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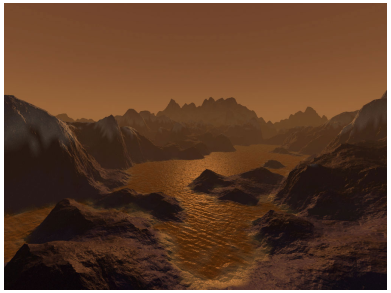

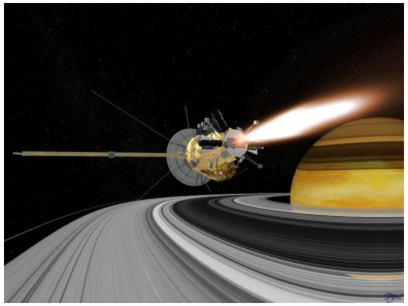

Modeling and Validation of CN Violet Radiation Relevant to Titan Entry

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IPPW: Toulouse

Context

- To aid the design and selection of Thermal Protection Systems (TPS), measurements of radiation under conditions relevant to Titan entry have been made.
- Shock heated test gas in experiment simulates conditions found behind the vehicle's bow shock during entry.
- Previous comparisons of shock tube radiation data have shown significant discrepancies compared to theory (design uncertainty of TPS can be as high as a factor of 2).
- Understanding discrepancies may influence future margin policies.
- Present analysis attempts to improve understanding of radiative heating for Titan entries.
- Focus on non-equilibrium radiation as would be relevant to a mission aiming to splashdown on a Titan sea, such as TiME.

CN Radiation

- Radiation during Titan entry more important at lower speeds (5 – 6 km/s) than other planetary entries due to formation of CN in above equilibrium concentrations.

- Non-equilibrium concentration is formed through interaction of following reactions:

1) $N_2 + M \leftrightarrow 2N + M$

2) $N_2 + C \leftrightarrow CN + N$

3) $CN(X) + M \leftrightarrow CN(B) + M$

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Comprehensive understanding of these mechanisms and corresponding rates is required for an accurate prediction of Titan non-equilibrium radiation.

Huygens Titan Studies

- Several studies performed to investigate Titan radiative heating for Huygens/Cassini mission.
- Boltzmann and Collisional Radiative (CR) models developed to simulate EAST experiments from NASA Ames.
- Boltzmann was identified to significantly over-predict the radiation as measured by experiments, so it was concluded that CR models would be required.

Huygens Titan Studies

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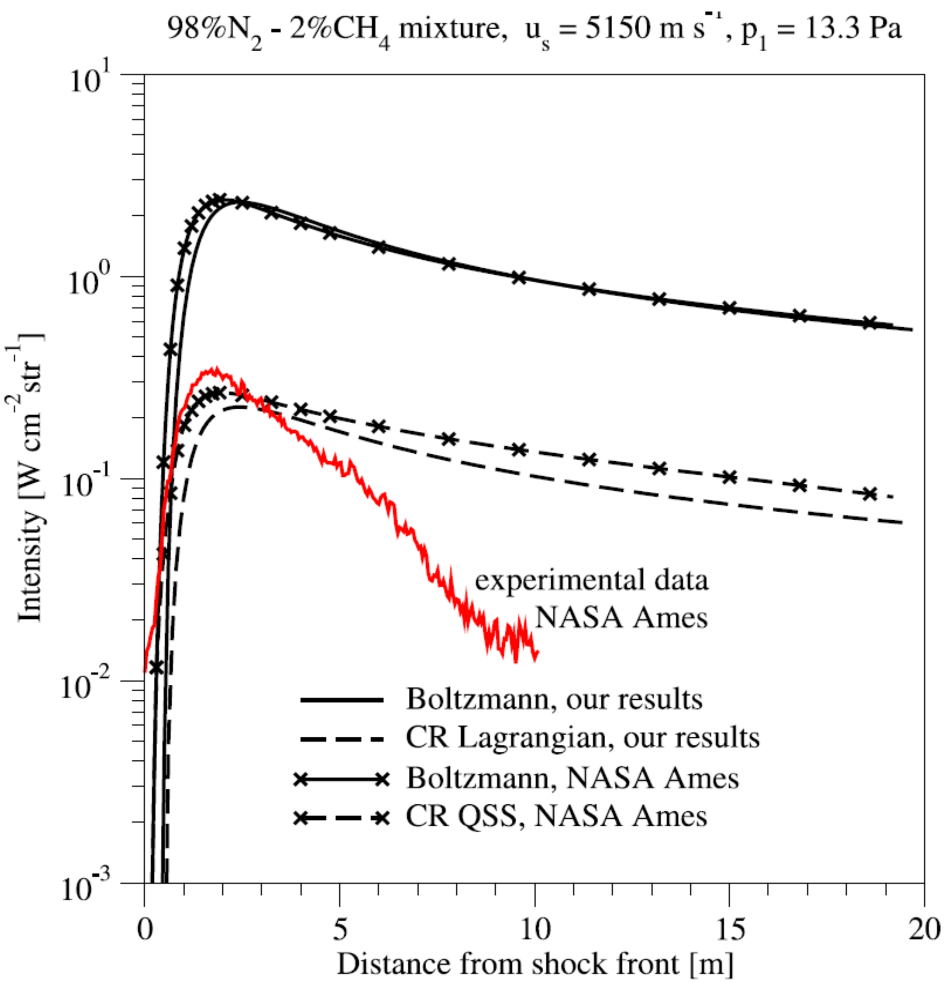
- The agreement between CR models and experiment for the peak was deemed to be satisfactory, however, significant discrepancies regarding the decay rate were observed.



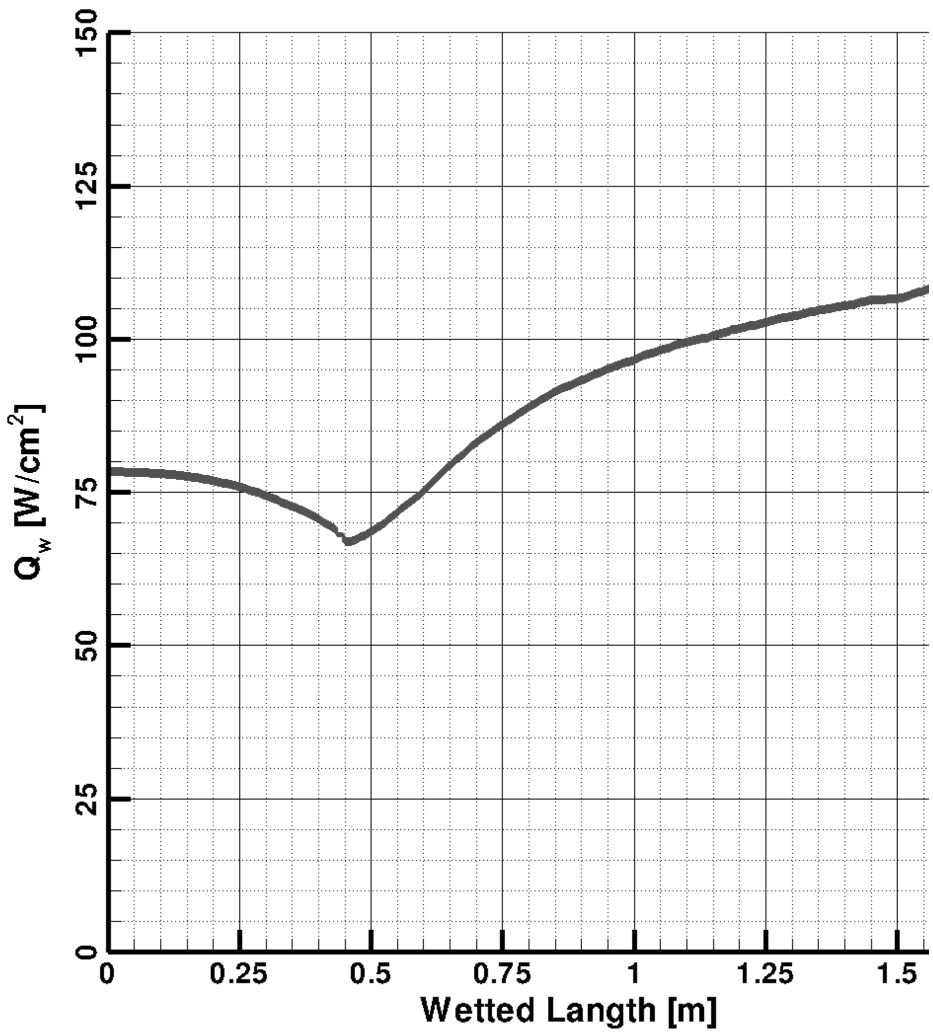
Procedure for Titan Heating Estimates

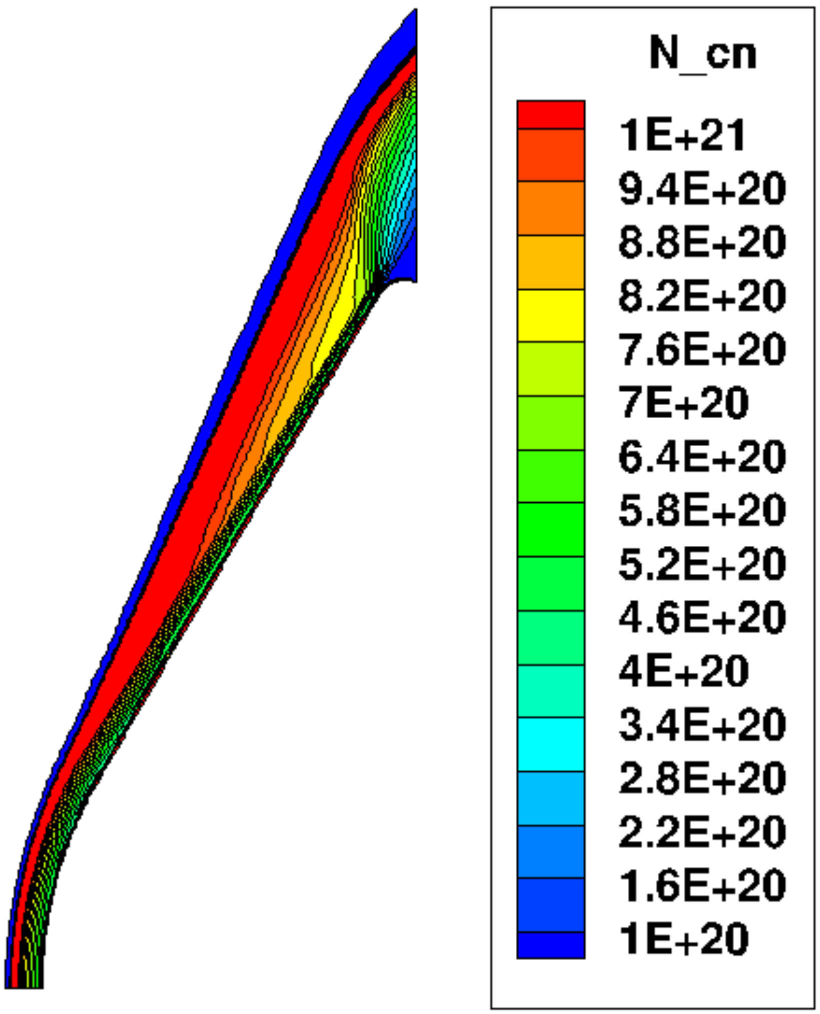
- 2-D axisymmetric capsule simulation using a coupled DPLR/NEQAIR solution to determine total body heat flux (both convective and radiative) based on Boltzmann assumptions.

- Run 1-D Boltzmann and CR model to determine over-prediction factor of Boltzmann with respect to CR. This factor is then used to scale down the radiative component of the DPLR solution.

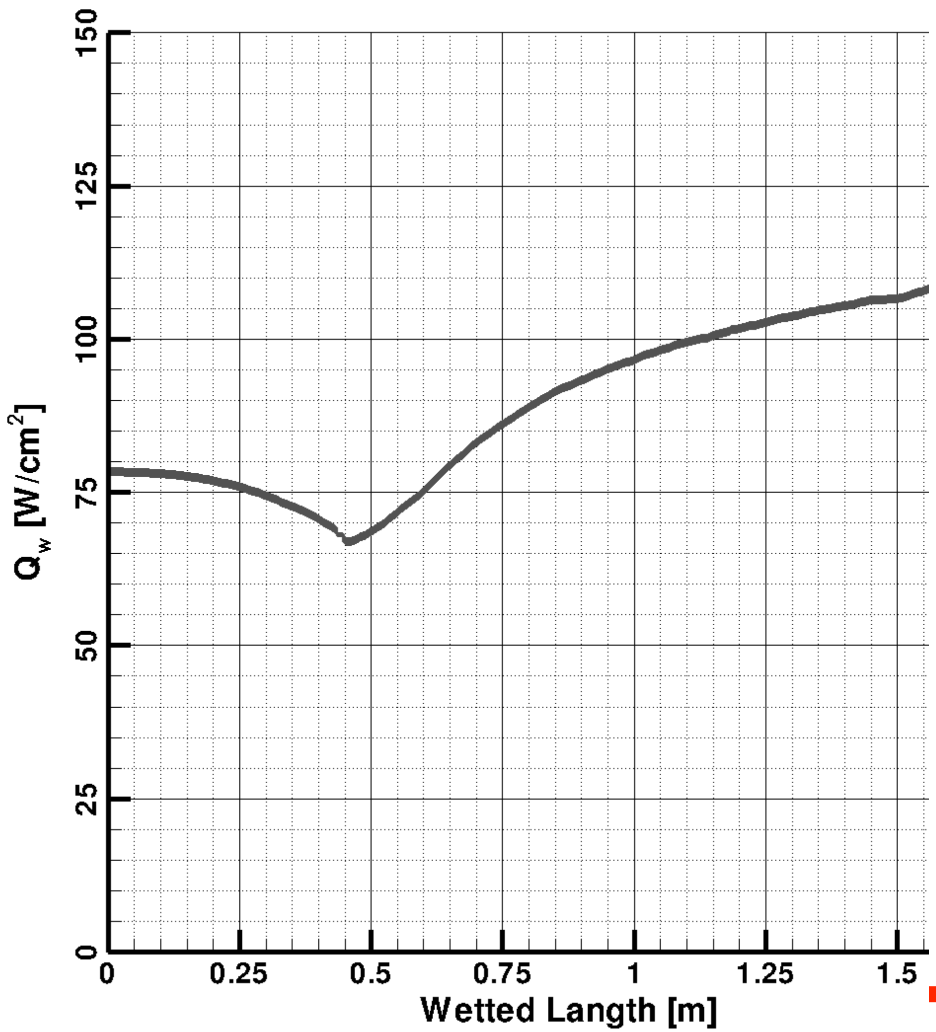
- CR model compared to X2, confirm that the CR model is conservative with respect to the experimental data.

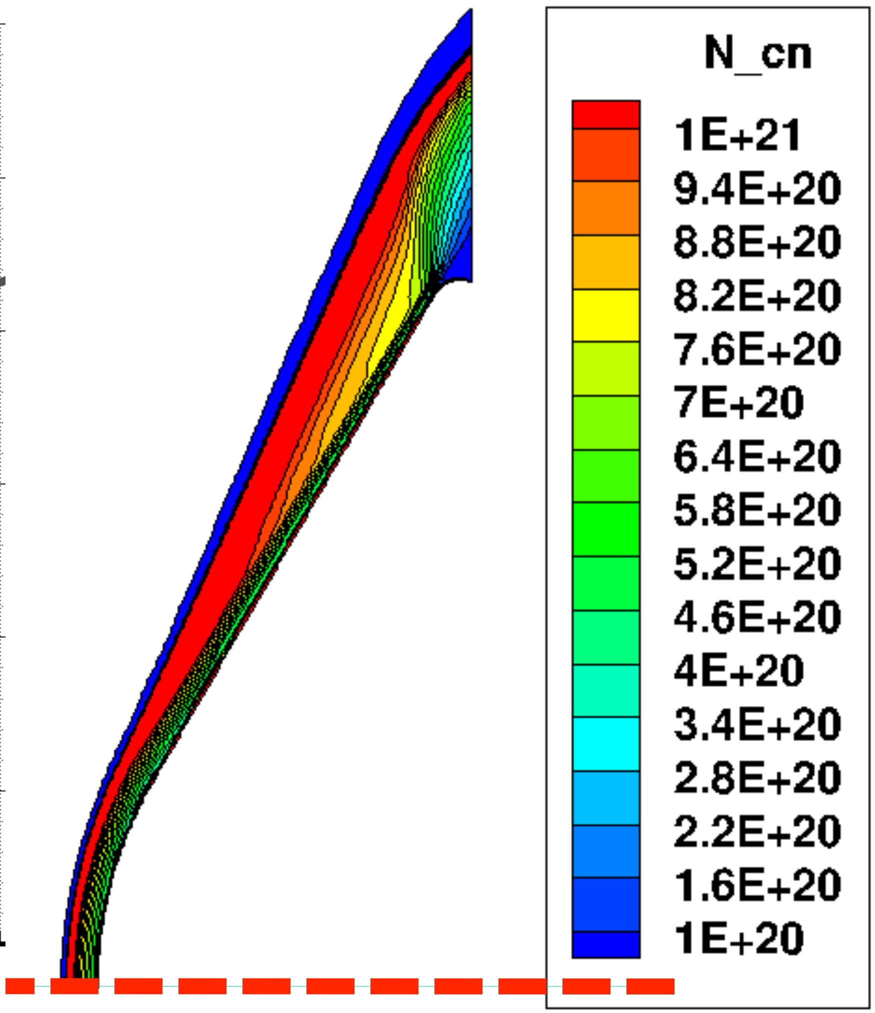
CFD Titan Capsule Solutions





CFD Titan Capsule Solutions





Collisional Radiative Model

- Flow Field computed by solving 1D conservation equations of mass, momentum, global energy, vibrational energy of N_2 molecule
- Collisional Radiative Model
    - Predicts nonequilibrium levels of CN(A,B) and N_2(A,B,C)
- CR Model comprises:
    - spontaneous emission of excited states
        - eg: CN(B) -> CN(X) + *hv*
    - collisional (de)excitation with nitrogen
        - eg: CN(X) + $N_2 \leftrightarrow$ CN(B) + N_2
    - electronic impact (de)excitation
        - eg: $N_2(X) + e^- \leftrightarrow N_2(B) + e^-$
    - pooling
        - eg: $N_2(A) + N_2(A) \leftrightarrow N_2(X) + N_2(C)$
    - quenching
        - eg: $N_2(A)$ + CN(X) $\leftrightarrow N_2(X)$ + CN(B)
- Coupling effects are not included, however, as the radiation predicted by CR models is substantially less than Boltzmann, coupling effects become less significant.

X2 Shock Tube

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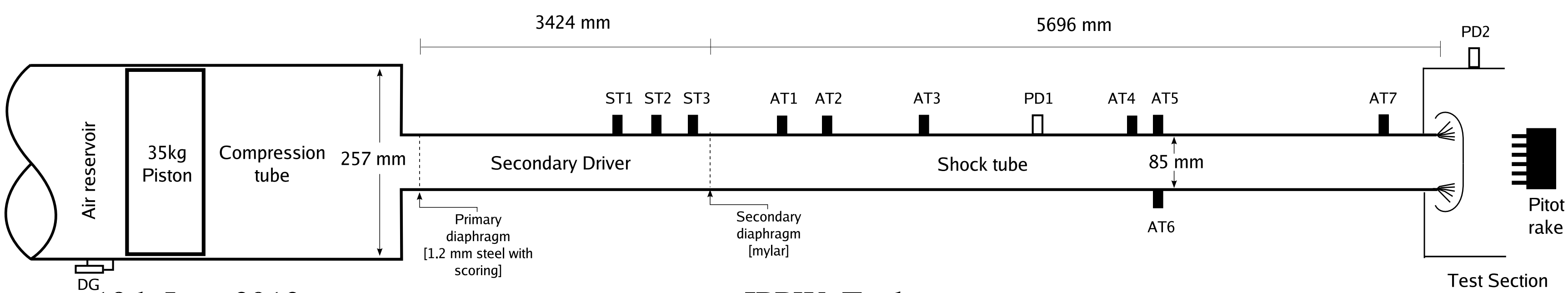
- Free Piston driver used to build pressure and burst diaphragm
- Radiation behind shock wave analyzed just after shock exits the tube
- For Titan, spectral and spatially resolved CN emission has been observed over a range of conditions:
    - From 4 – 7.6 km/s at 133 Pa (1 Torr)
    - From 6 – 1000 Pa at 5.7 km/s
- X2 condition of 5.7 km/s and 30 Pa, close to potential TiME peaking heating of 5.24 km/s and 28.5 Pa



Comparison of X2 Data and Models Relevant to TiME

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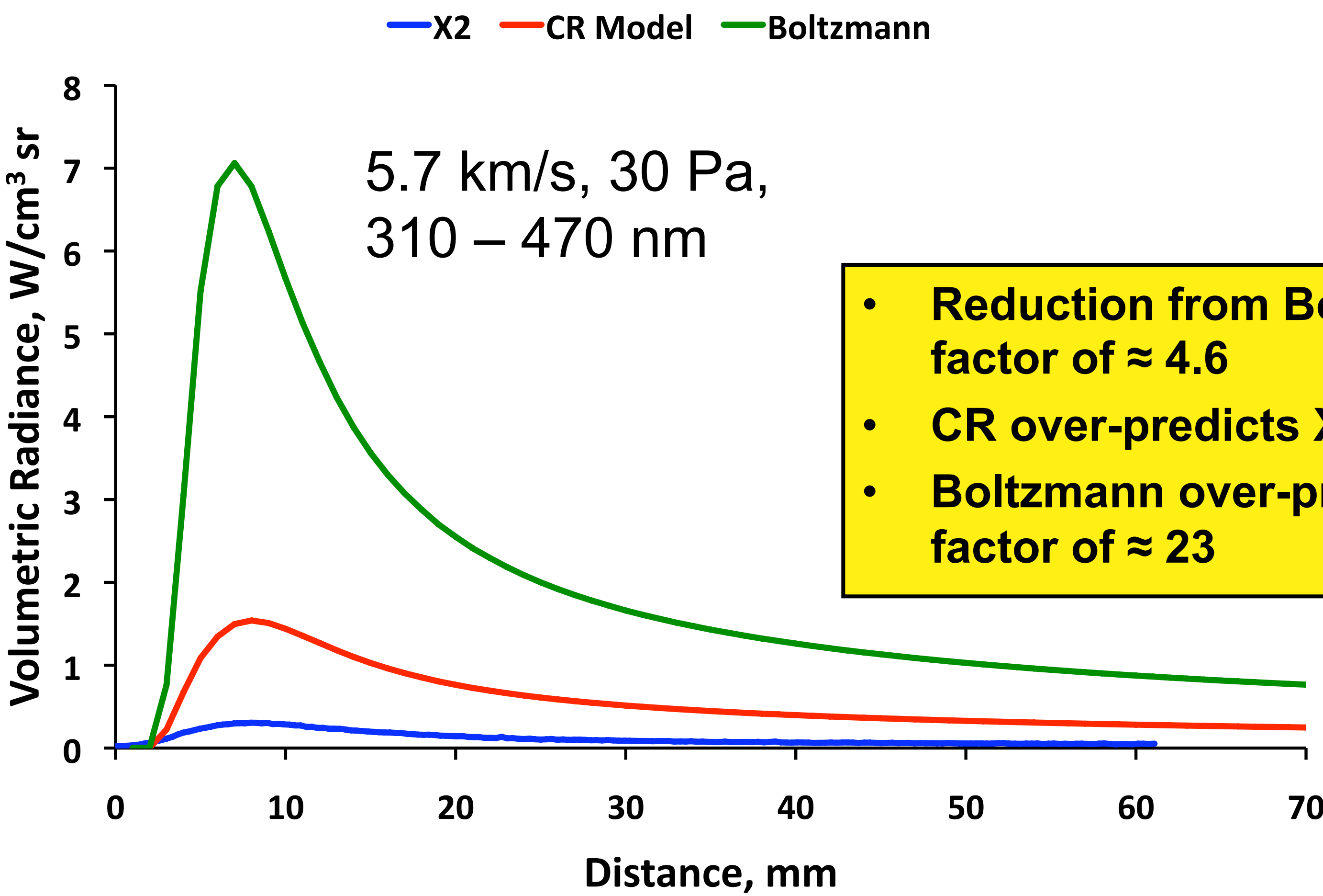

- **Reduction from Boltzmann to CR factor of ≈ 4.6**
- **CR over-predicts X2 by factor ≈ 5**
- **Boltzmann over-predicts X2 by factor of ≈ 23**

Reduction in TiME Estimated Heat Flux

- CR model is conservative compared to experimental data
- Boltzmann over-predicts CR model by a factor of 4.6 for a condition measured on X2 similar to peak heating for TiME
- Therefore, this factor can be used to reduce full flow field DPLR calculation using Boltzmann assumption and still be a conservative approach compared to experimental results

Boltzmann estimate at peak heating for Qrad = 78 W/cm^2; with CN over-population correction based on CR model:
Qrad = 17 W/cm^2

TiME Trajectory vs X2 Conditions

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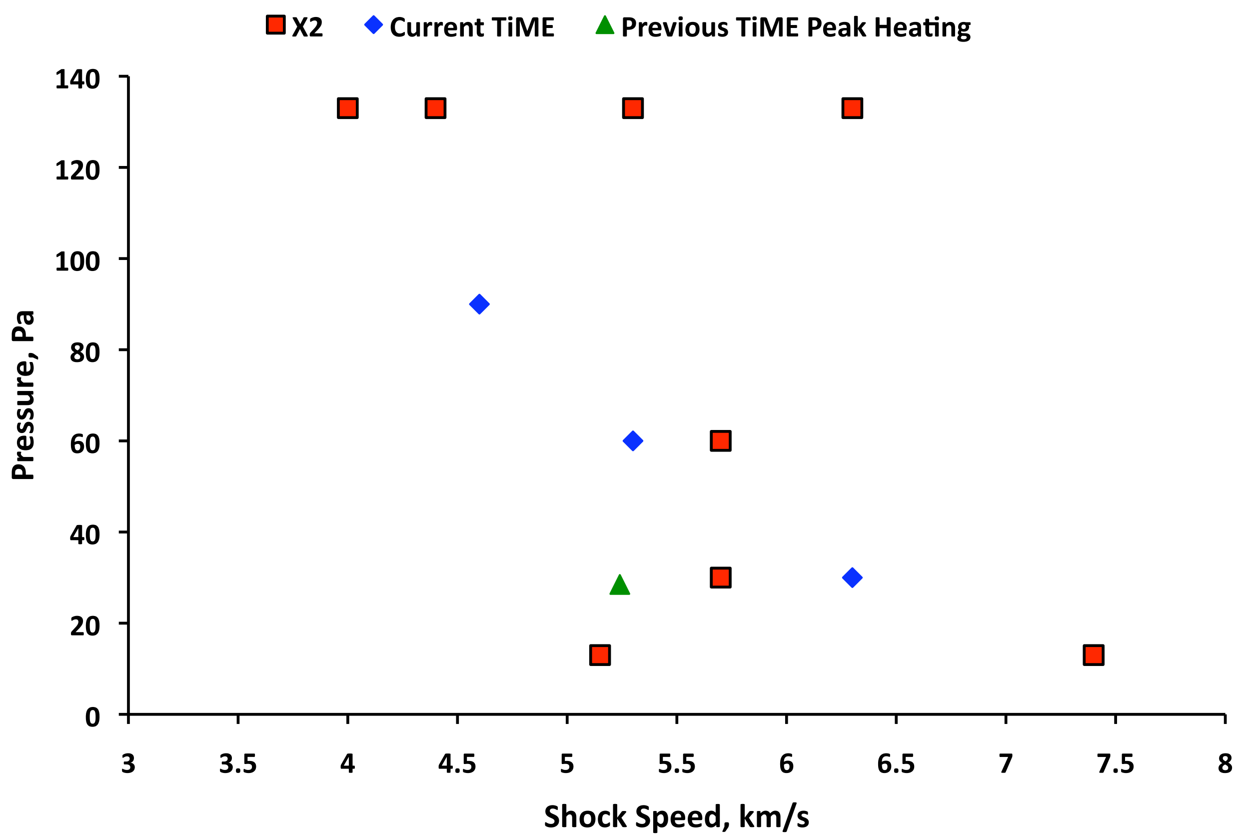
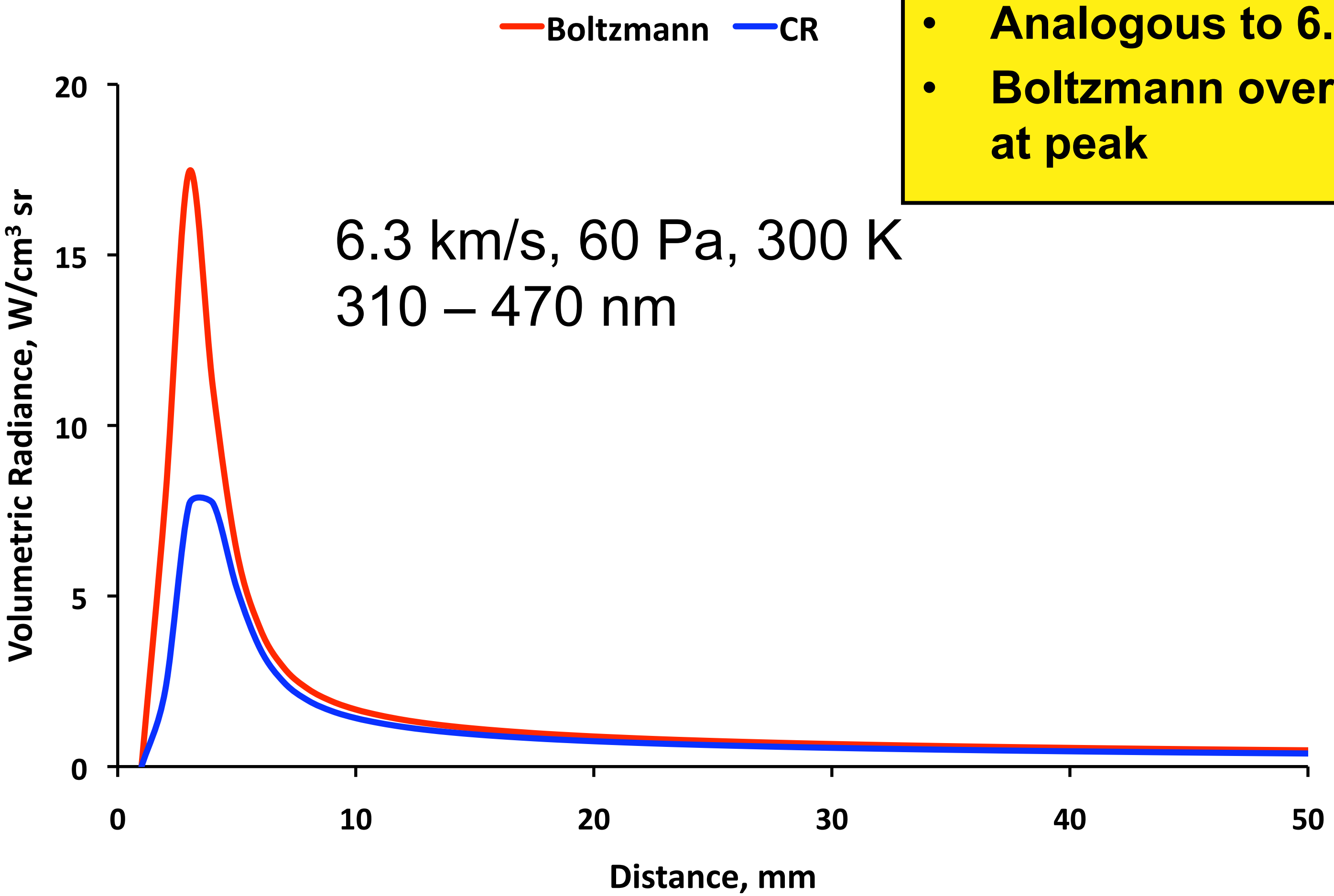


X2 conditions bound TiME conditions of interest with respect to heating

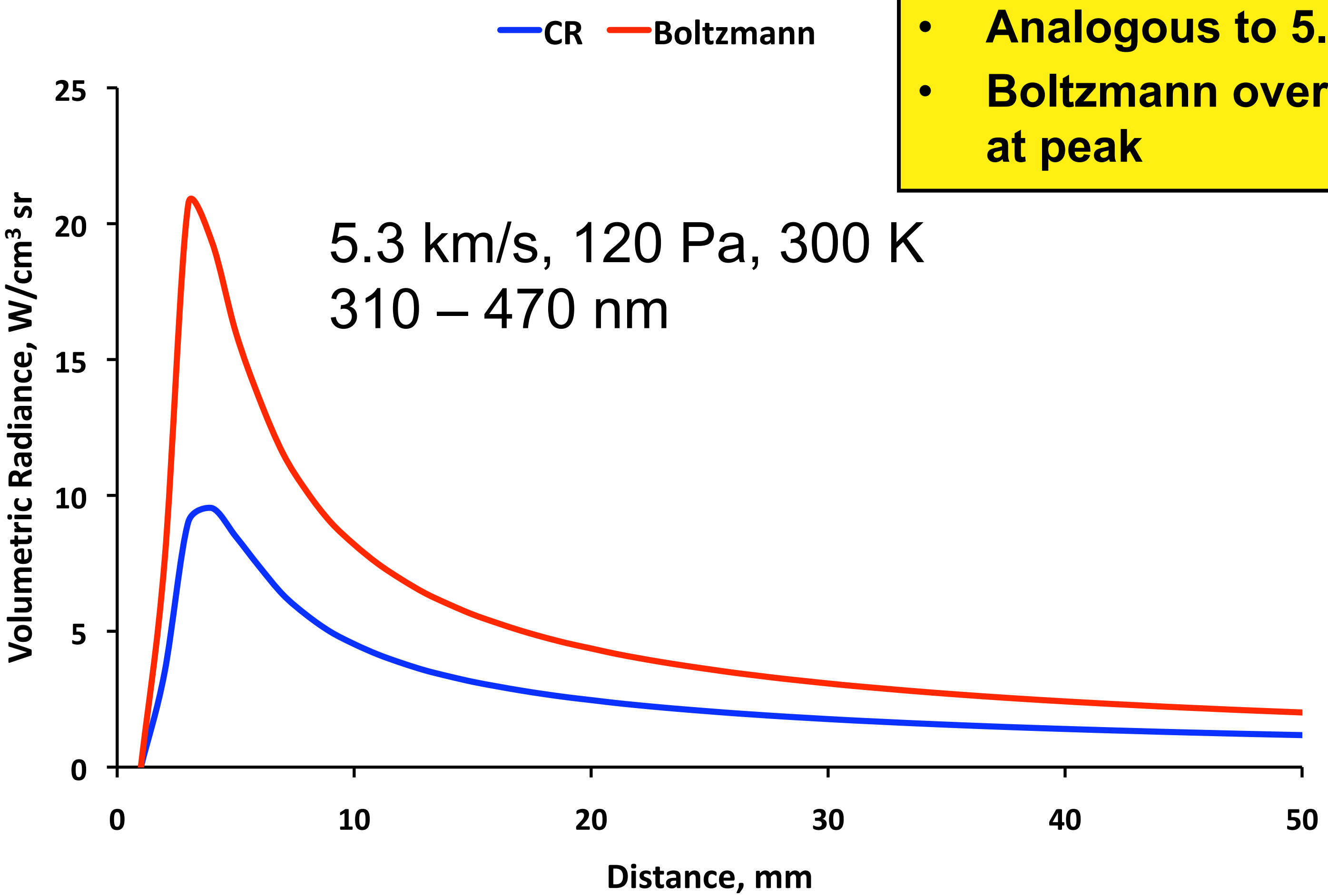
6.3 km/s, 30 Pa, 150 K

- **Analogous to 6.3 km/s, 30 Pa, 150 K**
- **Boltzmann over-predicts CR by 2.3 at peak**

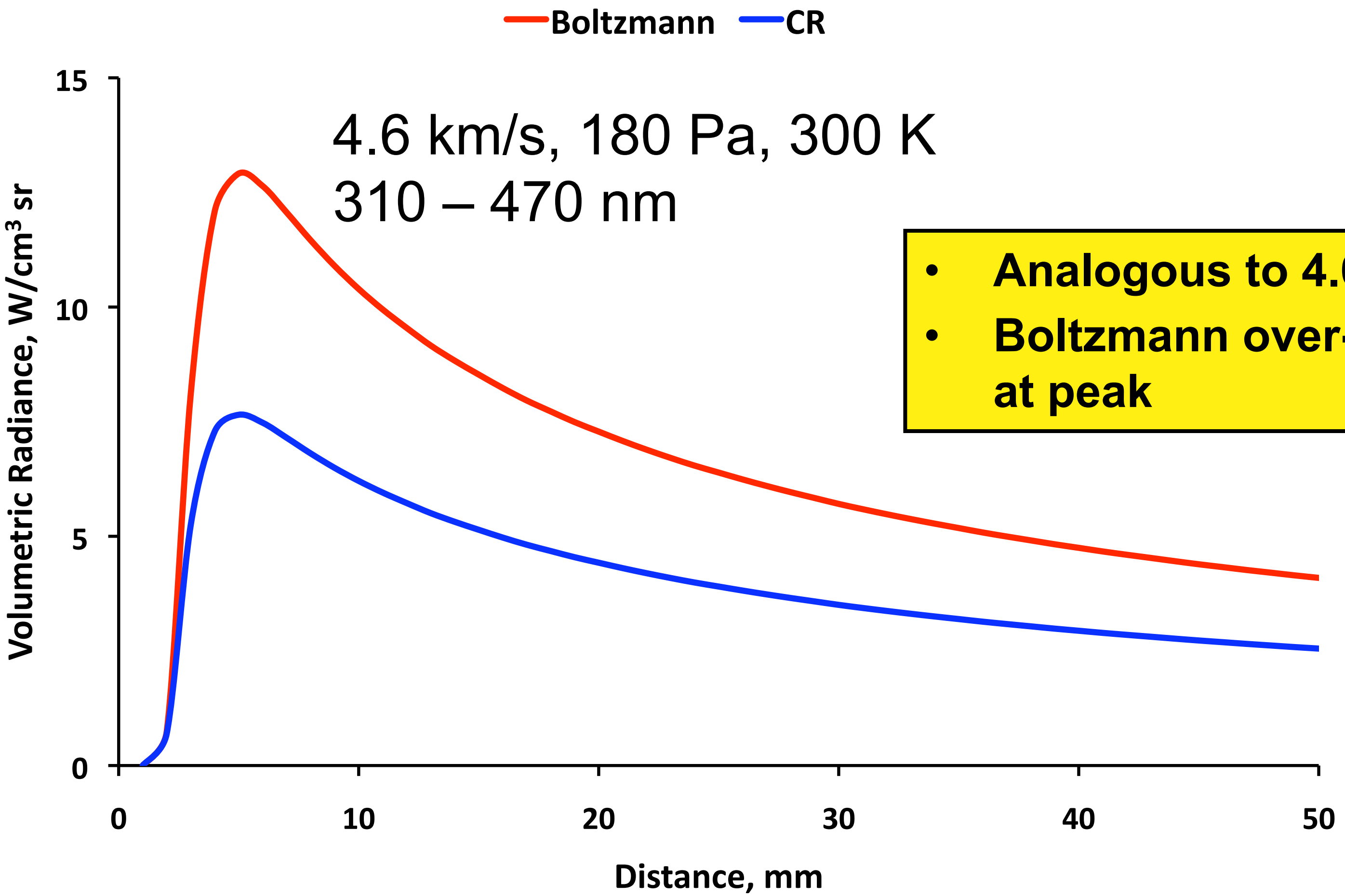


5.3 km/s, 60 Pa, 150 K

- **Analogous to 5.3 km/s, 60 Pa, 150 K**
- **Boltzmann over-predicts CR by 2.2 at peak**

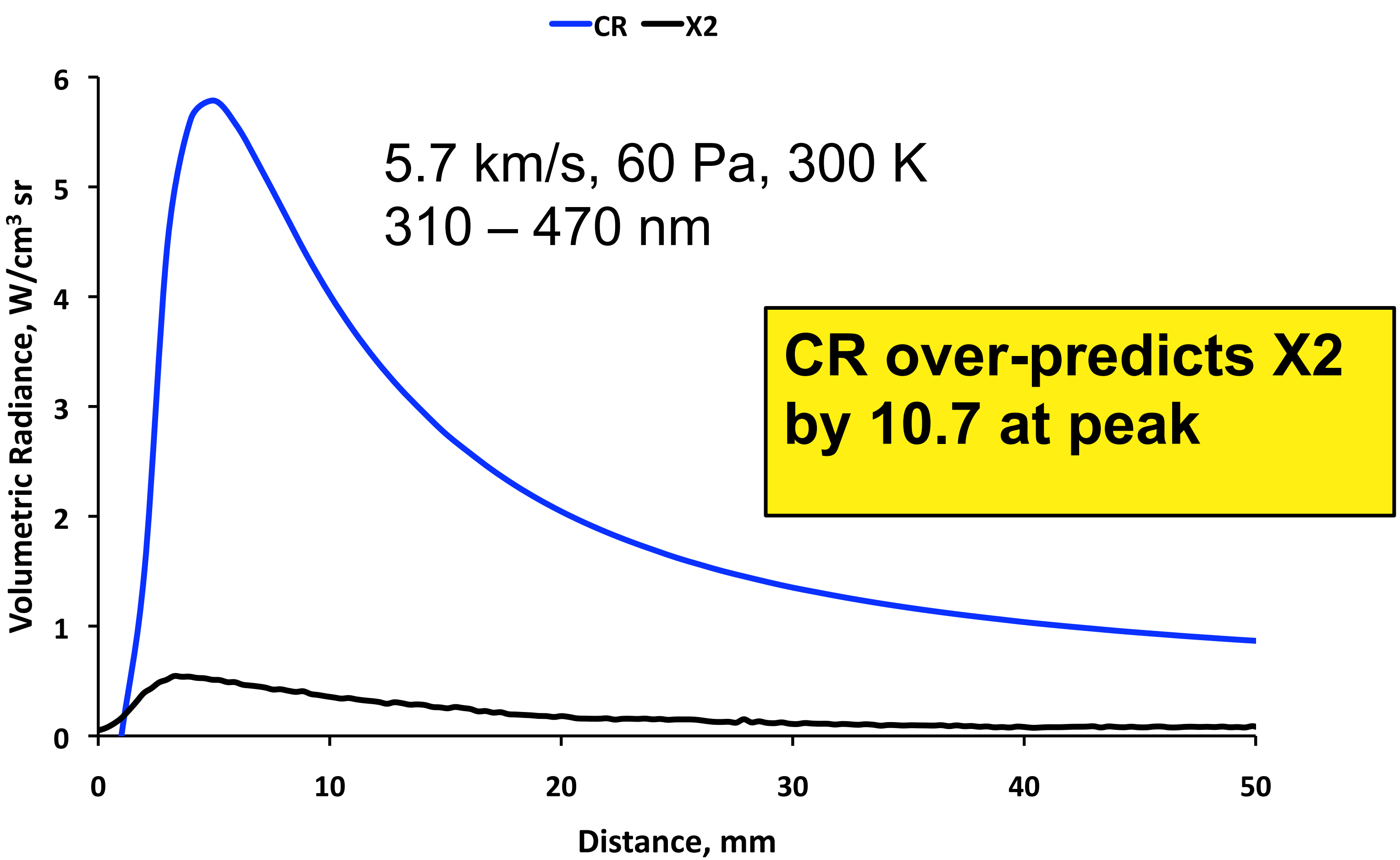


4.6 km/s, 90 Pa, 150 K



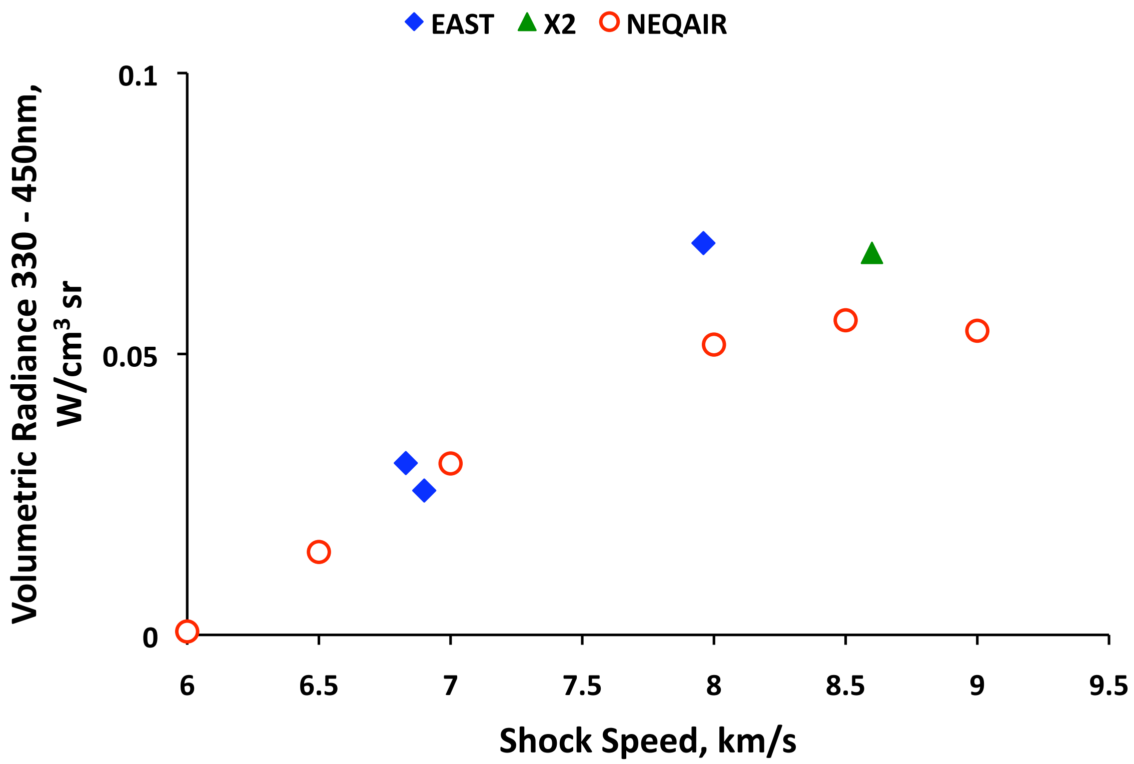
- **Analogous to 4.6 km/s, 90 Pa, 150 K**
- **Boltzmann over-predicts CR by 1.7 at peak**

X2 at 5.7 km/s, 60 Pa



Calibration Check for X2 Results

- Titan has not been a focus of recent EAST testing.
- In order to check the calibration of X2, it was decided to compare the results of equilibrium radiation for Mars with EAST and X2.



- X2 result within scatter of EAST, and in good agreement with NEQAIR.

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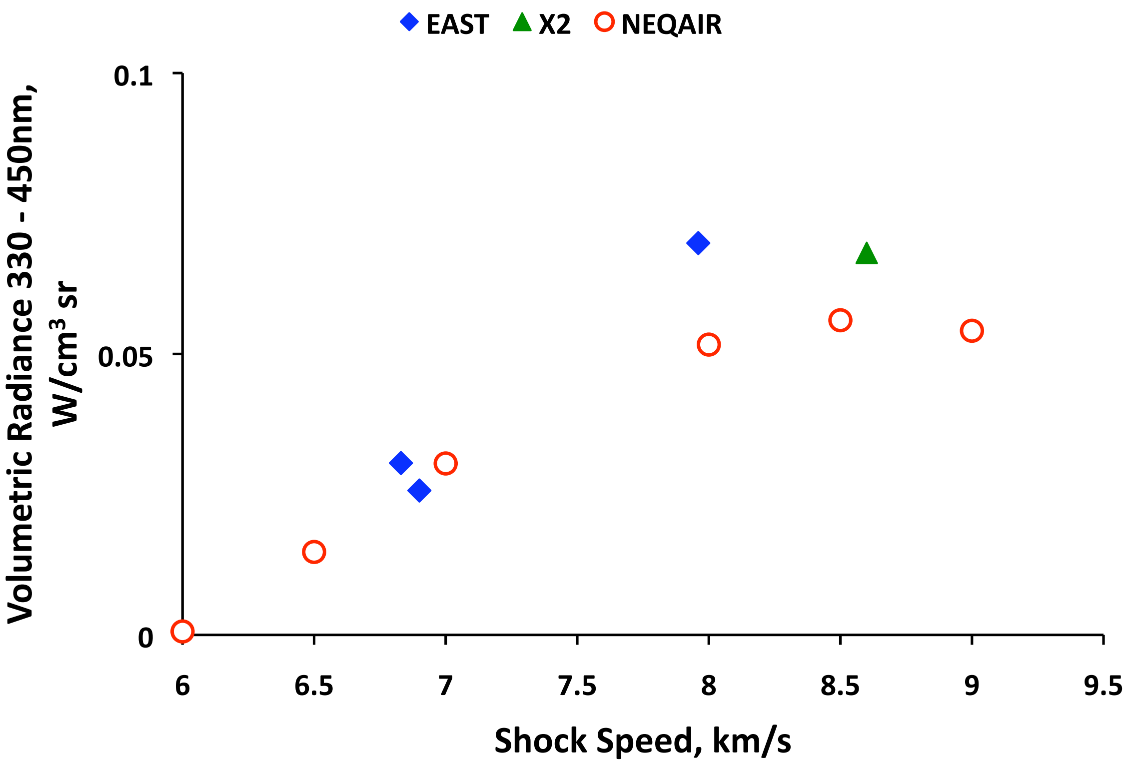
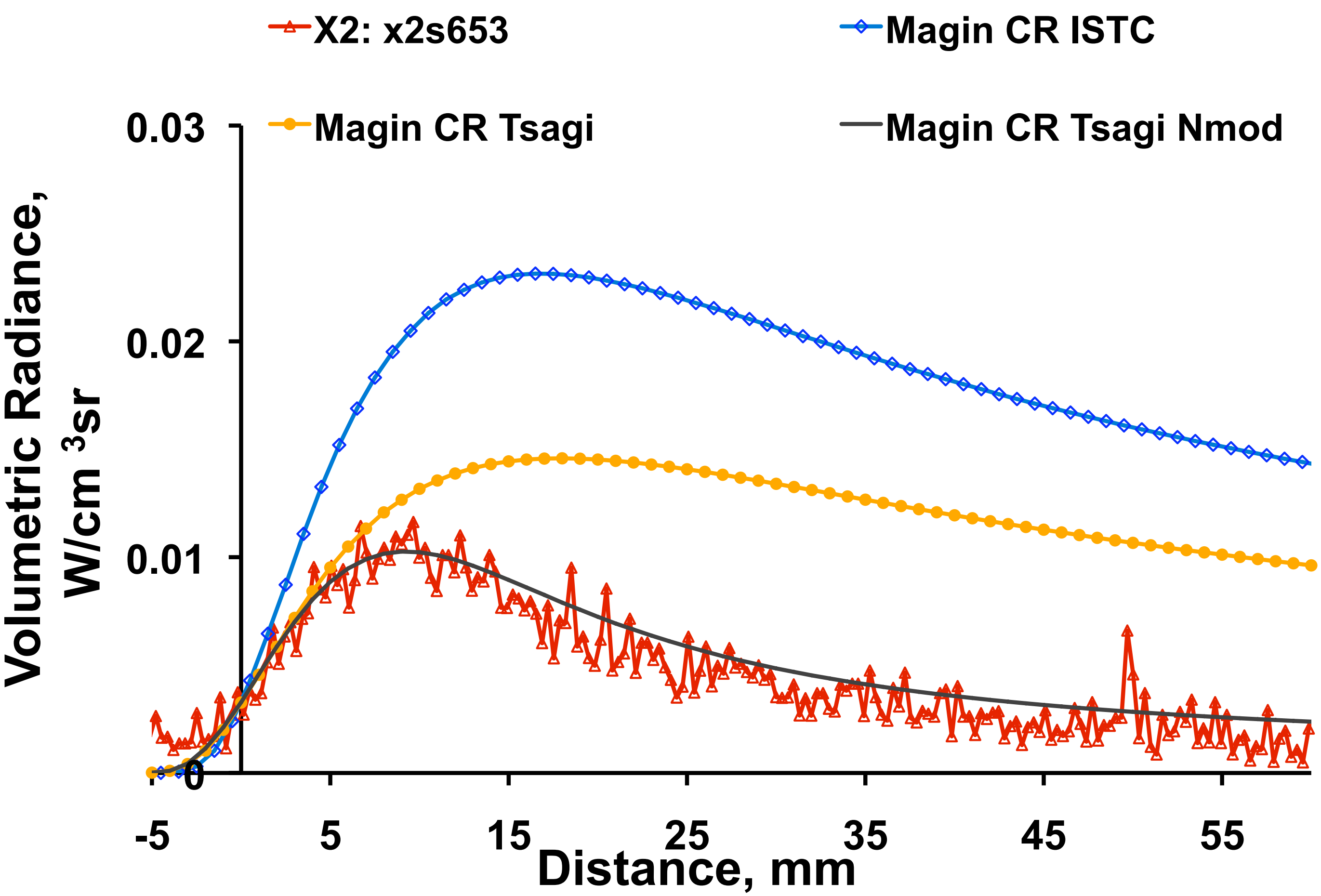


- X2 result within scatter of EAST, and in good agreement with NEQAIR.

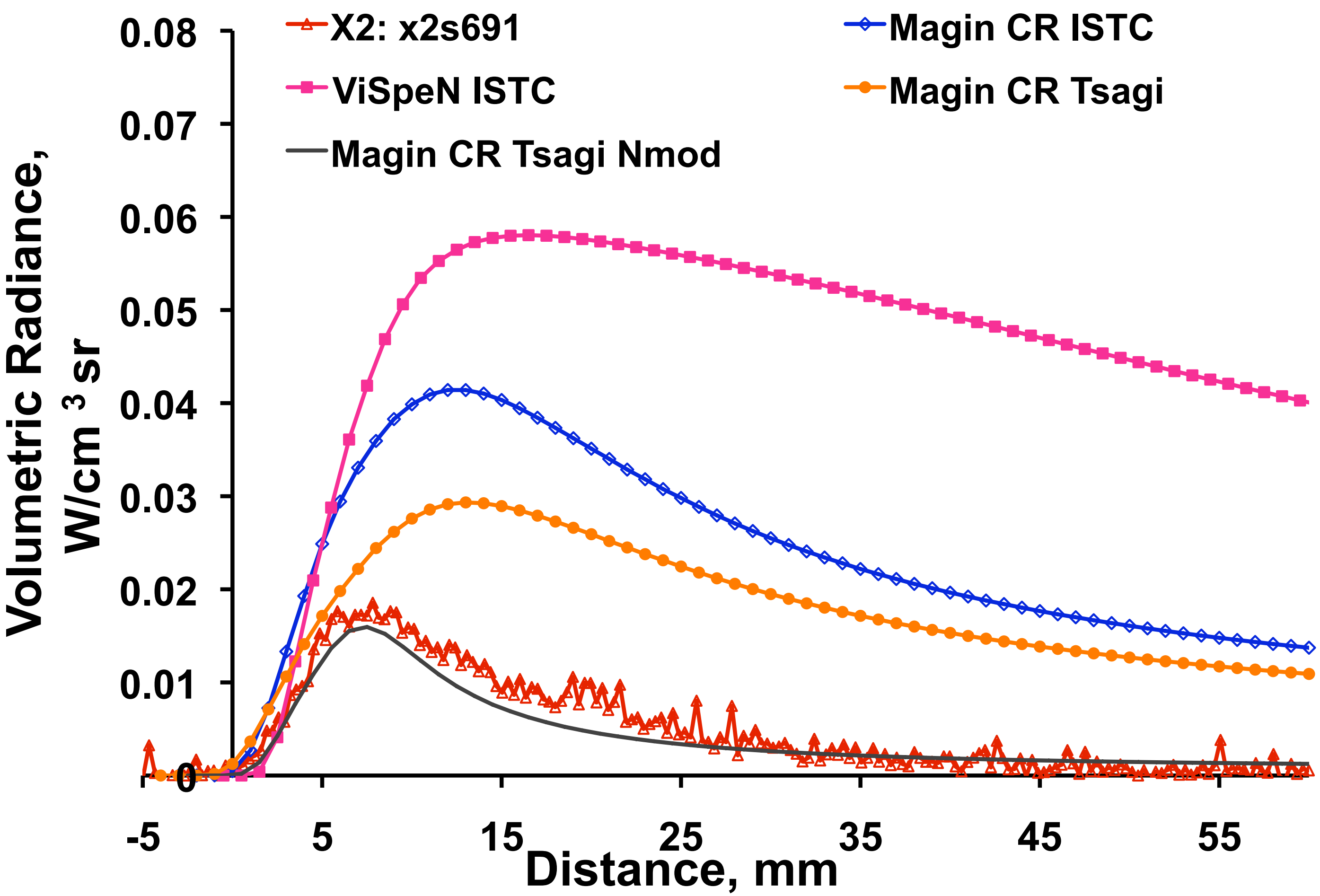
X2 intensity calibration confirmed by comparison with EAST and NEQAIR

Effect of Rates on Radiance



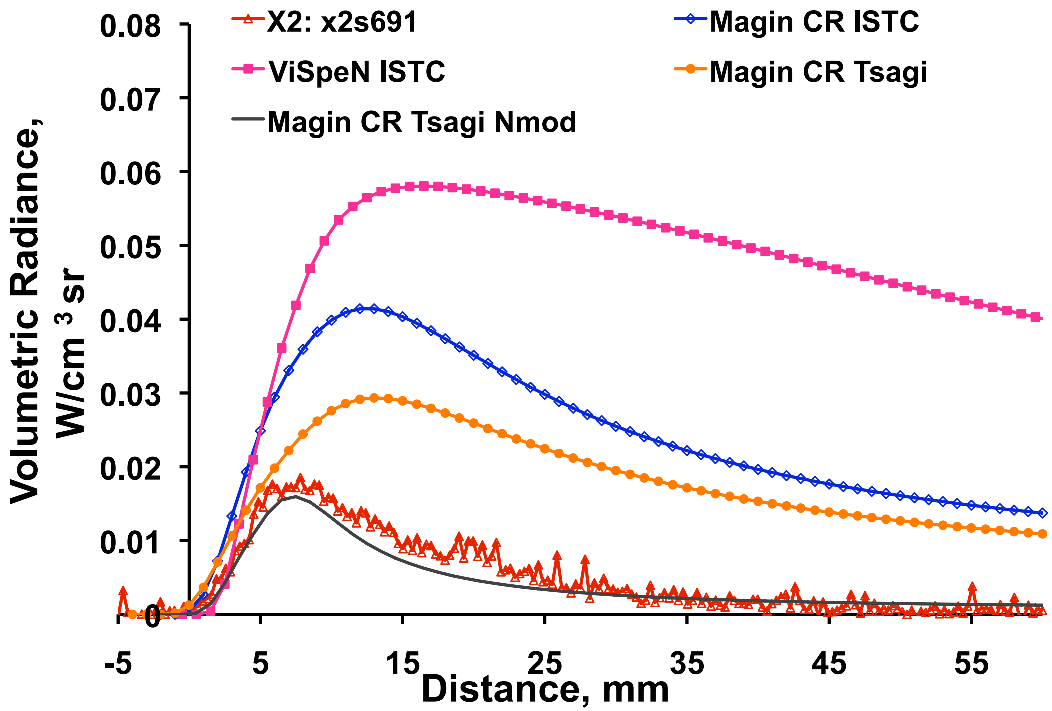
5.15 km/s
13 Pa
310 – 450 nm

Effect of Rates on Radiance



5.7 km/s
13 Pa
310 – 470nm

Effect of Rates on Radiance



5.7 km/s
13 Pa

Using the Tsagi rate for CN(B) excitation & multiplying N_2 dissociation rate by 10, excellent agreement has been obtained with X2.

Nonequilibrium Analysis of X2

- Parameter developed to quantify level of non-equilibrium found in either an experiment or simulation.

- Designed to be independent of 1) experimental settings, such as gate with and spectrometer resolution and 2) the absolute intensity calibration.

- Parameter grounded to equilibrium level of radiation.

- Can be used for robust comparisons with simulations and for evaluating different reaction rates.

Nonequilibrium Analysis of X2

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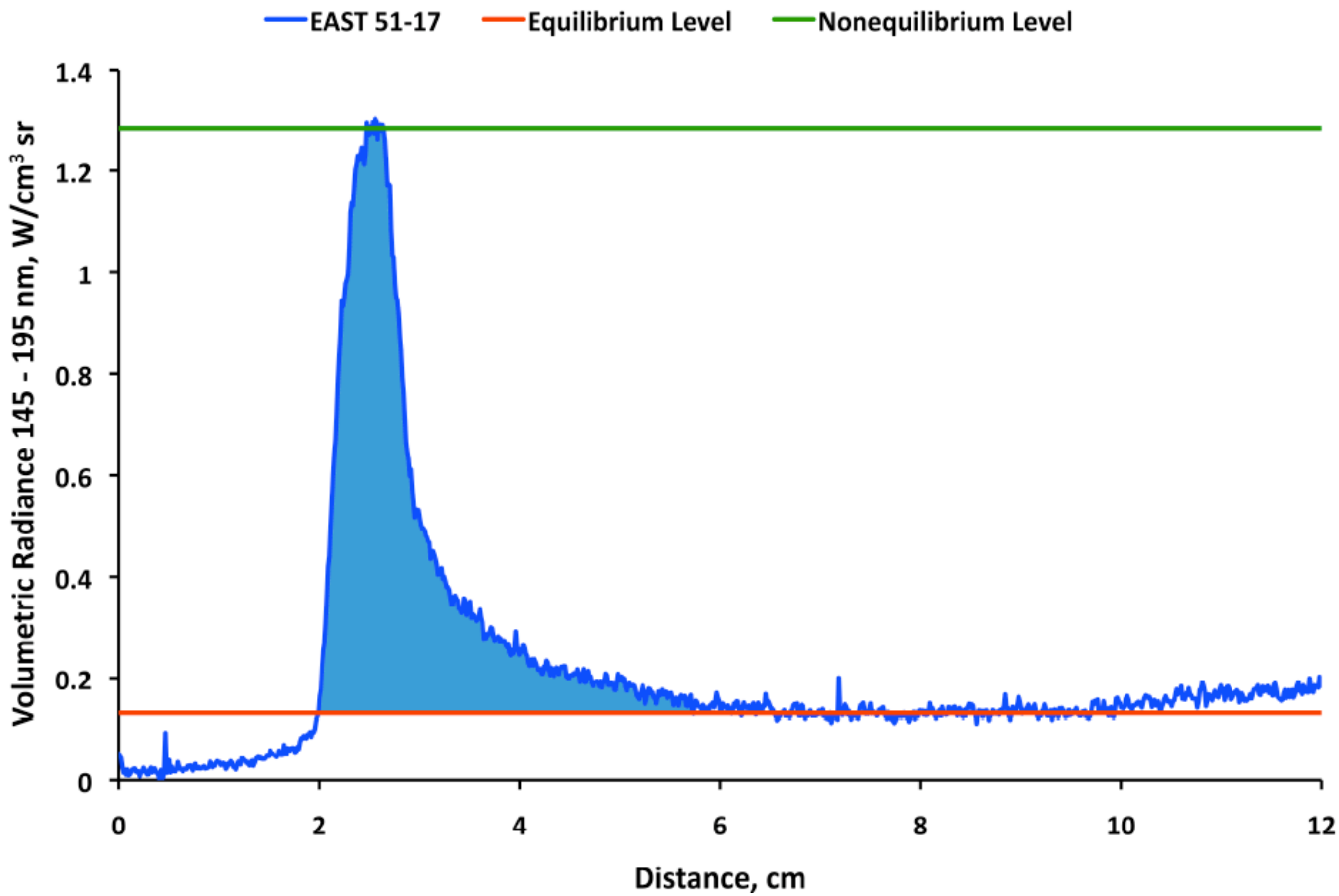
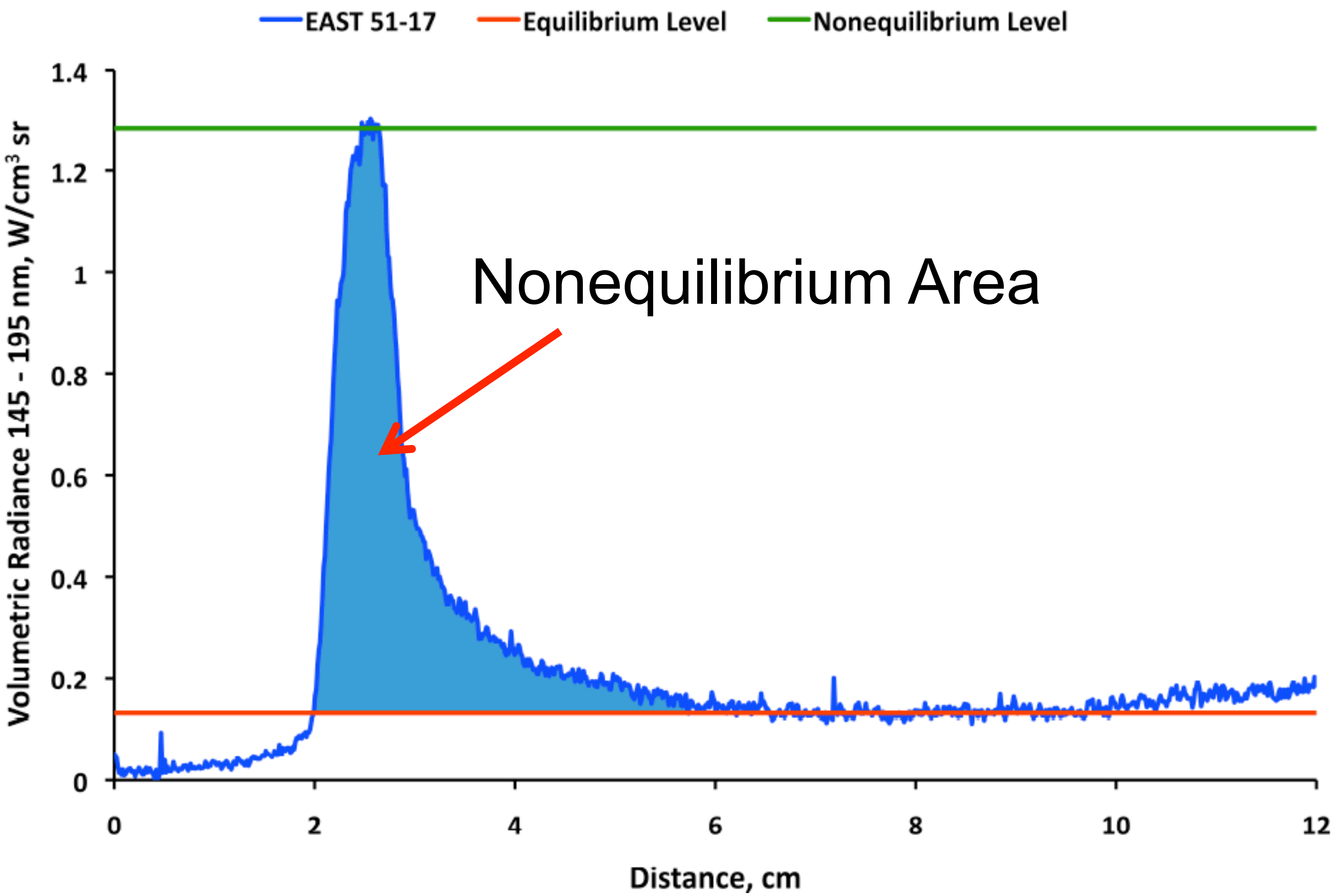


Nonequilibrium parameter = Nonequilbrium Area / Equilibrium Level

Nonequilibrium Analysis of X2



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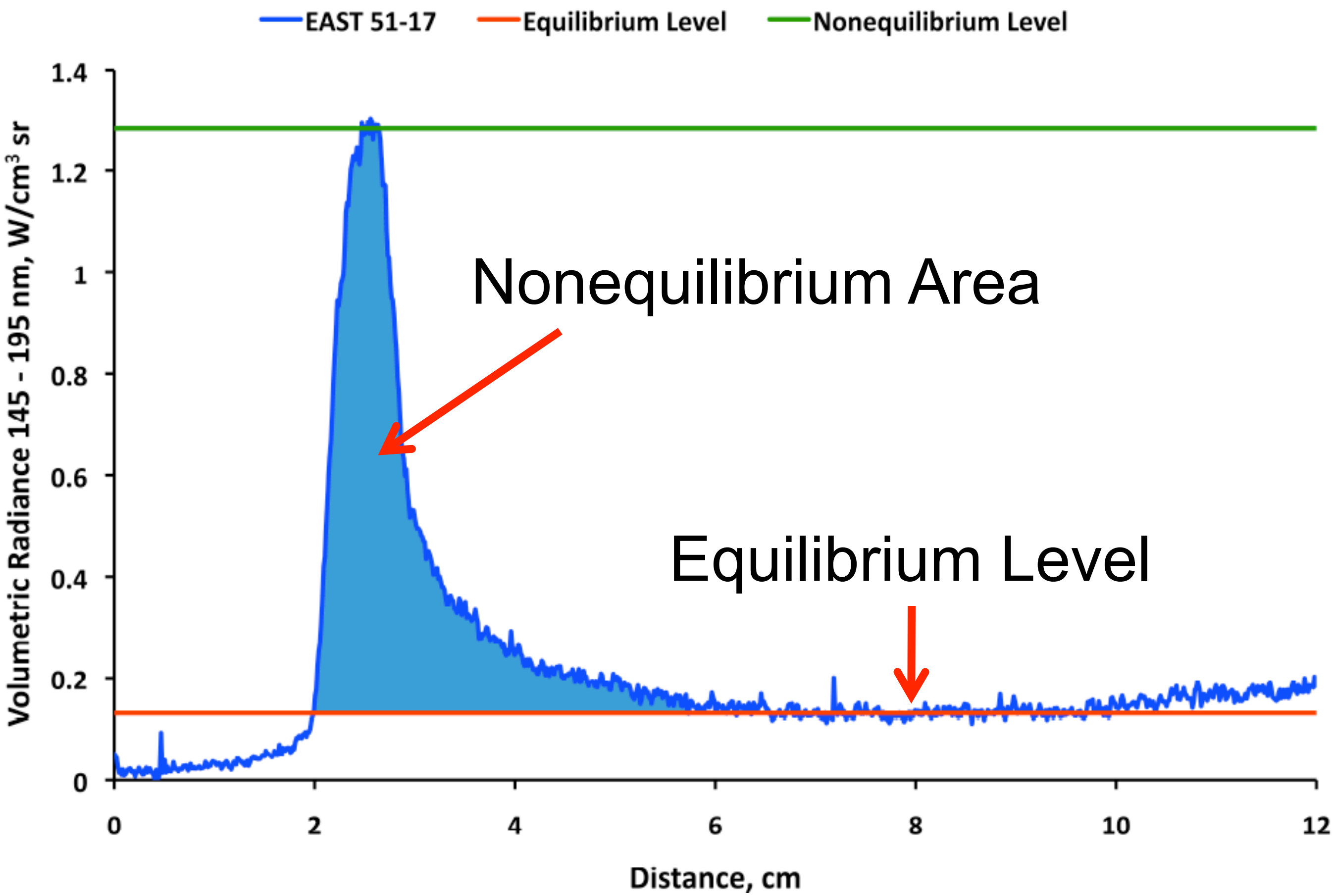

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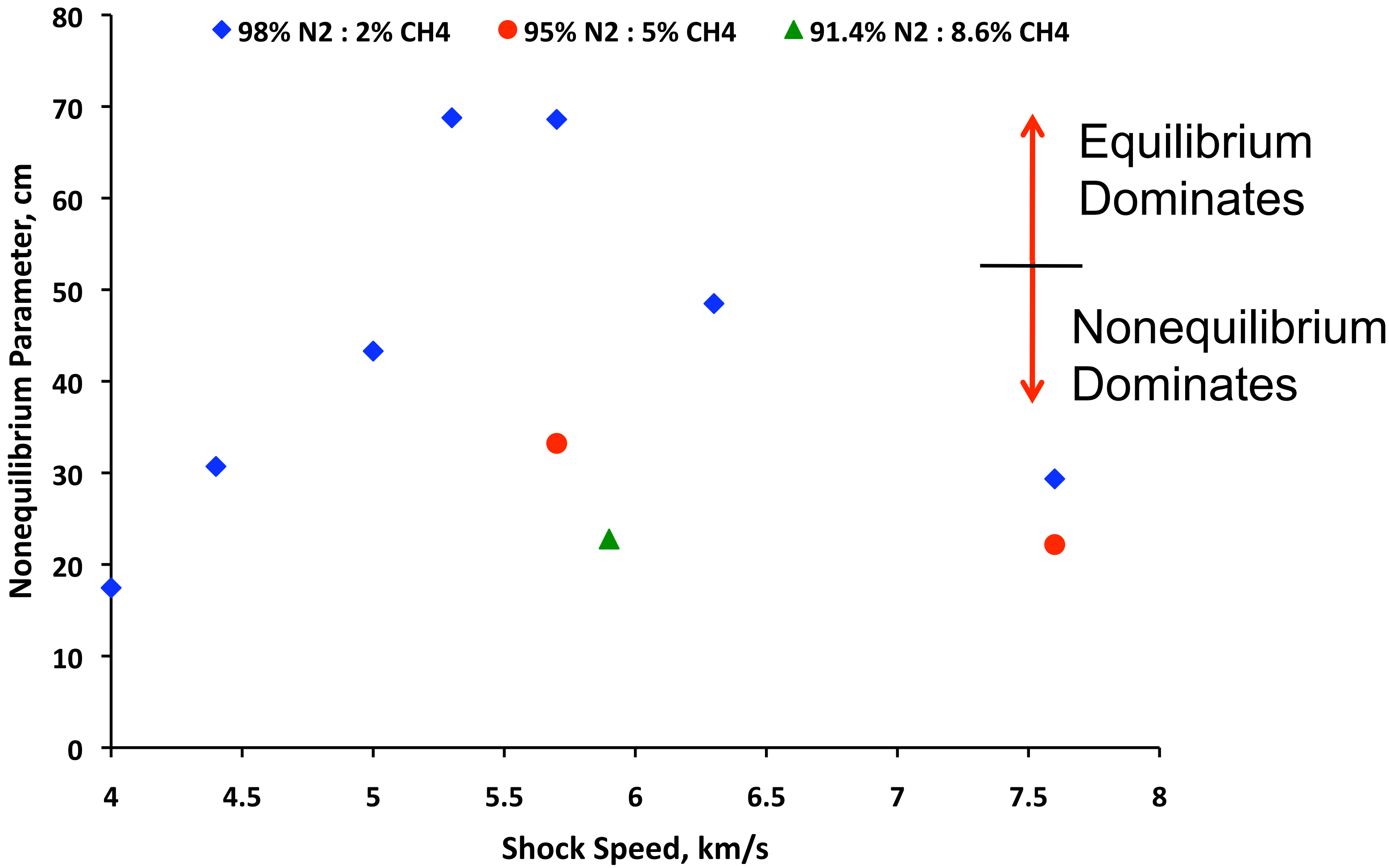


Current issues of importance

- Reaction rate for the excitation from ground state CN(X) to excited state CN(B).
- Reaction rate for the dissociation of nitrogen
- Experimental data from the EAST facility to confirm most relevant conditions from X2 data and to expand spectral range of experimental data.
- Implementation of CR to full CFD

Conclusion

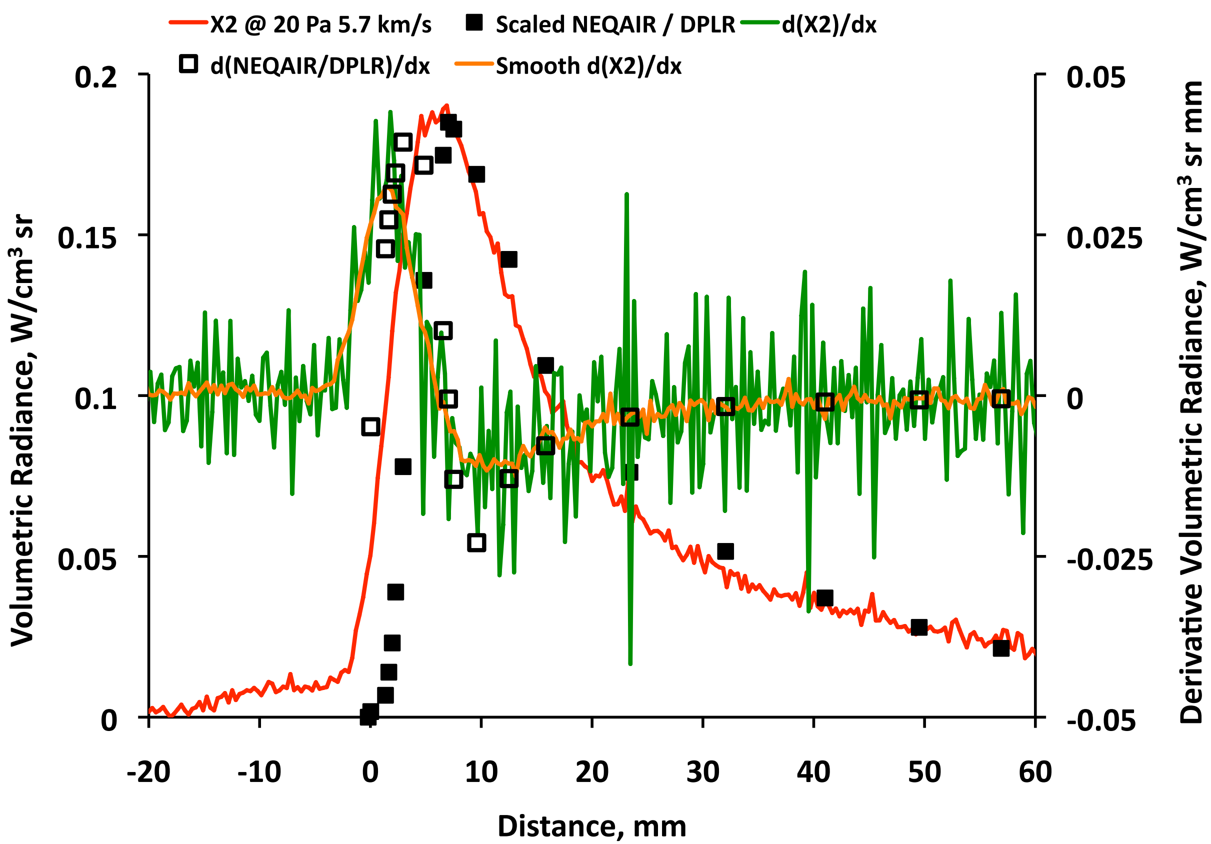
- Preliminary method for determining total capsule heat flux presented.
- X2 testing bounds conditions of relevance to TiME.
- X2 calibration verified by comparing equilibrium Mars radiation data with EAST and NEQAIR.
- Effect of changes to important reaction rates shown.
- Non-equilibrium parameter devised for future comparisons.

CR models and experimental results show a reduction factor of up to approximately 10 – 20 compared to results based on Boltzmann. Reducing total heat flux by approximately 50%.

Questions?

Titan Decay Rate

- **Titan decay rate analysis**



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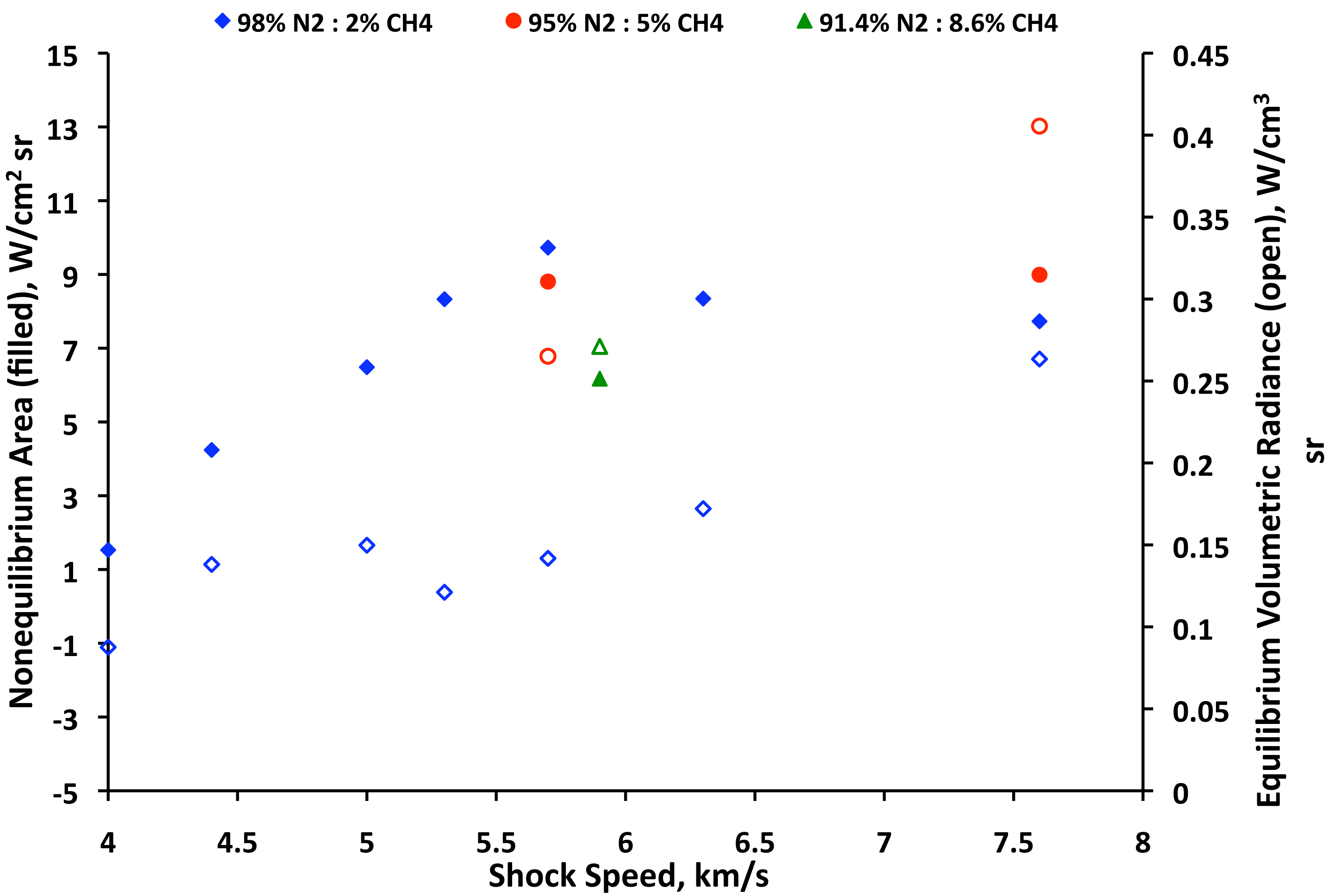

Non-equilibrium Mars Calculations

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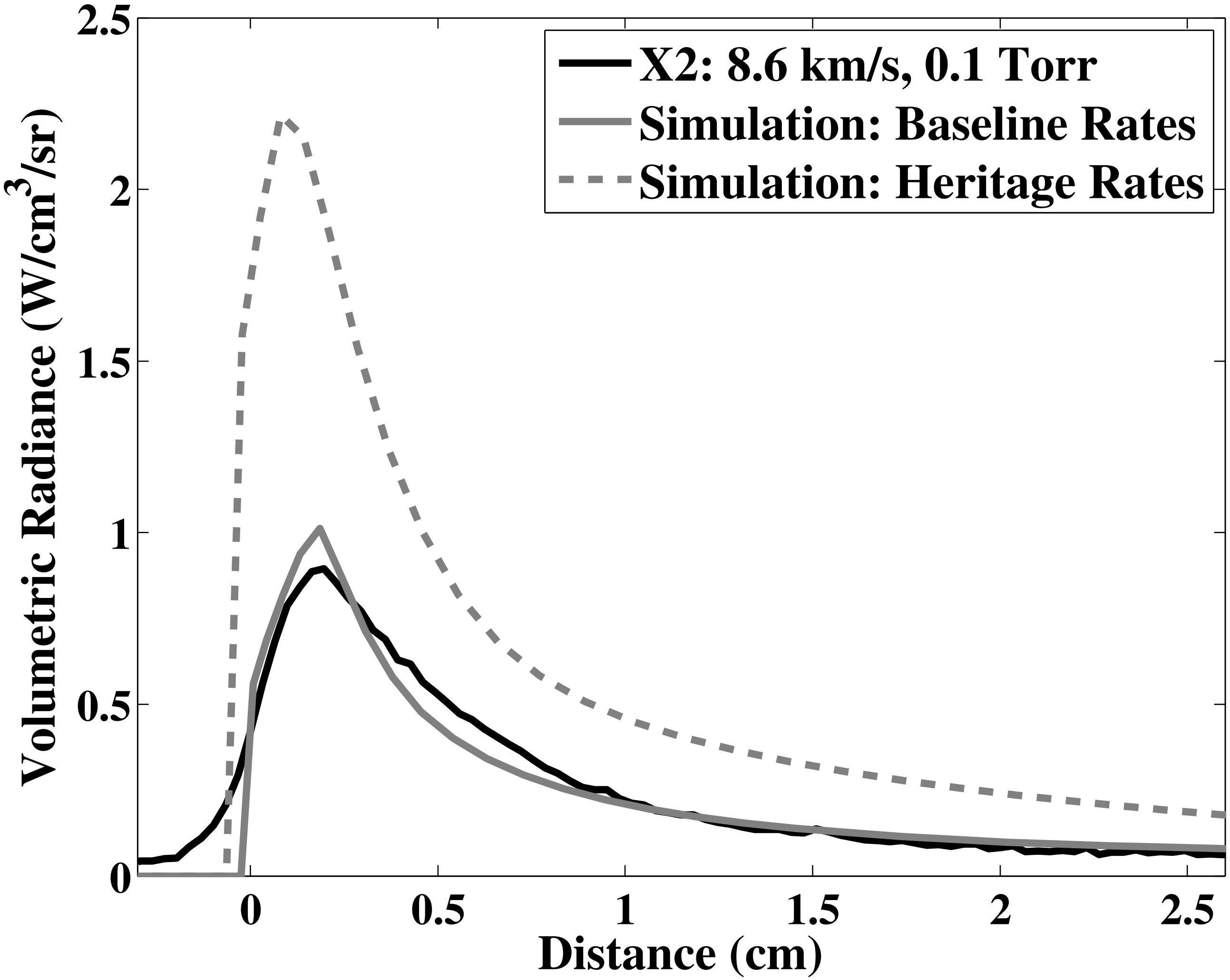
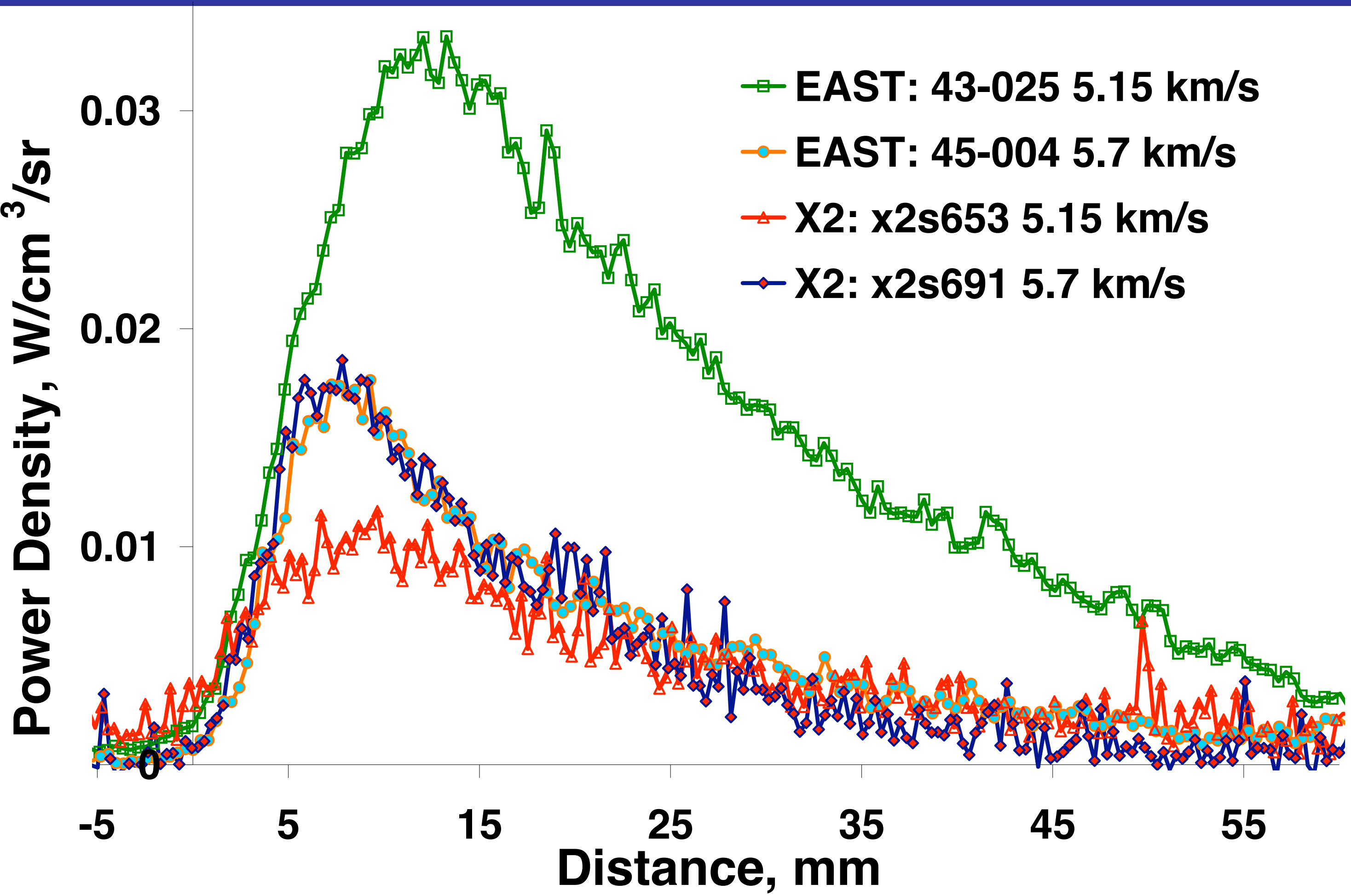


EAST vs X2


EAST: 43-025 5.15 km/s
EAST: 45-004 5.7 km/s
X2: x2s653 5.15 km/s
X2: x2s691 5.7 km/s
Power Density, W/cm ^{3}/sr
0.03
0.02
0.01
0
-5
5
15
25
35
45
55
Distance, mm

CFD Back Up

- Atmospheric Composition
  - CH_4: 1.48%
  - N_2: 98.52%
- Turbulence Model
  - Baldwin-Lomax (Forebody)
- Turbulent Schmidt Number: 0.5
- 14 species Gokcen models used
- Fully catalytic radiative equilibrium wall boundary condition
- Boltzmann distributions used for radiation