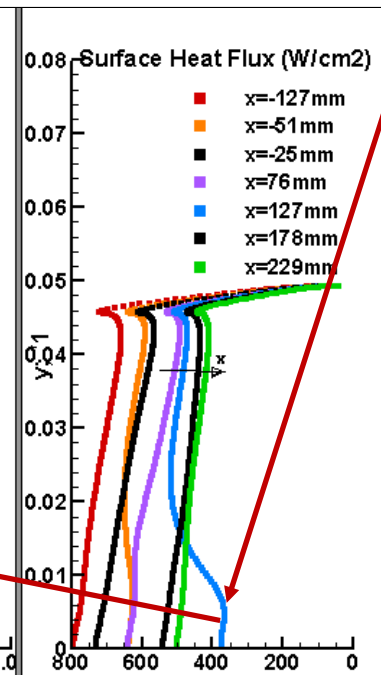
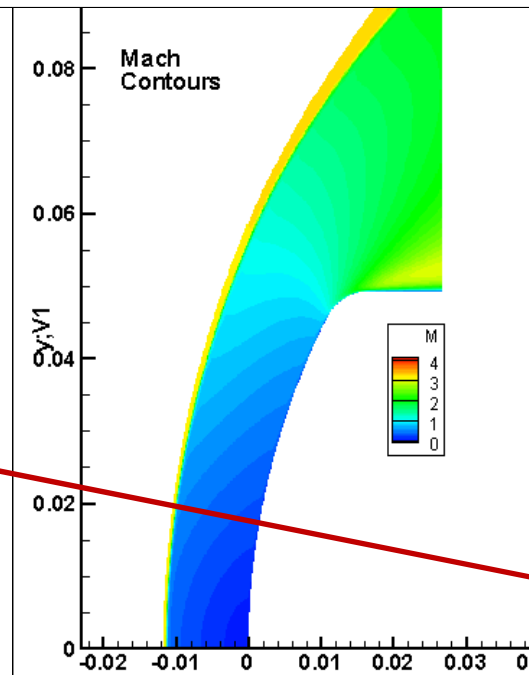


- Magnitude of $q_{cw} \sqrt{R}$ measured by 102mm Hemi and 13mm Sphere Cone agree
- But the smaller probe does not measure local extremes in heating

Effect on Teflon IsoQ Test Articles



Local Minimum in heating when model is at the $x=127\text{mm}$ location. Consistent with Teflon Burn



9" Nozzle

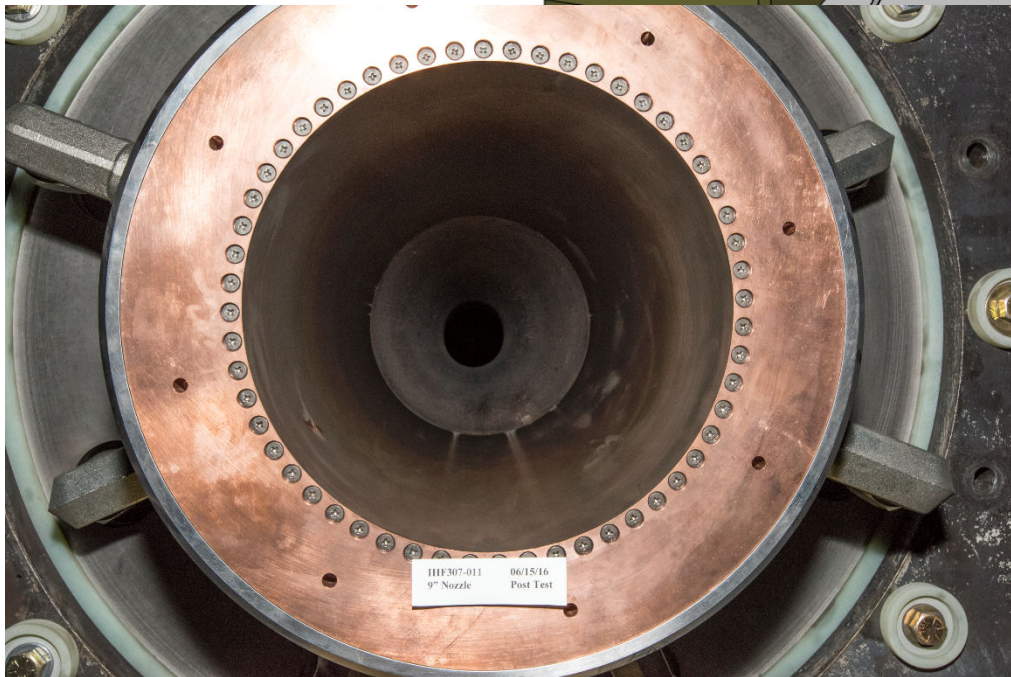
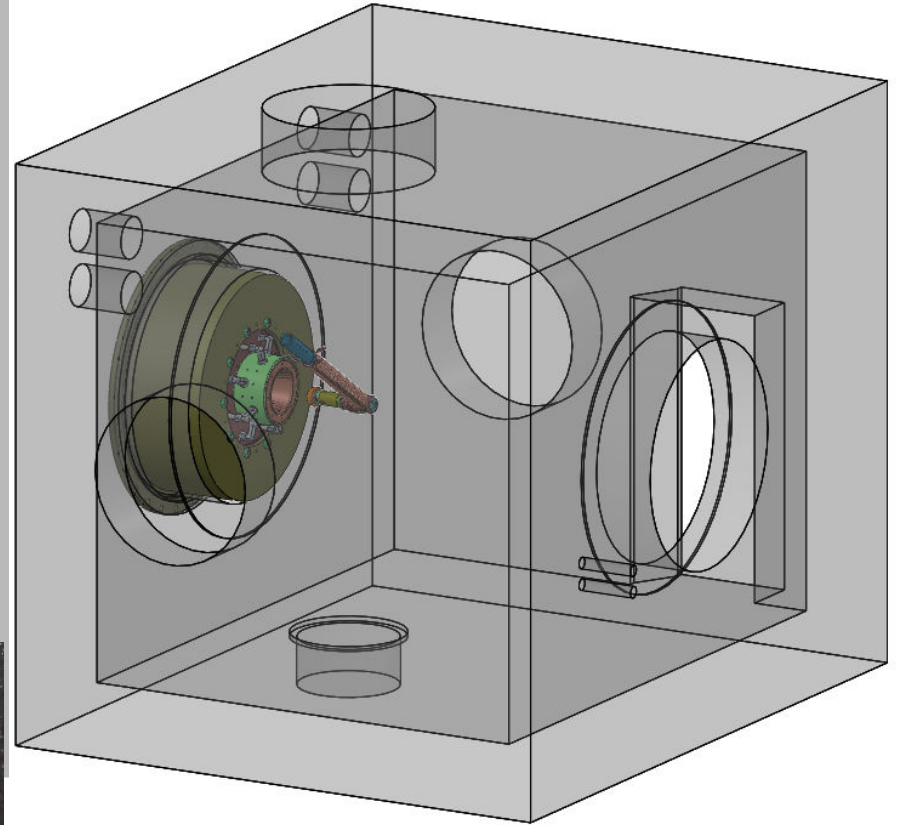
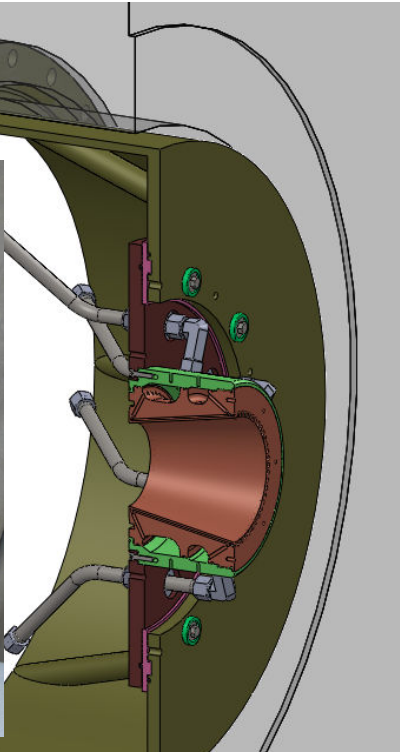
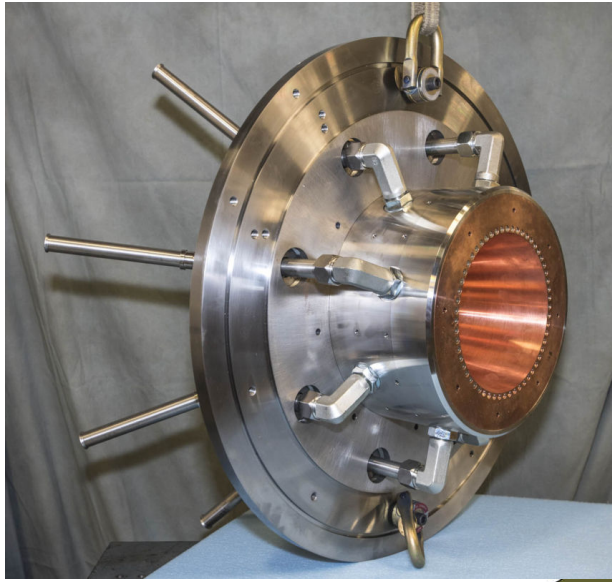


Photo of 9" nozzle after testing

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