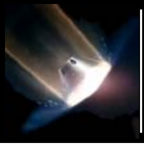

Exploration of Atmospheric Entries at Saturn, Uranus & Neptune with HEEET as Heatshield TPS

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Background

- ***In situ* exploration of the atmospheres of Uranus and Neptune are of interest to planetary science [1]**
  - How much of the solar nebula encoded in the atmospheres of these planets?
  - Winds, ices (water, methane, ammonia, …) in the troposphere, …
  - Planets have been studied remotely by Voyager-2 flybys

- ***In situ* exploration of a planetary atmosphere requires an entry system**
  - Traditionally a rigid aeroshell (45° sphere-cone) houses a probe containing the science package
  - For Outer Planets, usually Galileo probe is scaled (up or down) – this is unnecessary!

- **An entry system requires thermal protection against aerodynamic heating**
  - The current choice for the primary thermal protection material is HEEET
    - NASA-developed material is a mass-efficient replacement for full-density carbon-phenolic (legacy material), and is ready for mission infusion (TRL 6)
  - For the backshell, PICA is the choice – material is already flight proven (TRL 9)

- **Preliminary exploration of entry trajectory space seemingly established feasibility of HEEET in terms of both performance and manufacture [2]**

How good are the aerothermal environments that were used in the previous study?

References:

1. Ice Giants – Pre-Decadal Survey Mission Study Report, JPL D-100520, June 2017
2. Prabhu, D., presentation at the Ice Giants Workshop, Marseille, France, 2019.

Experience Base

	Pioneer-Venus [1]	Galileo (Jupiter) [1]	Present Work
Configuration	45° S/C	45° S/C	45° S/C
Entry mass/kg	316.5	335	
Base diameter/m	1.26	1.26	
Nose radius/m	0.36	0.222	0.3*
Ballistic coefficient/kg.m^{-2}	190	225	200-350
Entry velocity (inertial)/km.s^{-1}	11.54	59.92	[2,3]
Entry flight path angle/deg	-32.4	-6.64	[2,3]
Max. deceleration/g	288	226	50 to 200
Heatshield material	FDCP	FDCP	HEEET

Given mass (m) & ballistic coefficient (β)

$$D_b = \sqrt{(4m)/(\pi\beta C_D)}$$

Given base diameter (D_b) & ballistic coefficient (β)

$$m = \pi\beta C_D D_b^2/4$$

Hypersonic C_D for a 45° sphere-cone = 1.05

*Nosecap of spherical radius 0.25 m demonstrated on HEEET ETU

References:

1. NASA Ames Research Center, "Planetary Mission Entry Vehicles," NASA/SP-2006-3401, 2006.
2. Ice Giants – Pre-Decadal Survey Mission Study Report, JPL D-100520, June 2017
3. Hwang, H. (2018), *15th IPPW*, Boulder, CO, June 11–15.

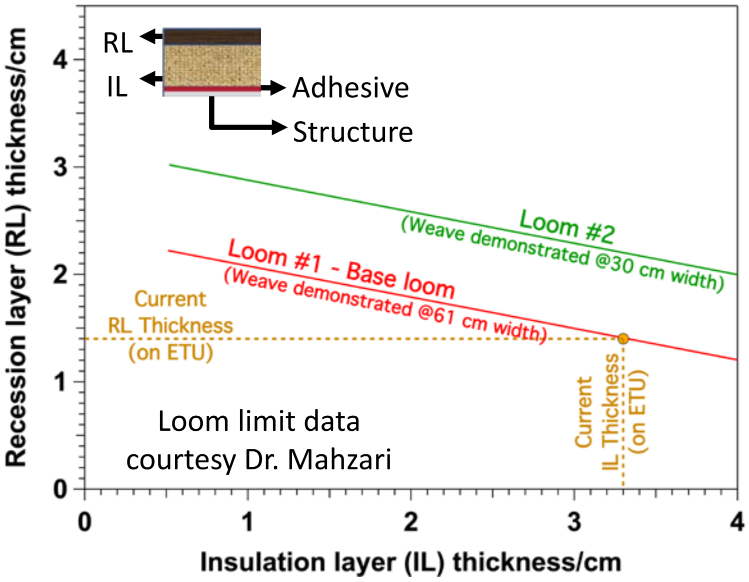
Previous Results (1/2)

- **Direct ballistic entries – 45° sphere-cone** (C_D=1.05)
  - Nose radius = 0.3 m (no scaling of Galileo geometry!)
  - Ballistic coefficient (β) range – 200-350 kg/m^2
  - Entry flight path angle (γ) such that 50 to 200 g decel.
  - Representative entry velocities [1]
- **3DOF trajectories [2] + stagnation point sizing [3]**
- **Aerothermal uncertainties & Margins [4]**
  - 1.1x on pressure, 1.25x on convective heating
  - 1.2x on RL & 0.83x on IL for turbulent flank heating
  - 0.38 cm add to RL & 0.51 cm add to IL - manufacture

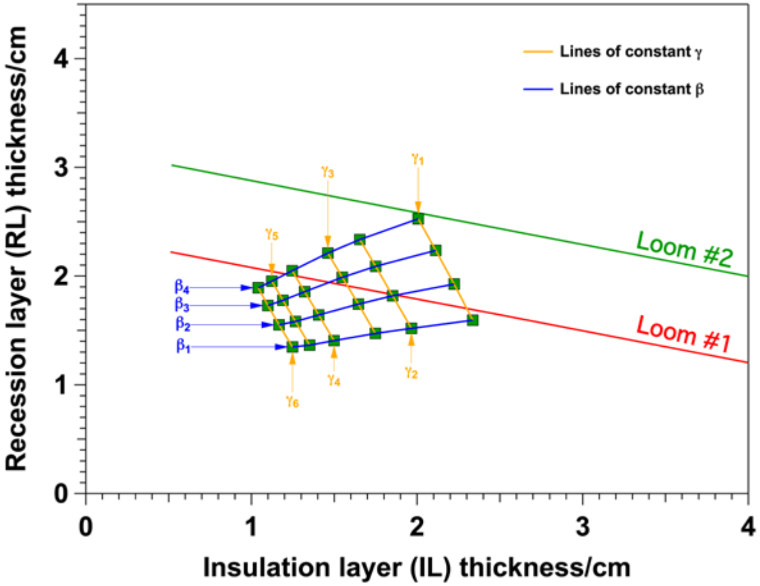
	Entry mass/kg		
	250	**300**	**350**
β/kg.m^{-2}	**Base diameter/m**		
200	1.231	1.349	1.457
250	1.101	1.206	1.303
300	1.005	1.101	1.189

References:

1. Hwang, H. (2018), *15th IPPW*, Boulder, CO.
2. Allen, G. A., Jr., *et al.* (2005) NASA/TM-2005-212847.
3. Milos, F. S. and Chen, Y.-K. (2013) *JSR*, **50**(1), pp.137-149.
4. Mahzari, M. and Milos, F. (2018), *15th IPPW*, Boulder, CO.



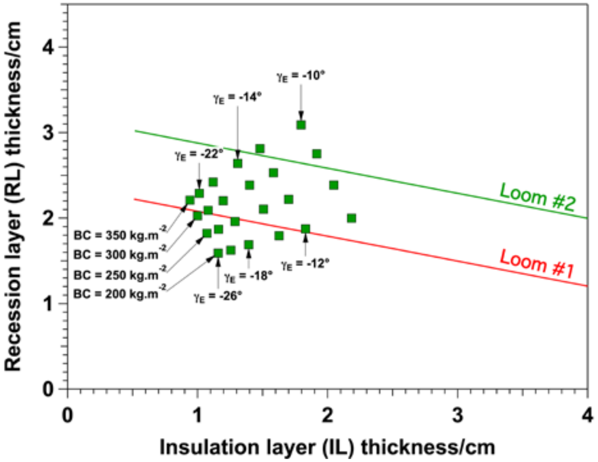
Loom limit data courtesy Dr. Mahzari



Previous Results (2/2) – R_n = 0.3 m

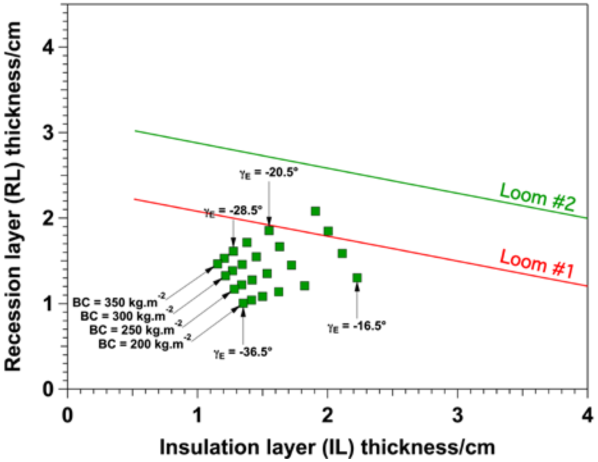
SATURN

Velocity = 35.66 km/s (Inertial)
Latitude = 0°, Azimuth = 67.05°



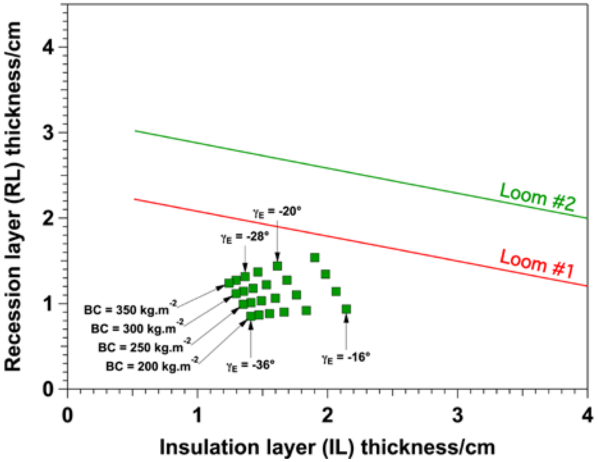
URANUS

Velocity = 22.34 km/s (Inertial)
Latitude = 0°, Azimuth = 37.7°



NEPTUNE

Velocity = 24.73 km/s (Inertial)
Latitude = -10°, Azimuth = 76.9°



- Sizing computations assume a 6.35 mm Al-2024 “structure” and 0.4 mm thick HT-424 adhesive
- Manufacturing margins of 5 mm and 3.8 mm on the computed insulation and recession layer thicknesses, respectively

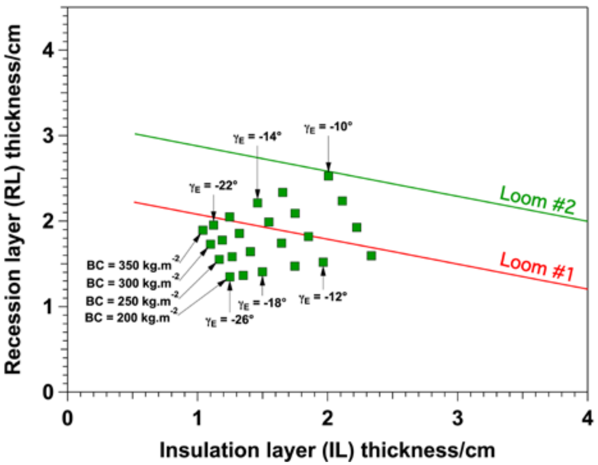
- Reducing (increasing) Rn moves points diagonally upward (downward)
- Regardless of entry flight path angle (γ_E) and ballistic coefficient (β) all solutions are feasible, except for a 3 shallow entries ($\beta \gtrsim$ -12°) at Saturn for $\beta \gtrsim$ 275 kg/m^2
- Limiting ballistic coefficient to under 250 kg/m^2 seems to solve the problem at Saturn

HEEET is well-suited for atmospheric entries at Saturn, Uranus, and Neptune! But …
Convective heat flux uncertainty of 1.5x used instead of 1.25x

Previous Results (2/2) - Corrected

SATURN

Velocity = 35.66 km/s (Inertial)
Latitude = 0°, Azimuth = 67.05°



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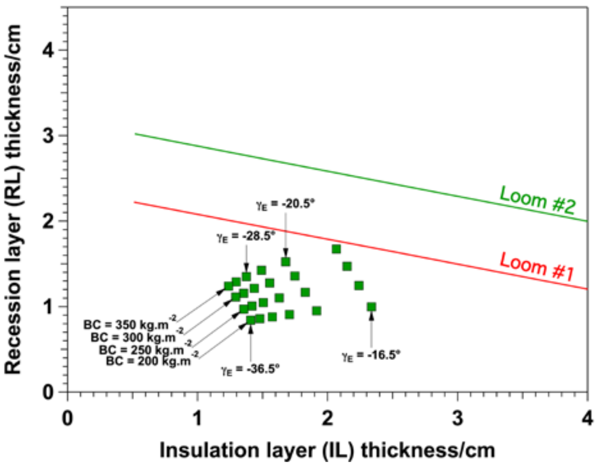

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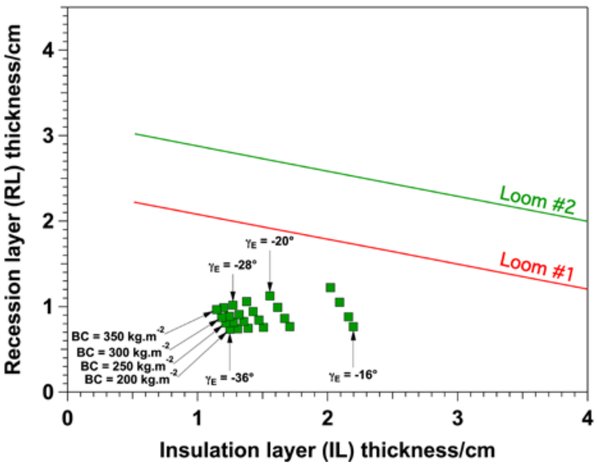


- Convective heating uncertainty set to 1.25x
- New results show significant decrease in recession layer thickness
  - A good result, given the recession layer has more mass density than the insulation layer

How good are the aerothermal environments used in these sizings?

Stagnation Point Convective Heating (1/2)

- Customary to report *cold-wall* heat flux as:

$$q_{\text{stag}} = K_1 \frac{\sqrt{\rho_\infty}}{\sqrt{R_{\text{eff}}}} V_\infty^b$$

  - $b \geq 3$, K_1 is a constant, R_{eff} is the "effective" hemispherical radius

- An alternate form [1] of the above is:

$$q_{\text{stag}} = K_2 \frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{eff}}}} (H_e - h_w)$$

  - Make the association - $H_e \approx \frac{1}{2} V_\infty^2 \gg h_w$ and $p_{\text{stag}} \approx \rho_\infty V_\infty^2$ to recover the first form

- The alternate form is a good first approximation for analysis of ablative materials
  - Analysis requires edge enthalpy, pressure, and film coefficient

$$C_H = \frac{q_{\text{stag}}}{(H_e - h_w)} = K_2 \frac{\sqrt{p_{\text{stag}}}}{\sqrt{R_{\text{eff}}}}$$

  - The film coefficient, as defined, is agnostic to wall condition – cold wall *vs.* hot wall
  - It is *always* positive definite, as long as impact theory holds
    - Does not pose a problem for convective cooling

References:

1. Sutton, K. and Graves, R. A., NASA TR T-376, November 1971.

Stagnation Point Convective Heating (2/2)

- The aerothermal problem then lies in determining the value of the constant K_2

$$q_{\text{stag}} \frac{\sqrt{R_{\text{eff}}}}{\sqrt{p_{\text{stag}}}} = K_2 \left(H_e - h_w\right)$$

- From the work of Sutton & Graves [1]
  - $K_{\mathrm{H_2}}$ = 0.0395 kg.m$^{-3/2}$.s^{-1}.atm$^{-1/2}$ and K_{He} = 0.0797 kg.m$^{-3/2}$.s^{-1}.atm$^{-1/2}$
    - These values depend strongly on transport properties (Lennard-Jones 6-12 potential used)
- K_2 for the H_2-He mixture is

$$K_2 \approx \left(\frac{Y_{\mathrm{H_2}}}{K_{\mathrm{H_2}}} + \frac{Y_{\mathrm{He}}}{K_{\mathrm{He}}} \right)^{-1}$$

  - $Y_{\mathrm{H_2}}$ and Y_{He} are the *mass fractions* of H_2 and He, respectively
- K_2 can be estimated using modern CFD (*DPLR* [2])
  - Focus of the rest of the presentation

Correlation used in *TRAJ* corresponds to Sutton-Graves form, but is composition independent

References:

1. Sutton, K. and Graves, R. A., NASA TR T-376, November 1971, p. 39.
2. Wright, M. J., White, T. R., and Mangini, N., NASA/TM-2009-215388, Oct. 2009.

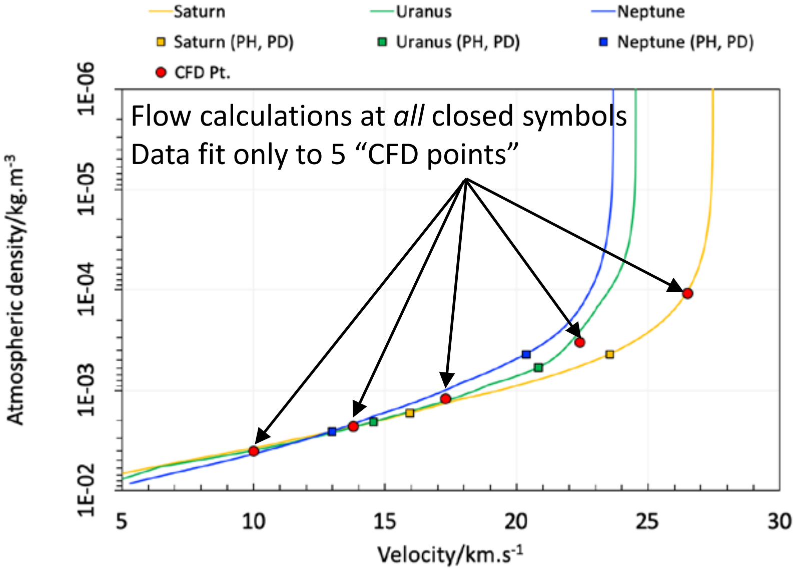
Modeling

- V4.04 of *DPLR* used in CFD computations
- Configuration is a hemisphere – radius = 0.3 m
  - Same as the nose radius of the 45° sphere-cone aeroshell
- 6-sp (H_2, H, H^+, He, He^+, e^-) used in computations
  - The two ionic species (H^+ and He^+) and free electrons (e^-) are not necessary, but…
    - Entry kinetic energies are insufficient to ionize the flow
  - Dissociation rate of H_2 from the work of Leibowitz [1]
- A simple one-temperature model for thermodynamics
  - Thermodynamic properties from curve fits [2]
- Laminar transport
  - Properties are derived from collision integrals [3]
  - Effective binary diffusion model
    - Could (should?) perhaps be replaced by simple binary diffusion model with constant Lewis number
- Wall boundary conditions
  - Isothermal cold wall with T_w = 300 K
  - Cold wall assures the reaction $\mathrm{H} + \mathrm{H} \rightarrow \mathrm{H_2}$+ 436 kJ/mol goes to completion

References:

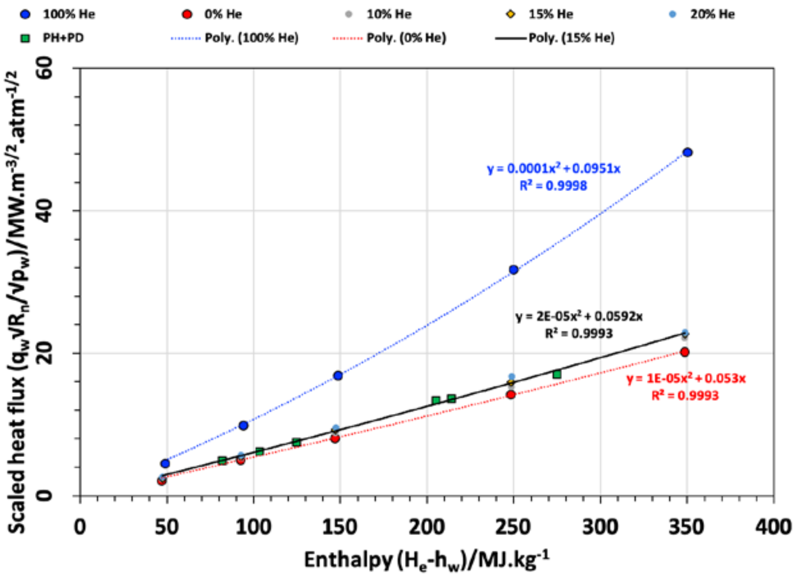
1. Leibowitz, L.P., *Physics of Fluids*, **16** (1), 1973, Leibowitz, L.P. & Kuo, T.J., *AIAA Journal*, **14** (9), 1976
2. Gordon, S. & McBride, B., NASA RP-1311, June 1996
3. Wright, M. J., unpublished work (based partly on work of Stallcop *et al.*, *JTHT*, **12**(4), 1998)

Heating Correlation from CFD



Flow calculations at *all* closed symbols
Data fit only to 5 "CFD points"

Enthalpy range: 50 – 350 MJ/kg

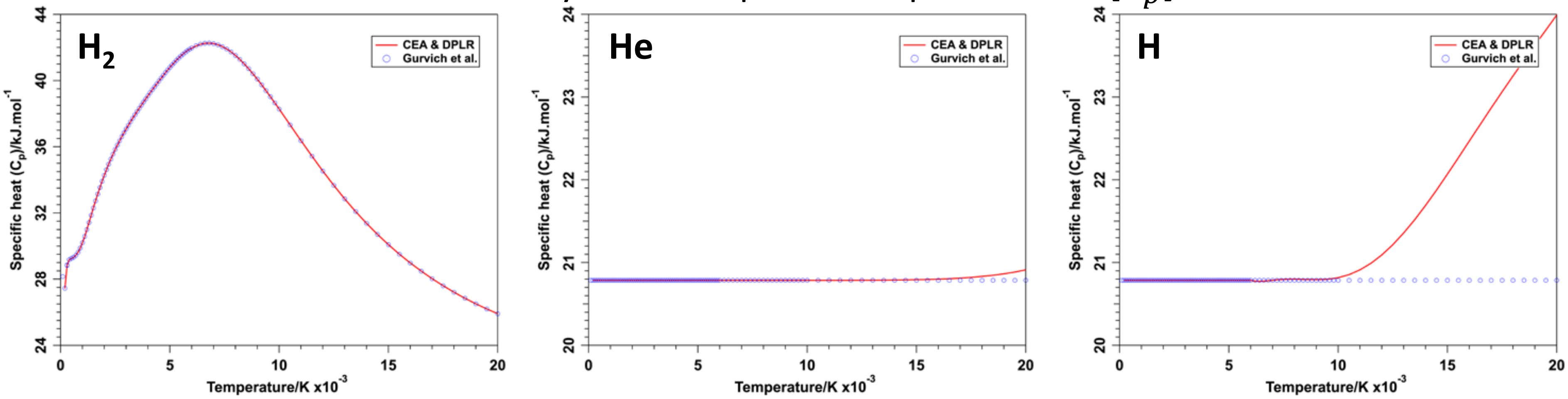


%He	K_2 (S-G)	K_2 (Present)	%Change
0	0.0395	0.0530	34.2
15	**0.0454**	**0.0592**	**30.4**
100	0.0797	0.0951	19.3

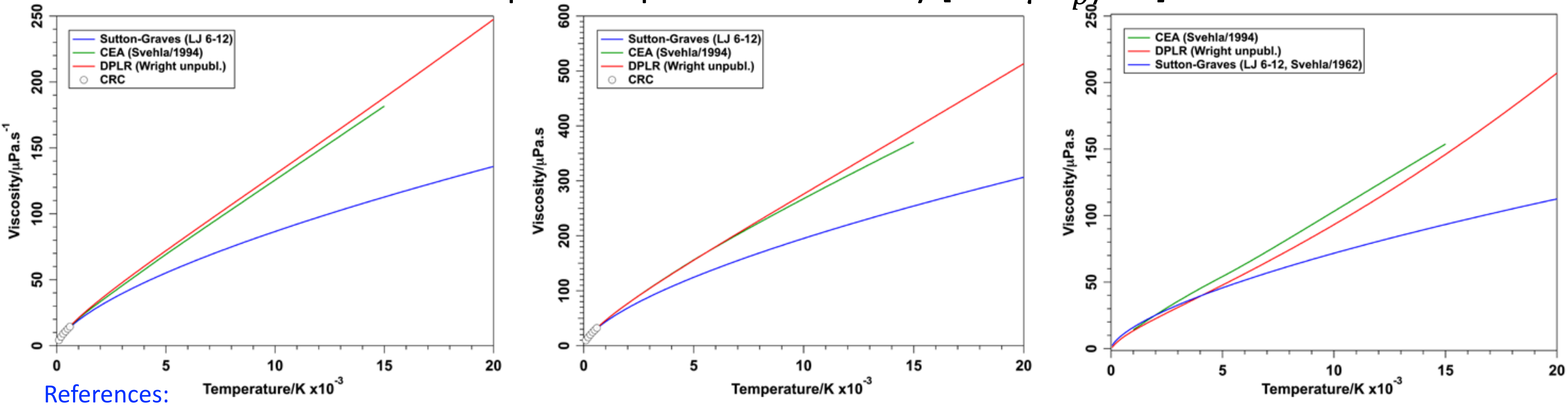
- Curve fits to 0% He, 15% He, and 100% He only
  - Curve fit is actually quadratic ($ax + bx^2$), but only a is used
    - The quadratic term is a "small" correction, but physical significance is unknown
- Nominal environments from correlations used in trajectory computations have to be boosted by a factor of 1.3, but there is still ±5% uncertainty in this value (transport prop.)

Thermodynamic and Transport Properties

Thermodynamic Properties – Specific Heat $[C_p]$



Transport Properties – Viscosity $[\kappa = \mu C_p / Pr]$



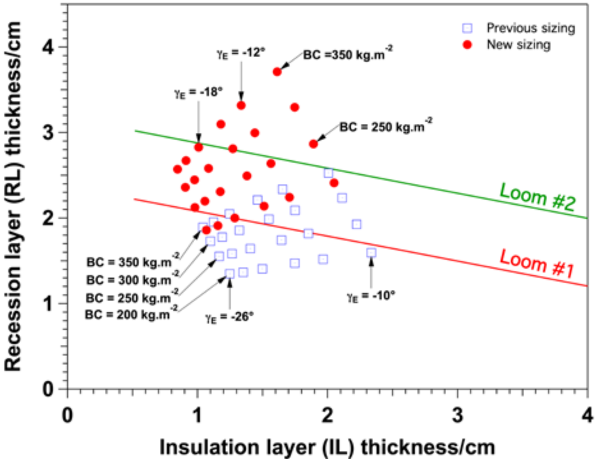
References:

1. Gurvich et al., Thermodynamic Properties of Individual Substances, Vol. 1/Part 2, Hemisphere Publishing, 1986
2. Svehla, R. A., NASA TR R-132, 1962, and NASA TM 4647, 1995
3. Wright, M. J., unpublished work (based partly on work of Stallcop *et al.*, *JTHT*, **12**(4), 1998)
4. CRC Handbook of Chemistry and Physics, 84th ed., 2003-2004, p. **6**-184.

New Sizing Based on CFD

SATURN

Velocity = 35.66 km/s (Inertial)
Latitude = 0°, Azimuth = 67.05°



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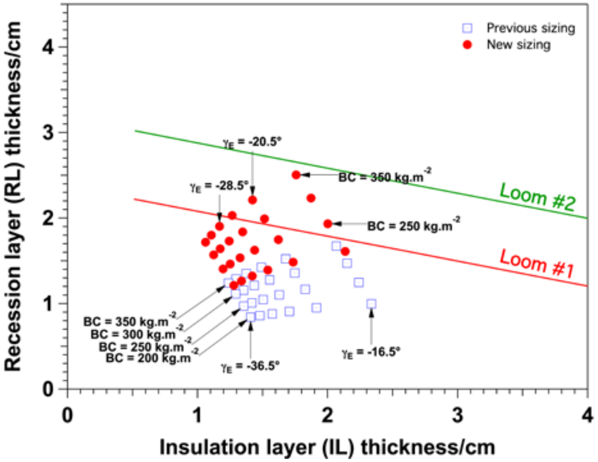
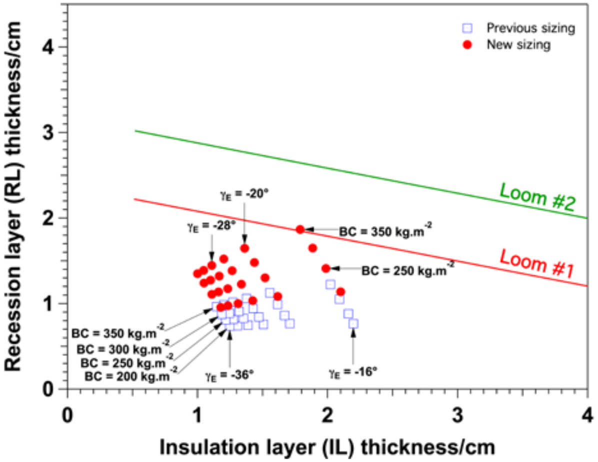


NEPTUNE

Velocity = 24.73 km/s (Inertial)
Latitude = -10°, Azimuth = 76.9°



- Nom. convective heat fluxes from *TRAJ* are magnified by a 1.3x multiplier in all 3 sizing branches
- The higher CFD-based heat fluxes result in thicker recession layers, and consequently, slightly thinner insulation layers
- Regardless of entry flight path angle and ballistic coefficient all solutions are feasible, except for 6 entries at Saturn for ballistic coefficients ≥ 250 kg/m^2
- Limiting ballistic coefficient to 200-225 kg/m^2 solves the problem at Saturn
- Loom #2 will be required for Saturn & Uranus entries, Loom #1 will work for Neptune
    - Caveat: These thicknesses are for representative entry velocities
    - Higher entry velocities => thicker recession layer --- offset by blunting nose further

Concluding Remarks

- **Initial estimates of HEEET thicknesses for Saturn, Uranus, and Neptune entries were promising**
    - Fixing the errors in the margining process made the estimates even better!
- **Better to work with film coefficient formulation directly instead of converting heat flux to film coefficient**
    - Will provide a better handle on surface recession/mass loss
- **The stagnation point heating correlation used in *TRAJ* is close to the Sutton-Graves one**
- **CFD-based stagnation point estimates are 30% higher than the *TRAJ* values**
    - Sizing HEEET using CFD-based stagnation point heating resulted in increased recession layer thicknesses (with reduction in insulation layer thicknesses)
- **HEEET is well-suited for atmospheric entries at all 3 destinations provided:**
    - Ballistic coefficient is ≤ 250 kg/m^2
    - Nose radius is ≥ 0.3 m [Scaling up/down Galileo geometry is unnecessary!]
- **Actual trajectory space may be constrained by environments (pressure, heat flux, and shear) achievable in ground-test facilities (arc jets)**
- **Turbulent flank heating environments included in sizing rely on empiricism**
    - Can be refined through CFD, including allowance for surface roughness
- **Ground-based tests in shock tunnels/tubes are necessary to validate CFD**

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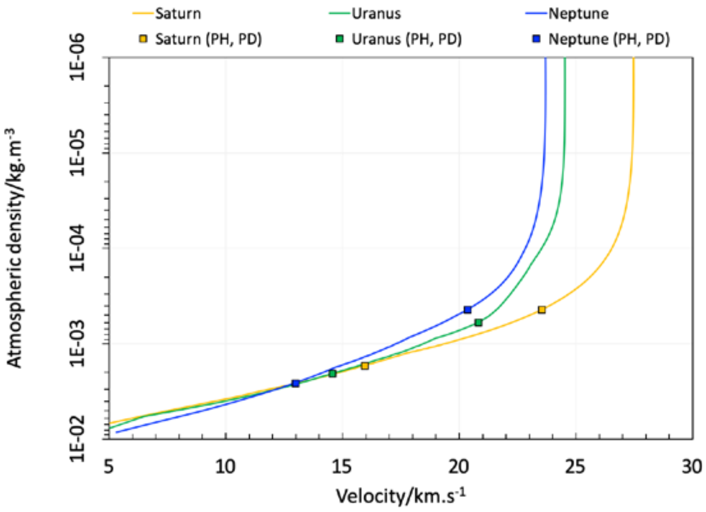
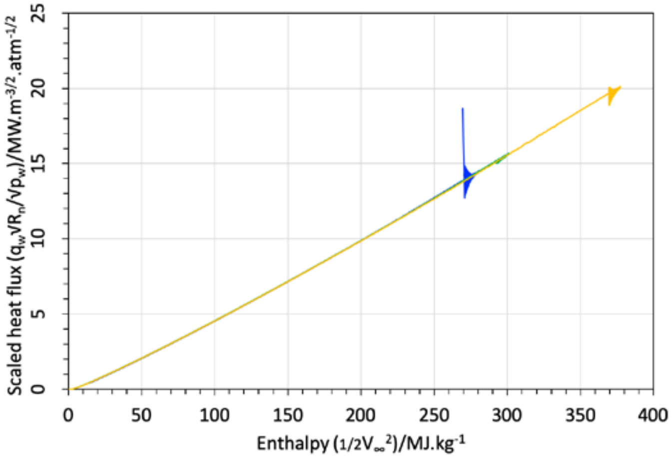
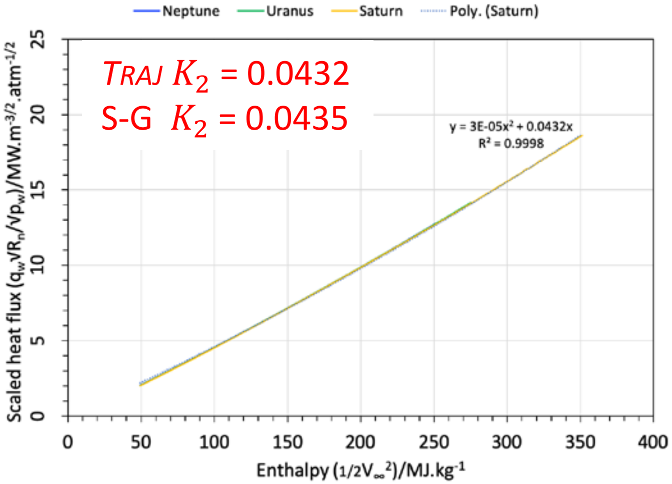
Heating Correlation in *TRAJ* [1]

- Trajectory for each destination picked randomly
- Stag. pt. heating for cold wall $q_{\text{Traj}} = K_1\sqrt{\rho_\infty}V_\infty^3/\sqrt{R_n}$
- Fit heating data with $q_{\text{Traj}}\sqrt{R_n}/\sqrt{p_{\text{Traj}}}$ *vs.* $\frac{1}{2}V_\infty^2$
  - The slope of the fit is K_2
- Compare slope value with Sutton-Graves estimate [2]







TRAJ K_2 = 0.0432
S-G K_2 = 0.0435

Correlation used in *TRAJ* corresponds to Sutton-Graves form, but is composition independent

References:

1. Allen, G. A., Jr., Wright, M. J., and Gage, P. J. (2005) NASA/TM-2005-212847
2. Sutton, K. and Graves, R. A., NASA TR T-376, November 1971.

Modeling (2/2)

		Saturn	Uranus	Neptune
	V_{esc}/km.s^{-1}	36.09	21.38	23.56
	$V_{rot, eq.}$/km.s^{-1}	9.87	-2.59	2.82
	H_2:He Composition (by vol.)	90:10	85:15	80:20
	Molar mass/kg.kmol^{-1}	2.215	2.314	2.413
	$K_{2\ (SG)}$/kg.m$^{-3/2}$.s^{-1}.atm$^{-1/2}$	0.0435	0.0454	0.0474
KE/MJ.kg^{-1}	**Velocity/km.s^{-1}**	**Enthalpy/kJ.mol^{-1}**		
650	36.1	1439.6	1504.1	1568.7
550	33.2	1218.1	1272.7	1327.4
450	30.0	996.6	1041.3	1086.0
350	26.5	775.1	809.9	844.7
250	22.4	553.7	578.5	603.4
Bond dissociation enthalpy of H_2 is 436 kJ/mol				
Ionization potentials of H_2, H, and He are 1488, 1312, and 2373 kJ/mol, respectively				

- Only H_2 dissociation is relevant for equatorial prograde entries (planetary rotation helps)
  - Influence of rotation decreases with increasing latitude!!
- Radiative heating can be neglected – first approximation!
  - At high latitudes at Saturn, ionization of H could become relevant