The Experimental Measurement of Aerodynamic Heating About Complex Shapes at Supersonic Mach Numbers

Richard D. Neumann
Delma C. Freeman

Presented By

Del Freeman

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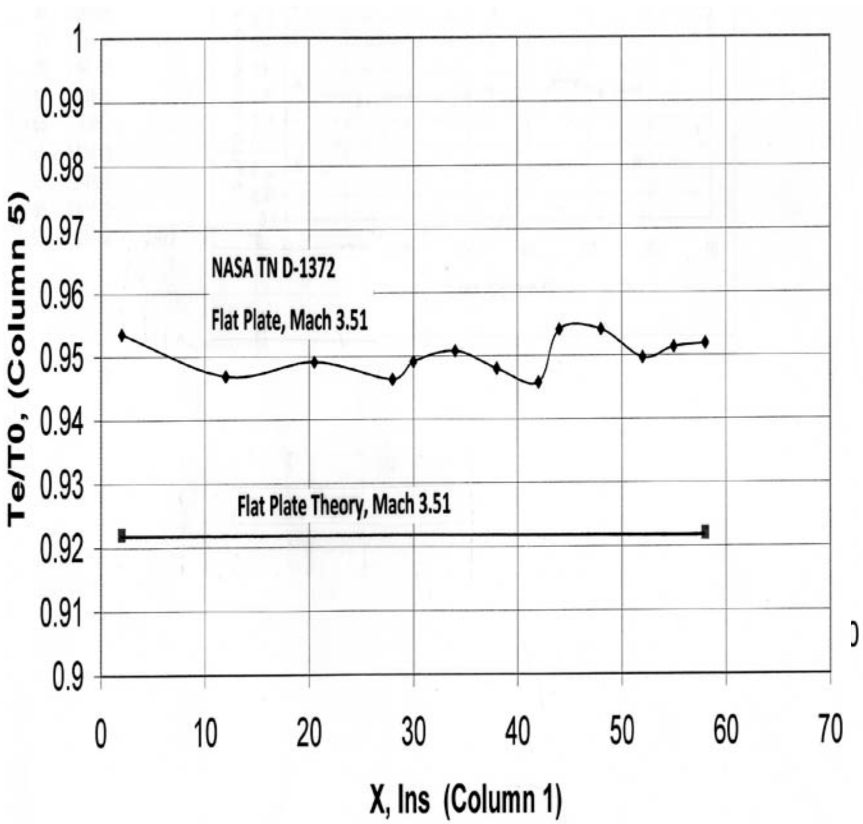
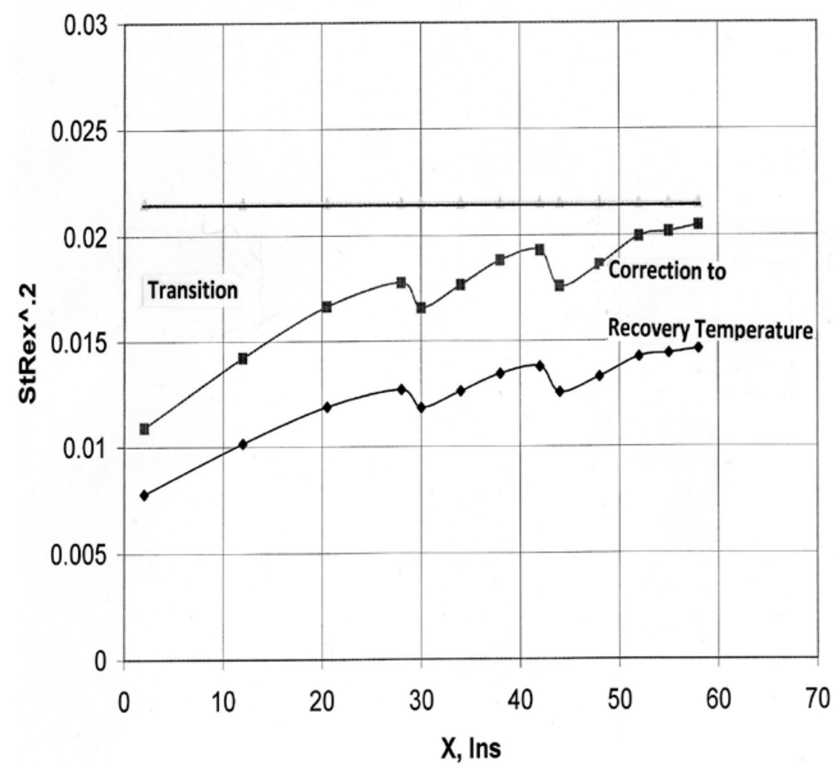
Legacy Heating Data: NASA TND-1372, Circa 1962

Flat Plate Recovery Temperature Compared to Theory



Corrected Heating Data Compared to Theory



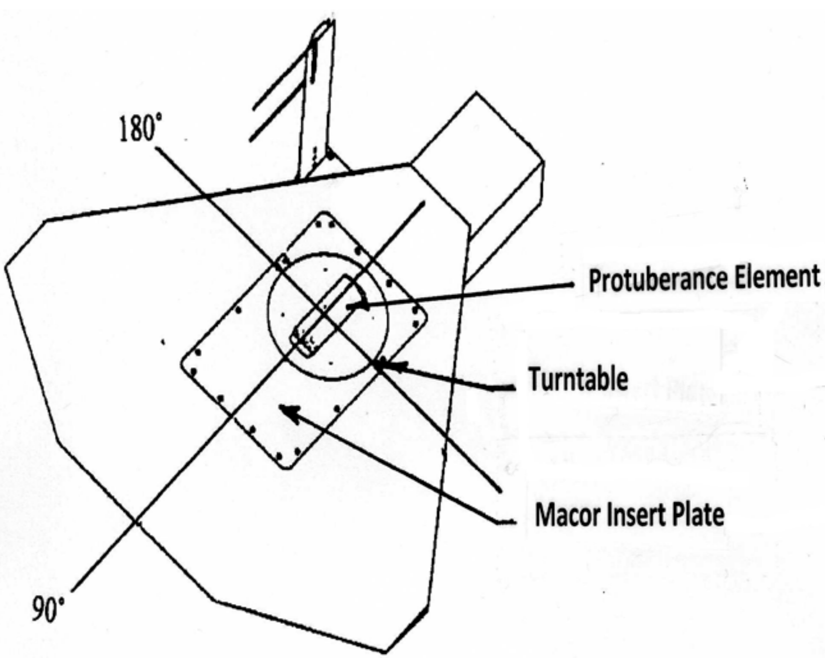
Protuberance Heating Measurements Revisited

In 2008 a wind tunnel test program was implemented to update the experimental data available for predicting protuberance heating at supersonic Mach numbers. For this test the Langley Unitary Wind Tunnel was also used. The significant differences for this current test were the advances in the state-of-the-art in model design, fabrication techniques, instrumentation and data acquisition capabilities.

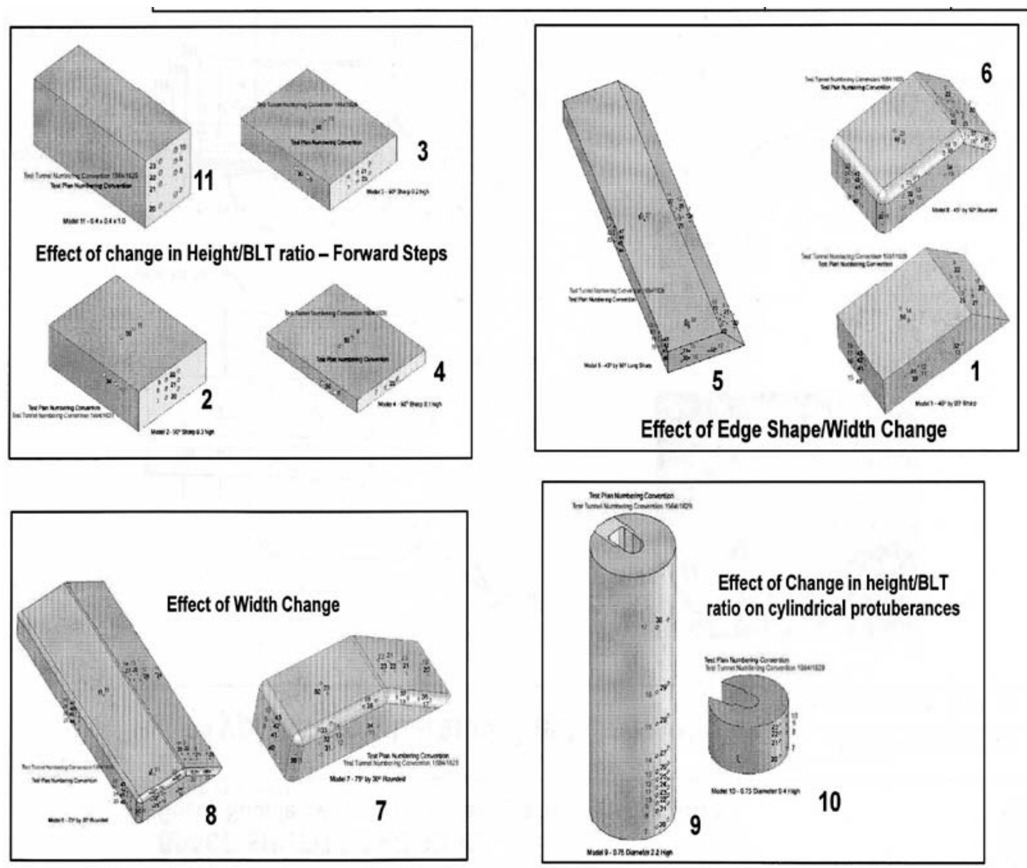
This current paper provides a focused discussion of the results of an in depth analysis of unique measurements of recovery temperature obtained during the test.

The Current Protuberance Heating Experiment

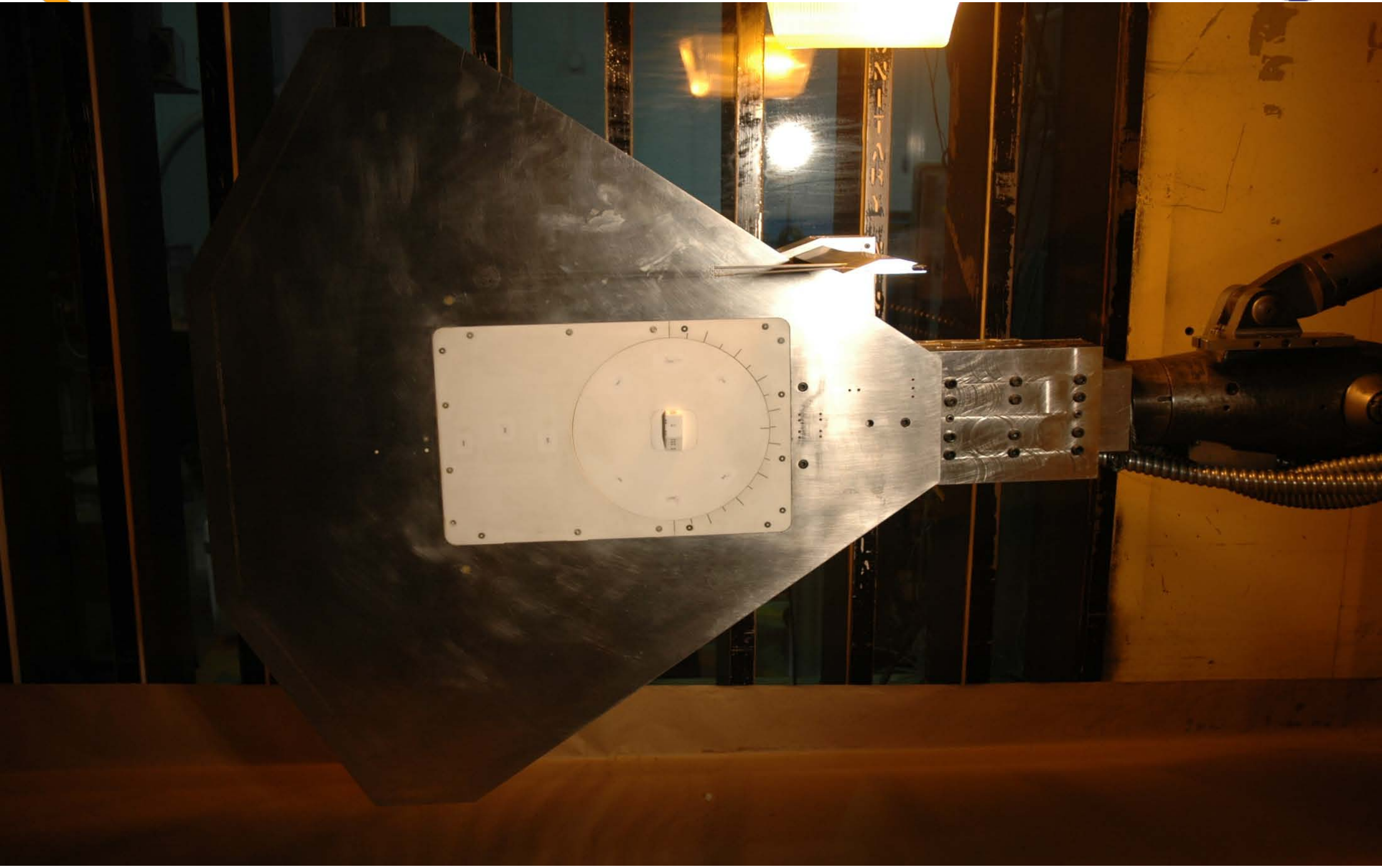
Overall View of Test Article



Protuberance Models Tested



Photograph of Test Setup



Thermal Pulse Operation of the Langley Unitary Tunnel

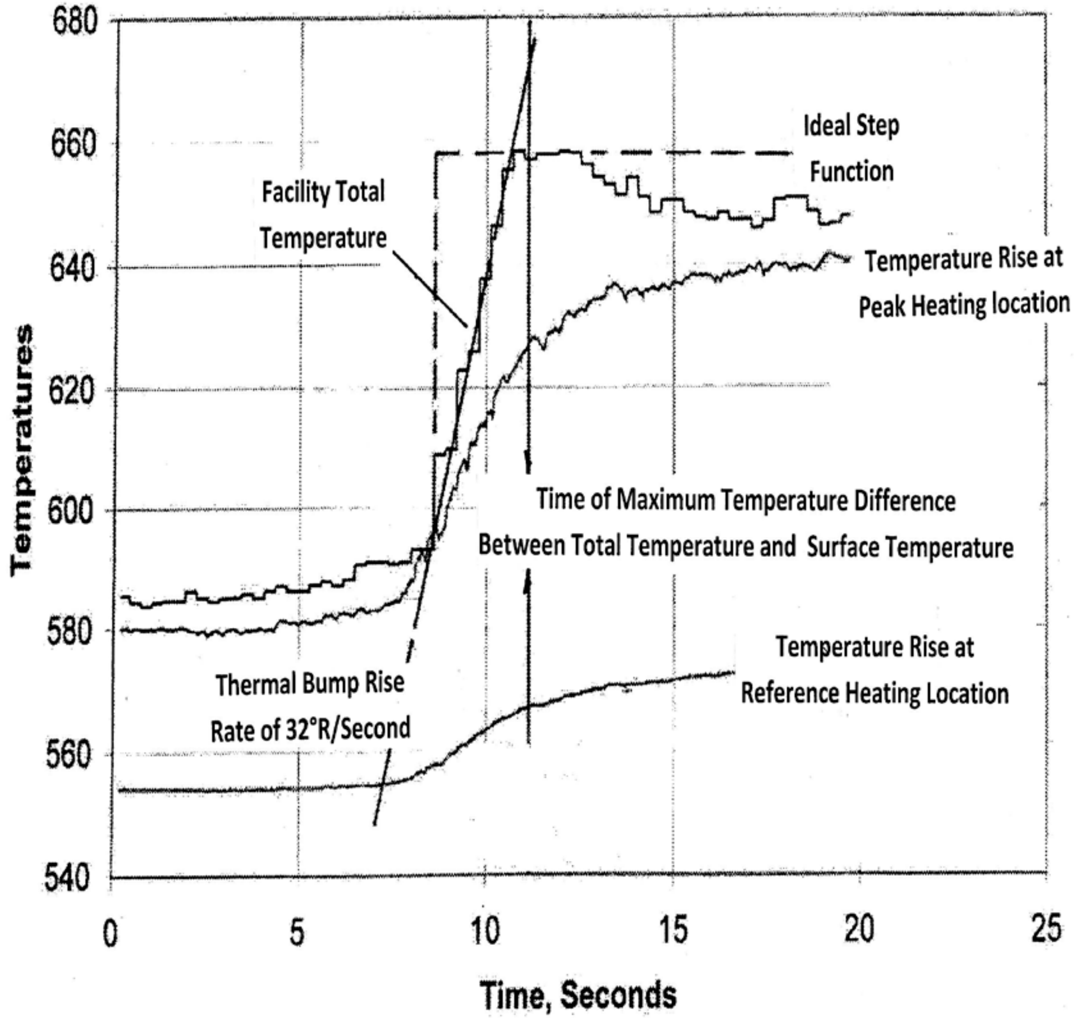
A thermal pulse is introduced by bypassing the tunnel heat exchanger and increasing the test section pressure

Two types of data are generated:

- (1) Recovery temperature for the initial 4 seconds

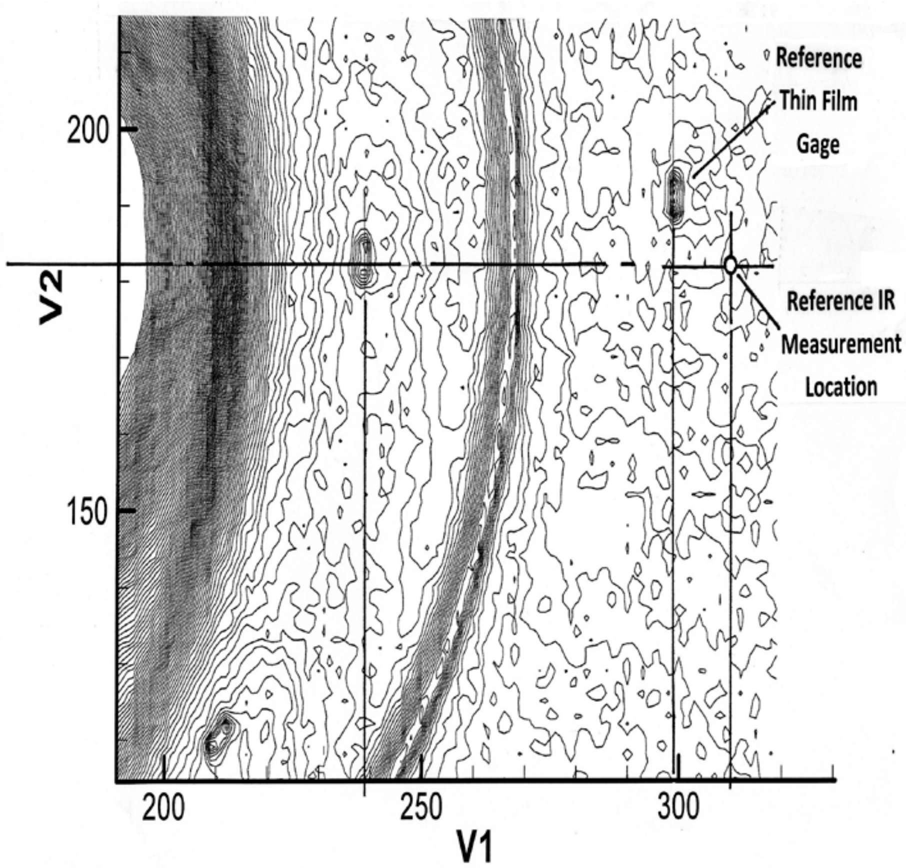
-(2) Heat transfer data at the time of maximum difference between total temperature and wall temperature

Data fusion allows the construction of the heat transfer coefficients

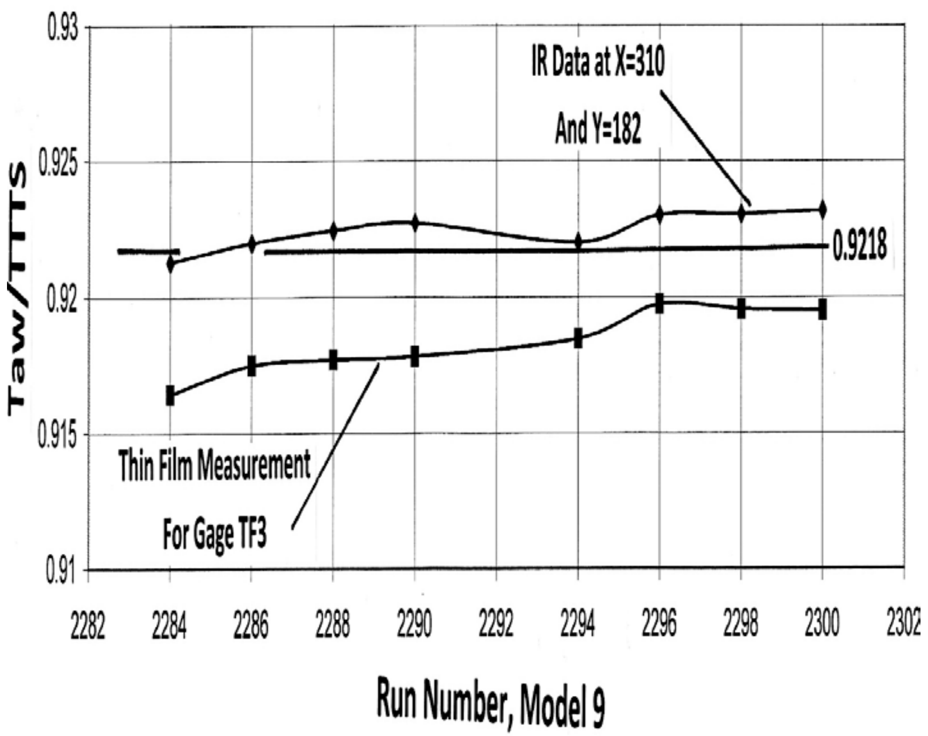


Reference Data Using IR and Thin Film Measurements

Contour Map Showing the Reference Location

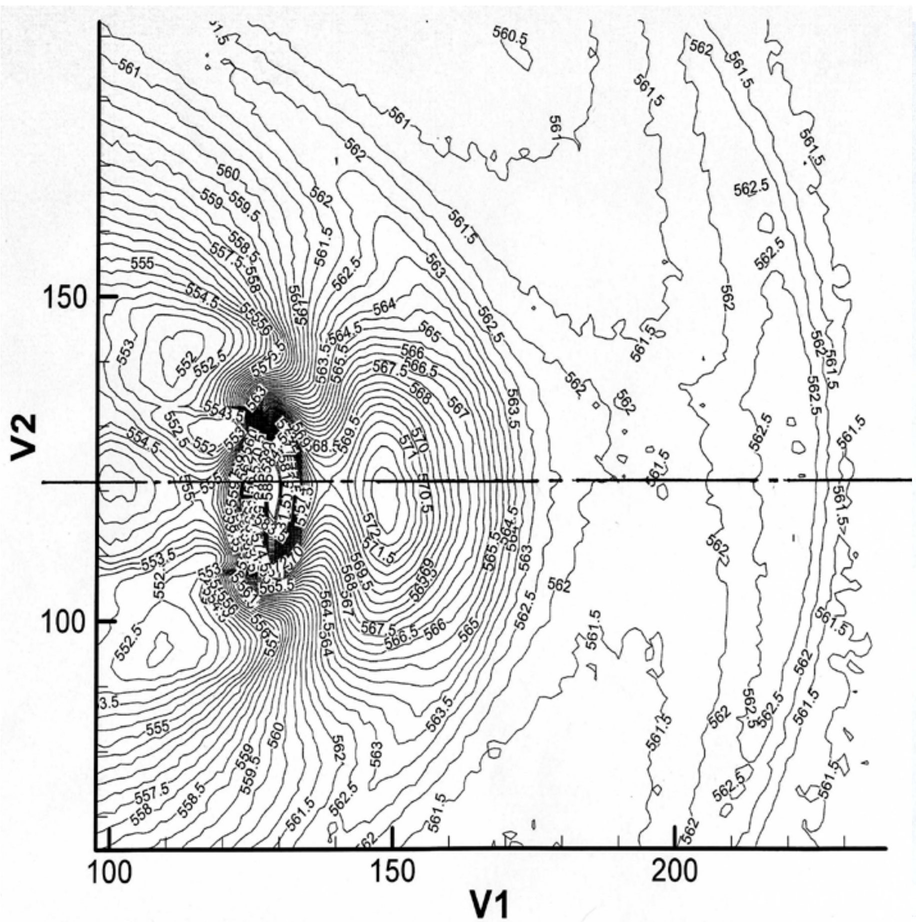


IR and Thin Film Data Obtained at Mach 3.51

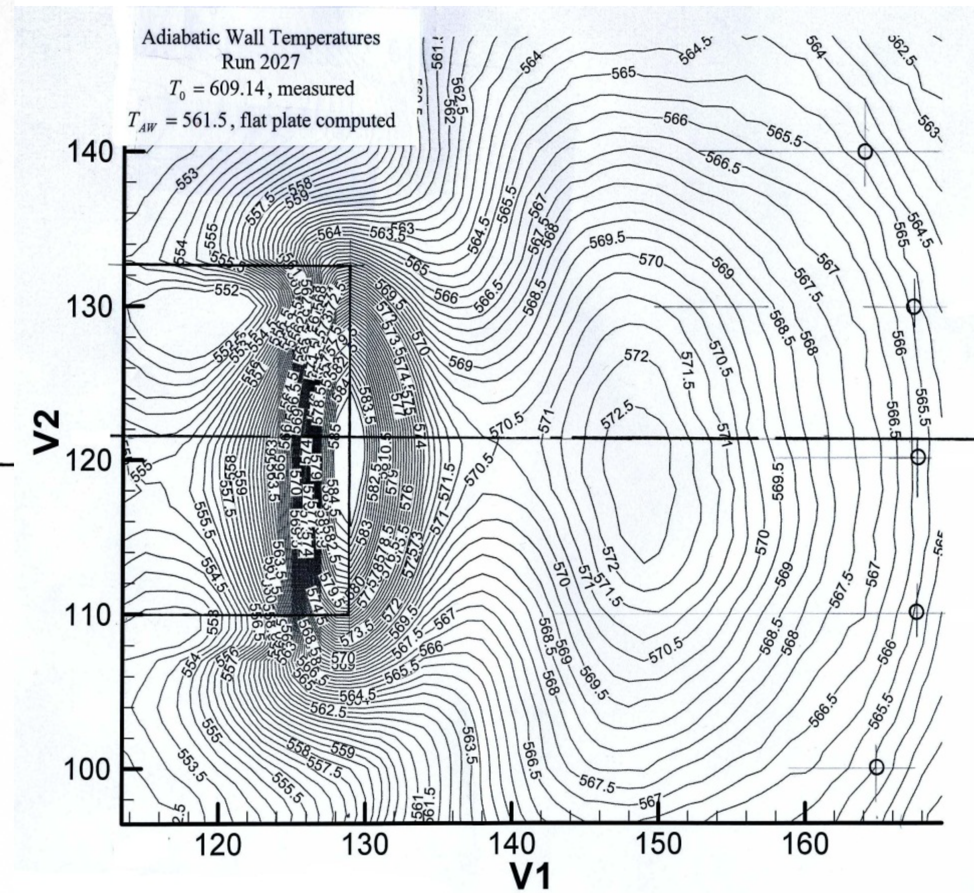


Recovery Temperature

Overall View of Recovery Temperature



View Focused on the Separation Region Ahead of the Protuberance



Experimentally

Inferred from measured wall Temperature $T_w(t)$ and model Properties, $\rho c k$

$$H = \frac{q(t_n)}{(T_R - T_w)}$$

Recovery temperature:
Normally an educated guess
Measured in this study
F($T_0, location, Mach\ Nr.$)

Measured surfac

Numerically

Computed fitting temperatures
In the boundary layer

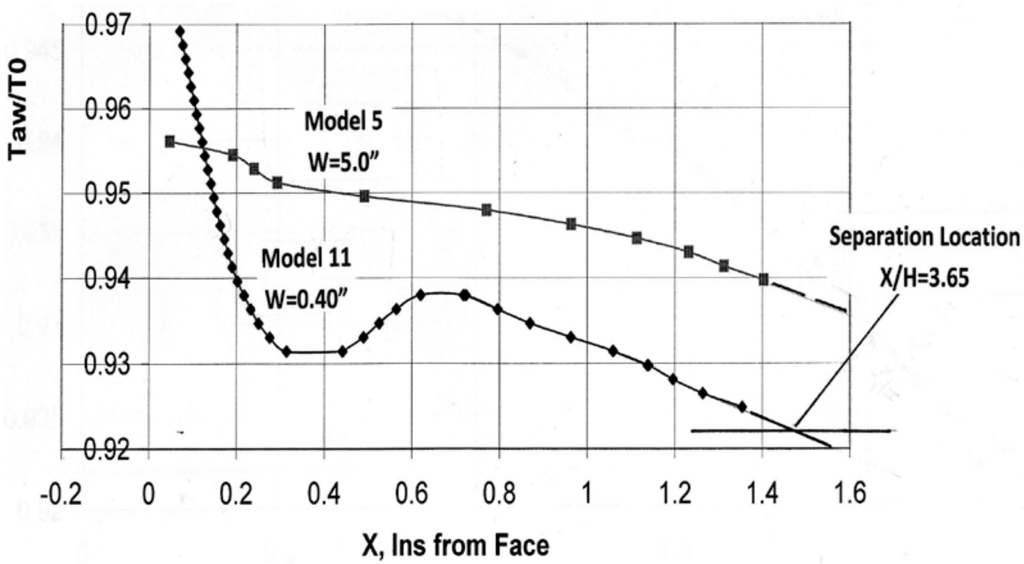
$$q(t_n) = k\frac{dT}{dz}$$

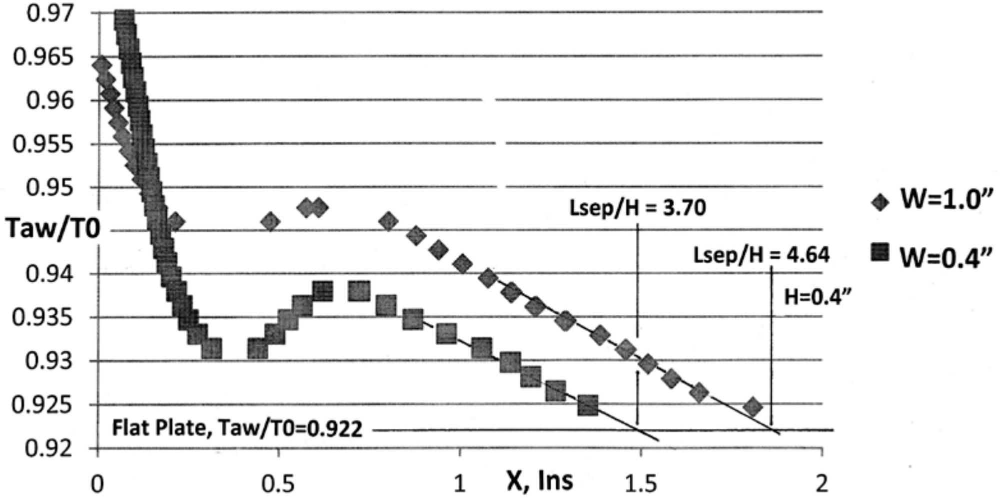
$$H = \frac{q(t_n)}{(T_R - T_w)}$$

Computed with a zero heat transfer boundary condition at the surface. Same code as for q(Tw) with a different wall boundary condition

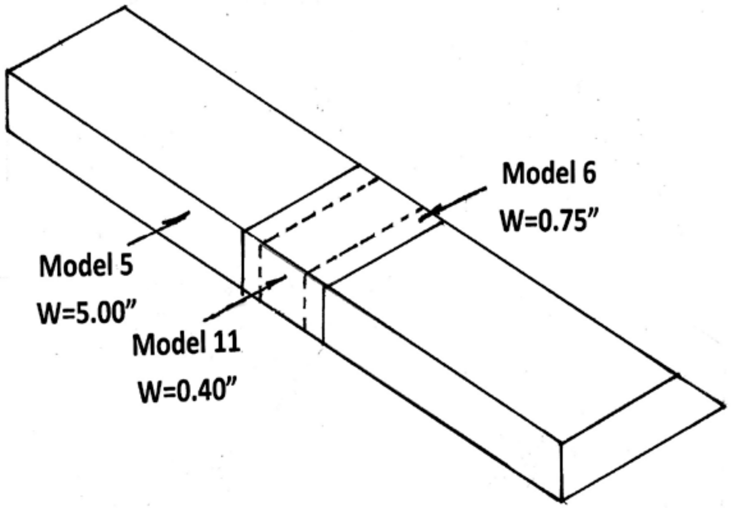
User specified, representative Surface temperature function

Recovery Temp on the Plate Ahead of 90 Degree Protuberances

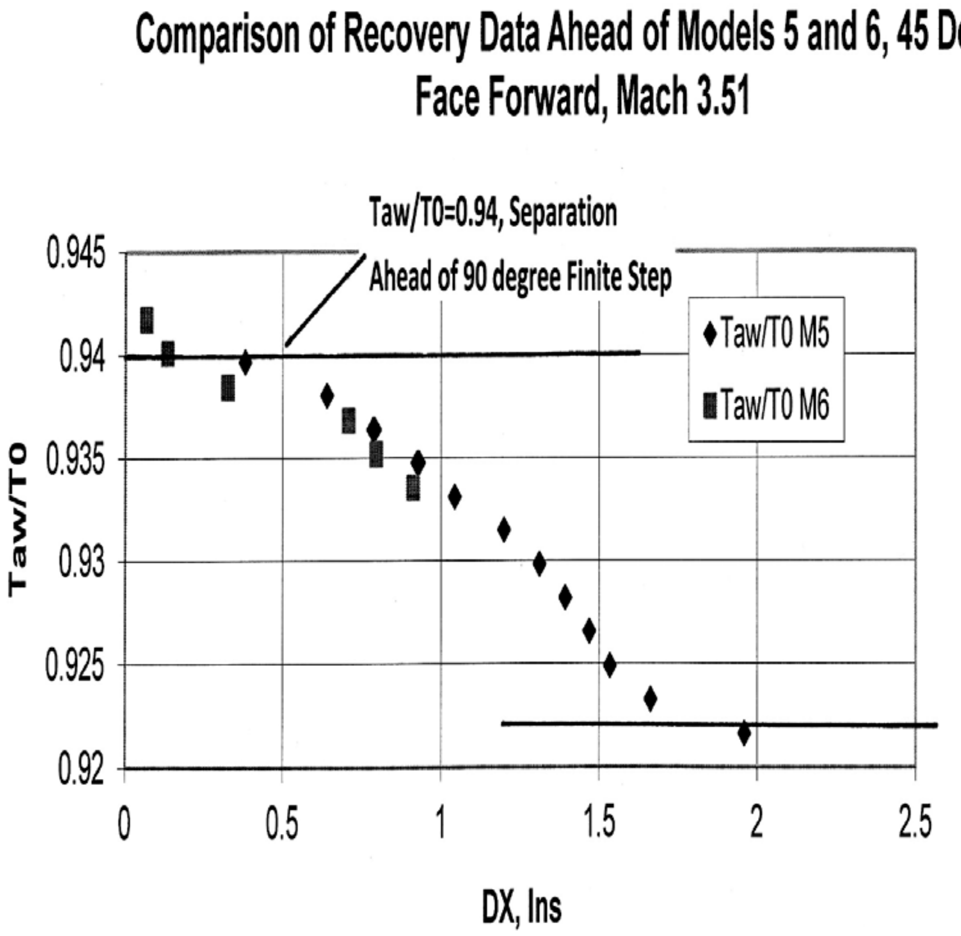




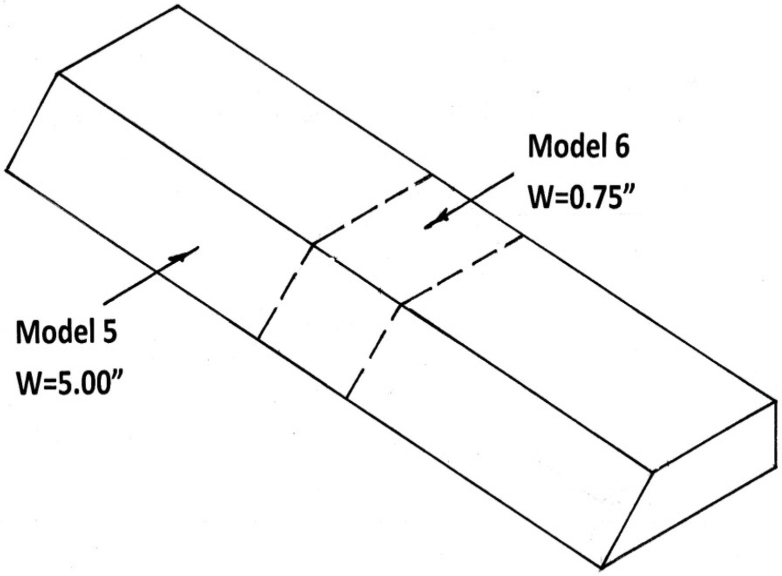
Protuberance widths of 0.40, 0.75 and 5.00 inches were evaluated.



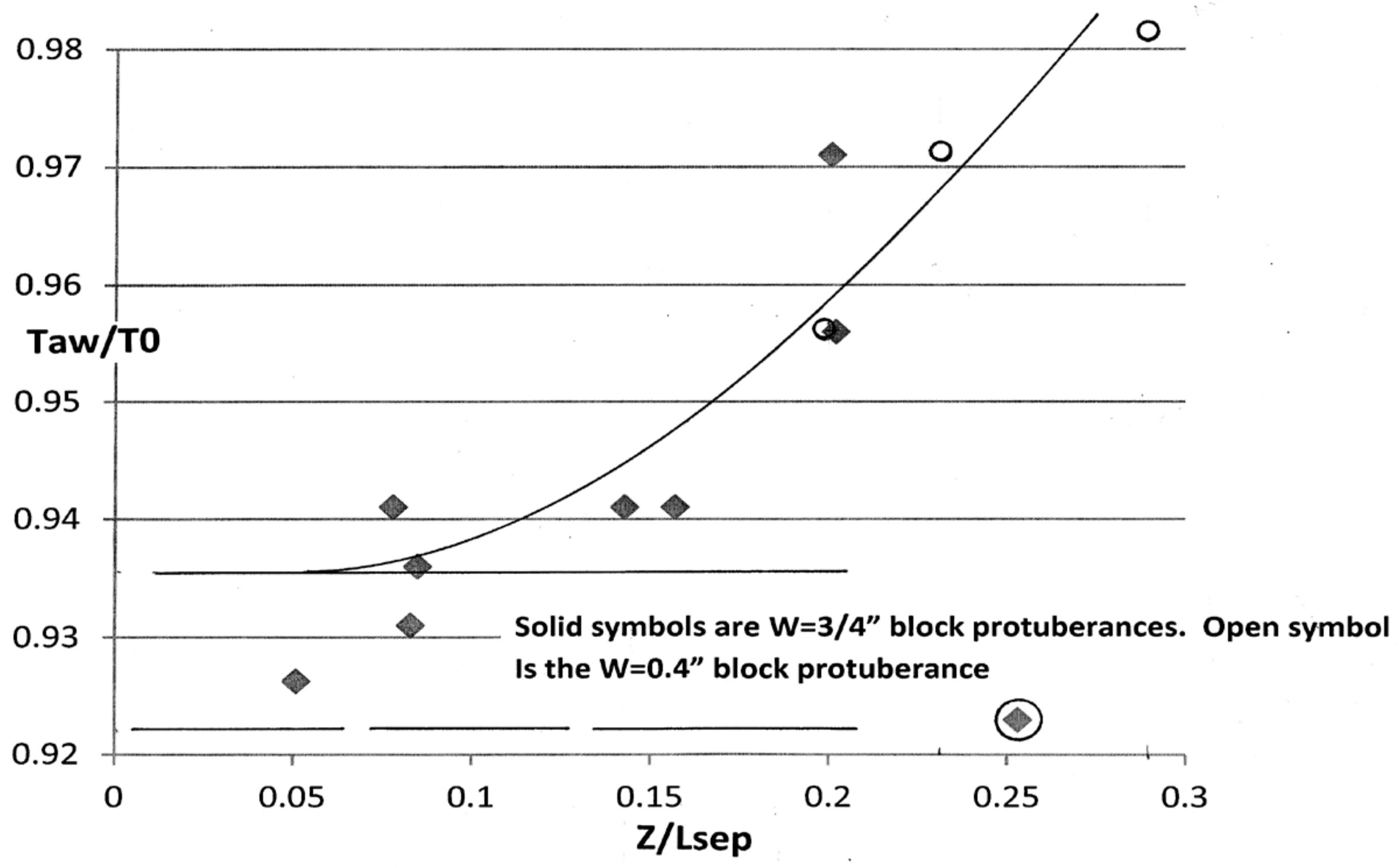
Recovery Temperatures on the Plate Ahead of Different Width 45 Degree Protuberances



Protuberance widths of 0.75 and 5.00 inches were evaluated



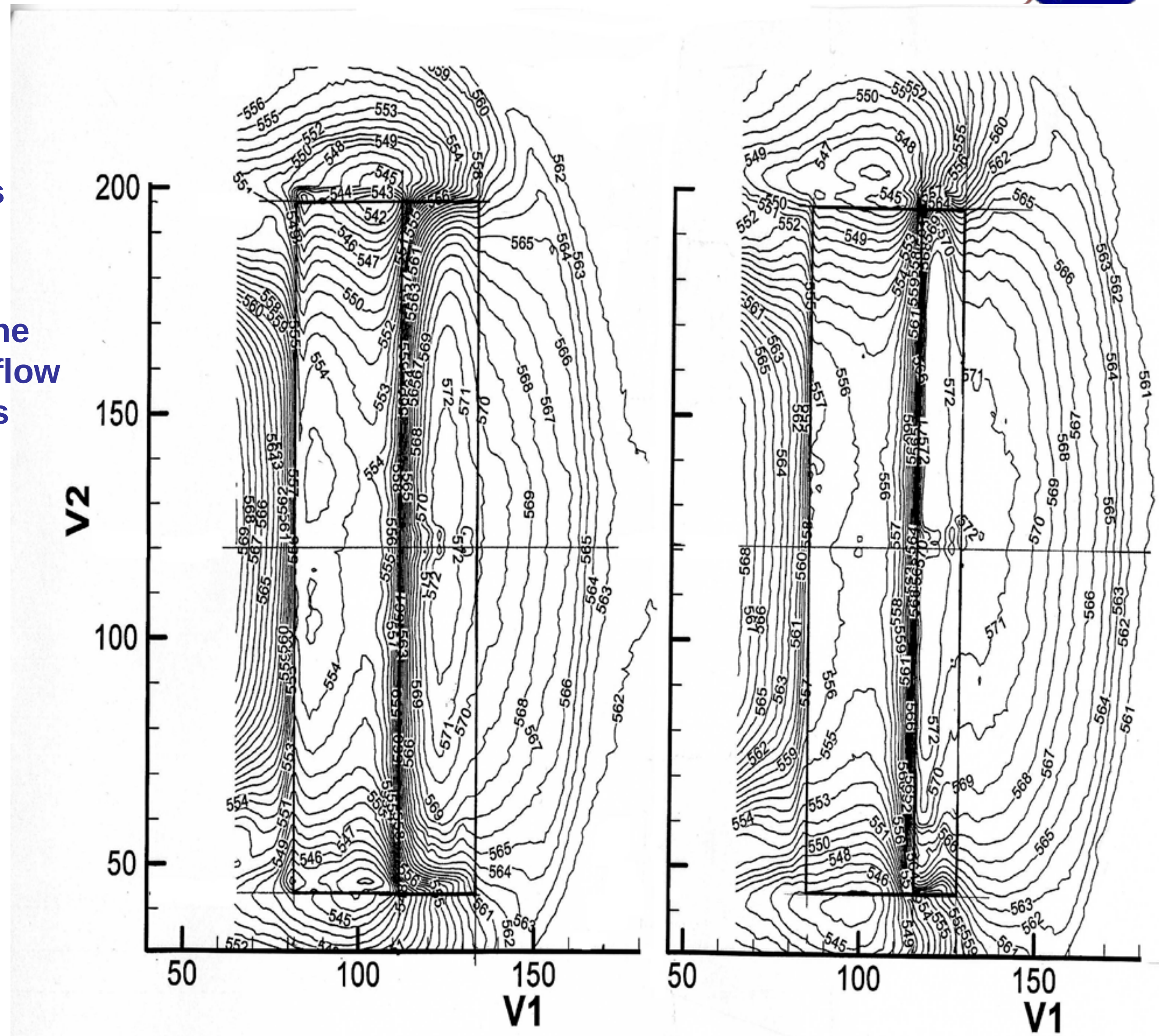
Recovery Temp Ratio on the Face of a Block Protuberance



Recovery Temperature Distribution on the Face of Block Protuberances

IR data used to develop the recovery temperature contours shown

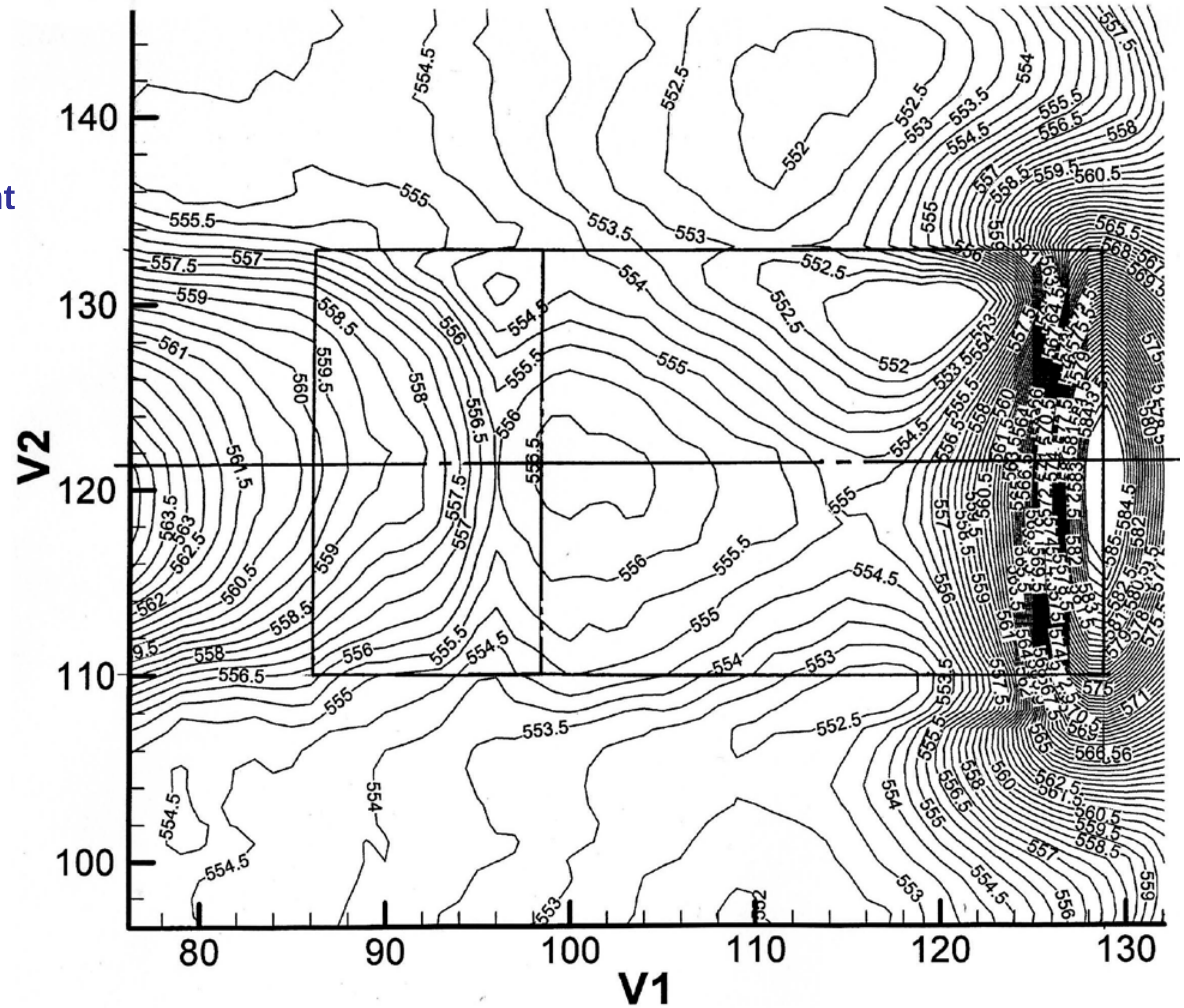
- The qualitative trends show the two dimensional nature of the flow and the significant edge effects away from the centerline



Recovery Temperatures on the Top of a Block Protuberance

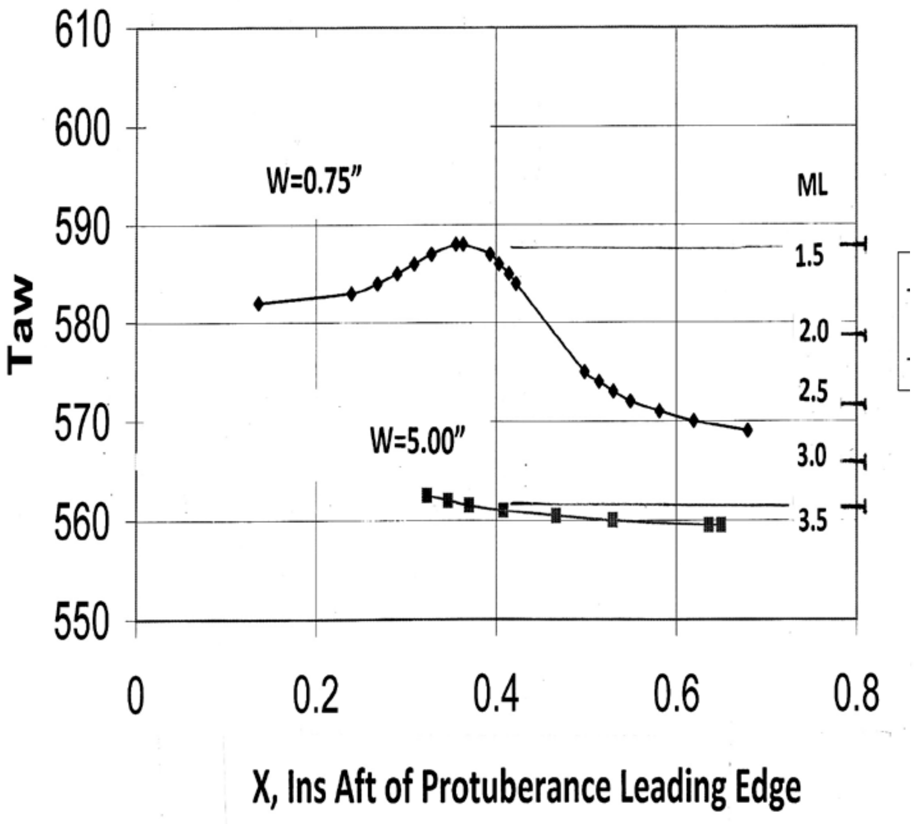
Width = 0.75 inch

- The data shows a significant gradient in the measured recovery temperature at and near the protuberance windward face



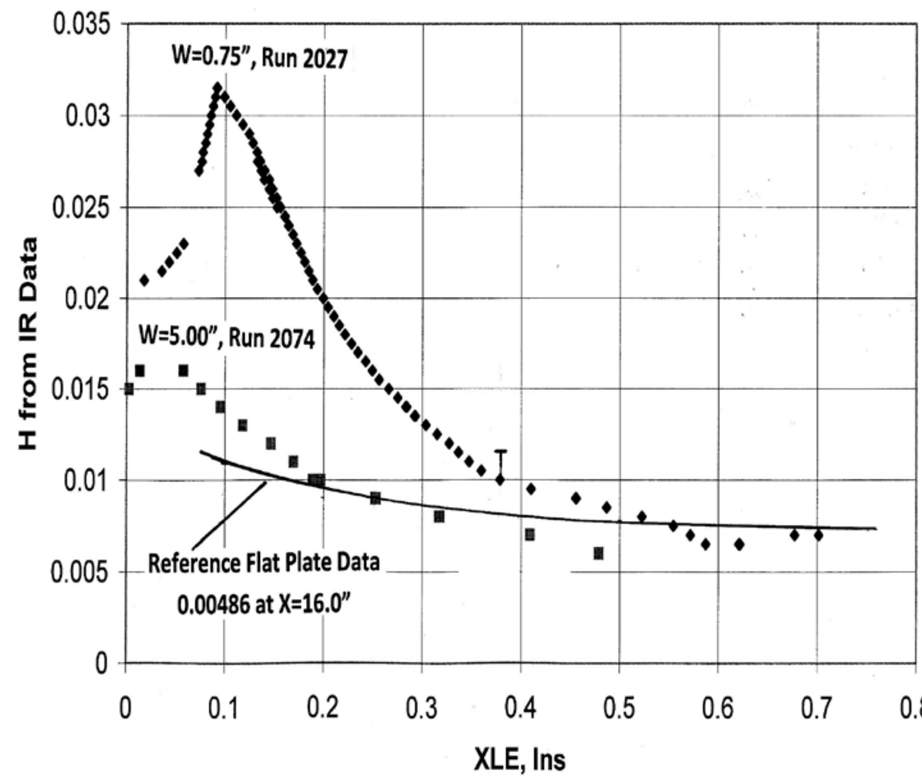
Heat Transfer on the Top of the 0.75" and 5" Wide Protuberances

Centerline Recovery Temperature



Centerline Heat Transfer Coefficient

(IR measured heat transfer coefficient derived using measured recovery temperature)

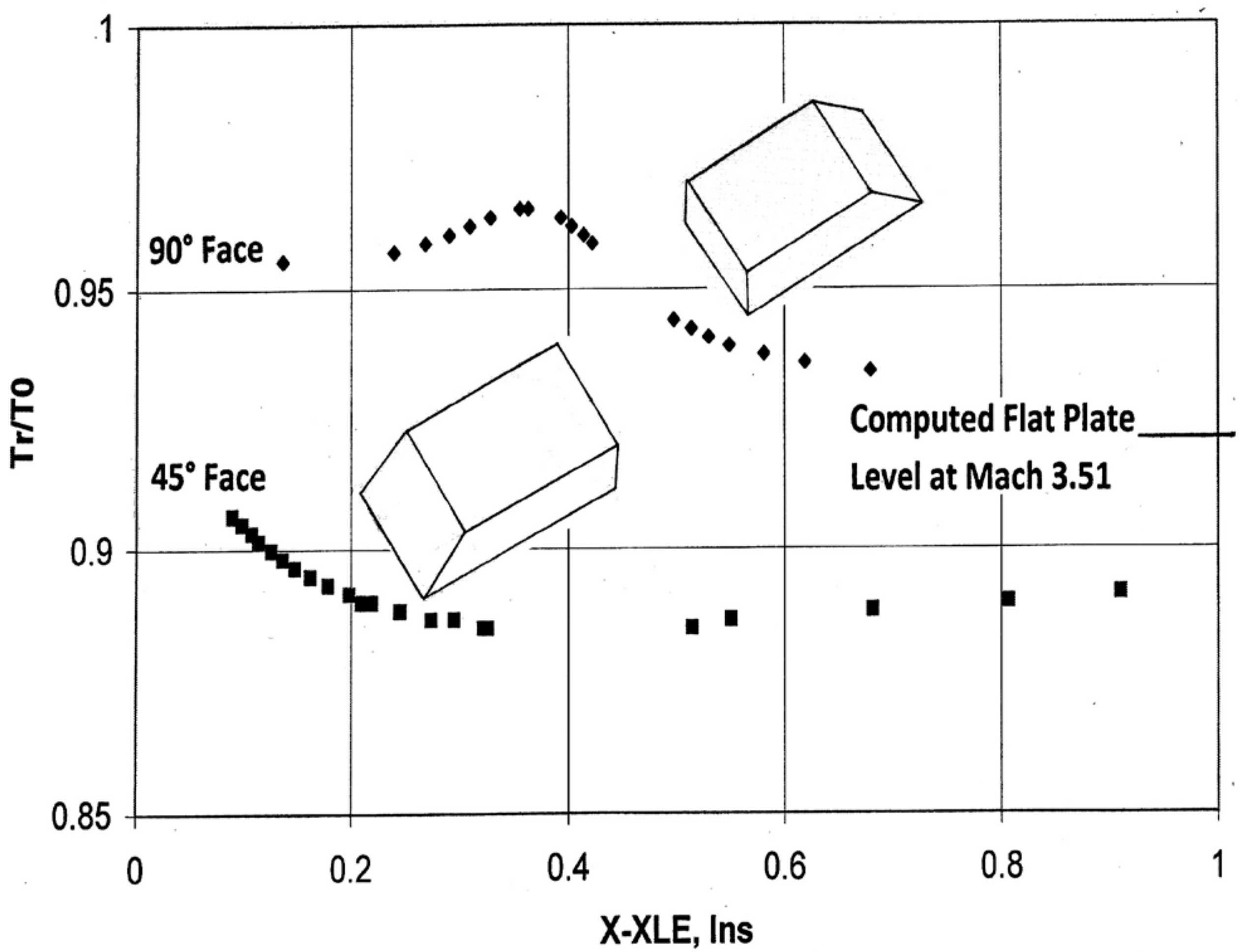


Recovery Temperature on the Top of the 45 and 90 Degree Protuberances

Recovery temperatures on a 0.75 inch wide protuberance with 45 and 90 degree leading edge bluntness are shown

-90 degree face shows low local Mach numbers

- 45 degree face shows much higher local Mach numbers because of a flow expansion on the top of the protuberance

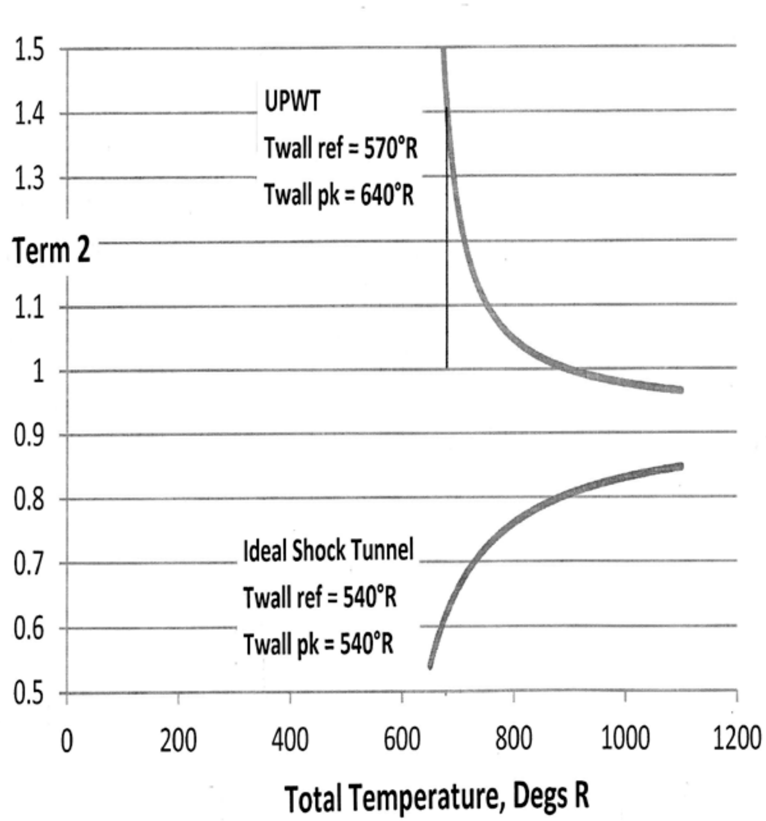


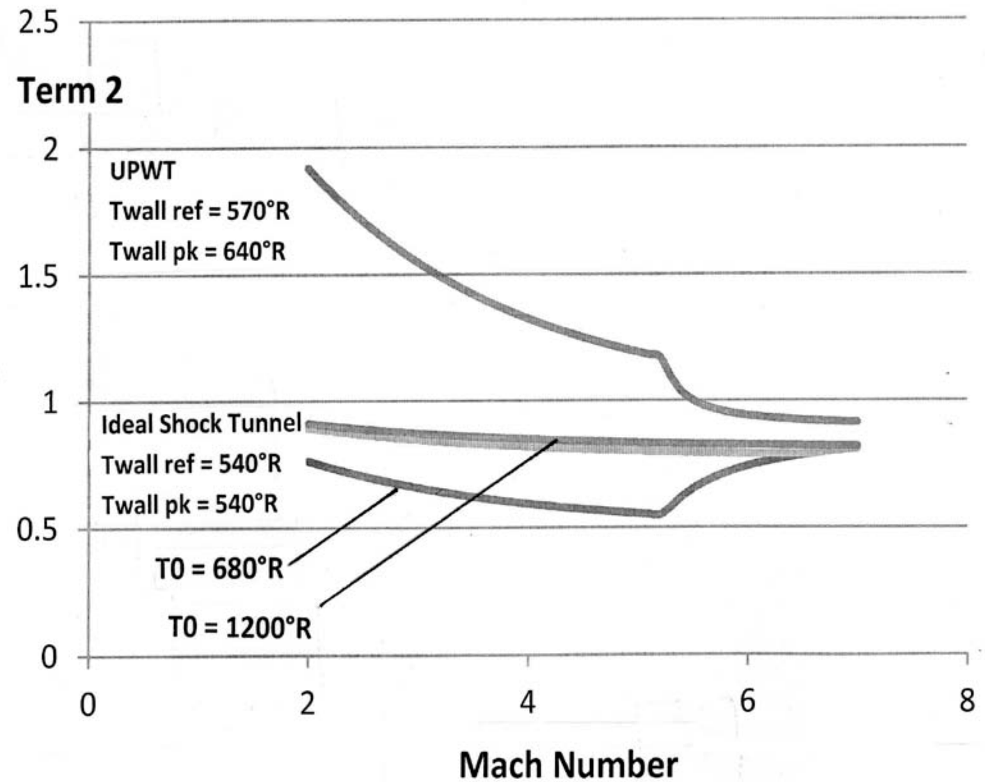
Total Temperature Effects

The Effect of Total Temperature on Term 2

The Effect of Mach Number on Term 2

$$\frac{H_{PK}}{H_{REF}} = \left(\frac{q_{pk}}{q_{REF}}\right)\left(\frac{T_{R-REF} - T_{w-REF}}{T_{R-PK} - T_{w-PK}}\right)$$





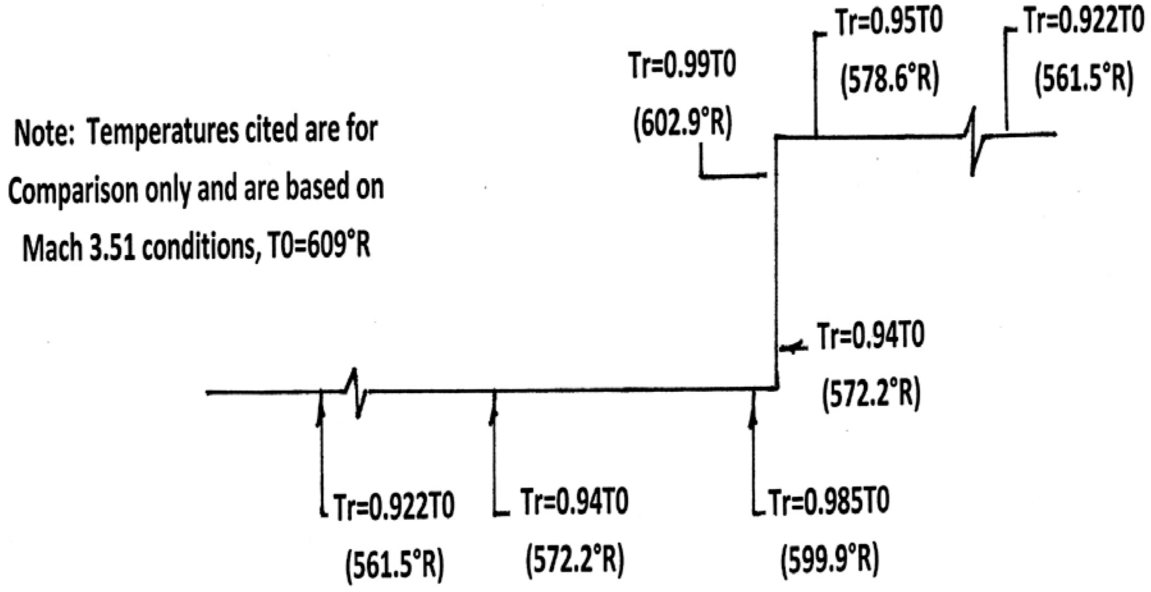
Recovery Temperatures About a Narrow Block Protuberance

Recovery temperature data was defined at seven locations, five of them are highly localized due to the Interference.

Two locations have ratios very near unity and high gradients between adjacent locations

It is physically impossible to have a recovery temperature ratio greater than 1.

Because the measured ratio is 0.99 and the peak cannot be greater than unity in regions of high temperature gradients, and therefore, the potential for conduction losses is very small and recovery temperatures is being measured.



Conclusions

The current protuberance experiment is the first clear view of recovery temperature distribution over/about complex shapes

- **The work is exploratory in nature and would benefit from additional supporting measurements and computations**
- **Contour plots of recovery temperature data have been observed to contain as much structure and geometric sensitivity as heating rate data**
- **Apparent scatter in past heating rate parameters could well be due to the spatial variations in recovery temperature; a component of these parameters**
- **These recovery temperature measurements are accurate and easy to acquire in legacy, continuous flow facilities with temperature stabilized flow**
- **Unless recovery temperature measurements are a part of the experimental data acquisition, data should be acquired at higher Mach numbers or higher total temperatures to minimize the impact of this uncertainty**
- **Recovery temperature data has been observed to be sensitive to local Mach numbers within the flow and could be a useful measurement in CFD validation**