



Identification and Study of Validation Level Test Cases for Ablation Workshop 2022

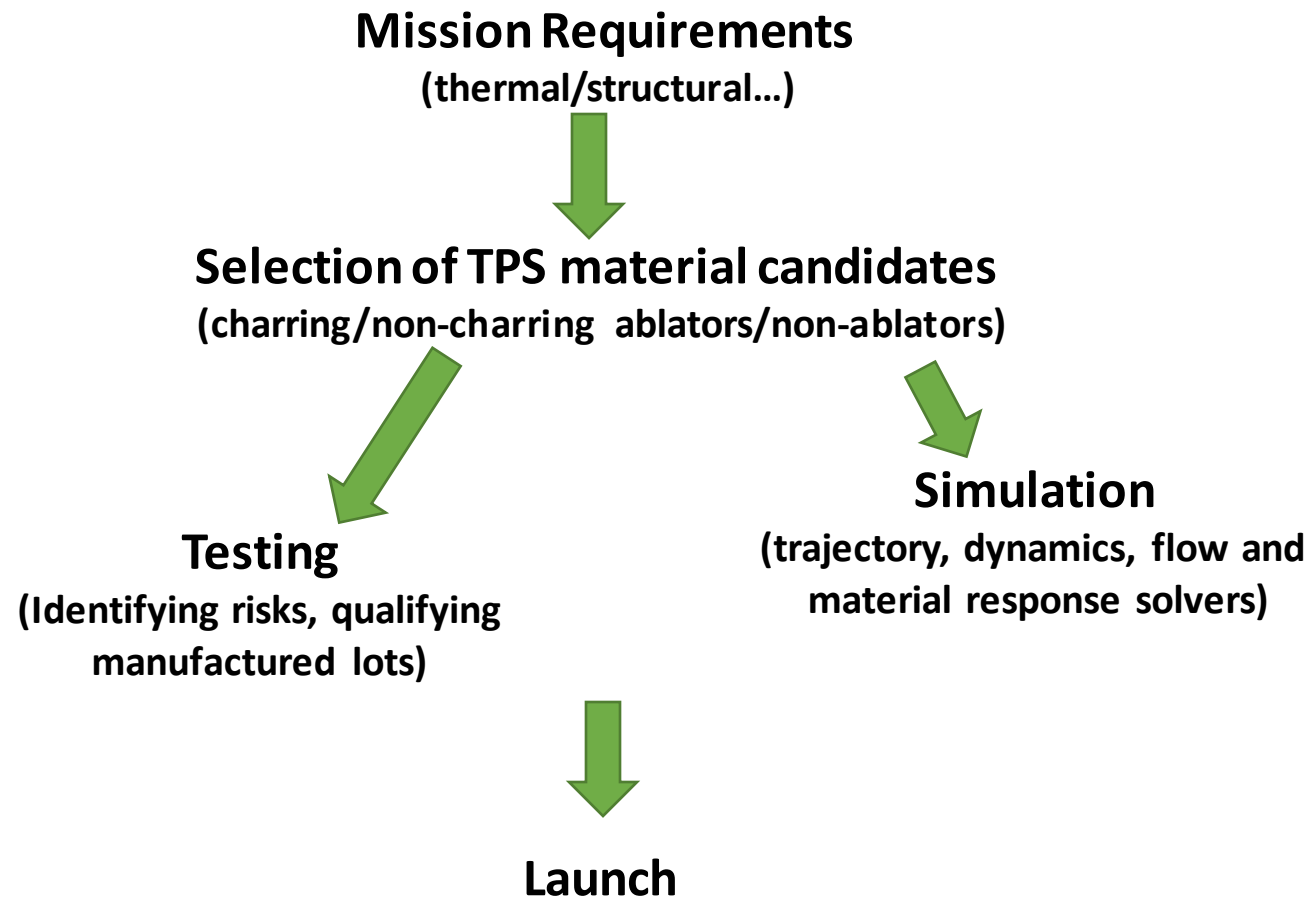
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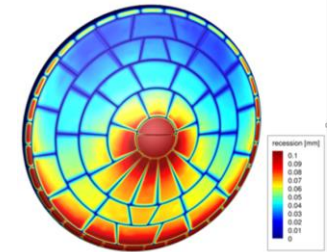
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Mentor: Eric Stern

Thermal Protection Materials



PATO simulation of MSL
heatshield recession



Arc-jet testing



PICA heatshield of MSL capsule



Motivation



- So far, in ablation modeling community in US and abroad, verification of ablation modeling tools was performed based on code-to-code comparison and published numerical data of TACOT material in a series of Ablation Workshops
 - Test case 1: 1D thermal response of charring ablator without recession
 - Test case 2: 1D thermal response of charring ablator with surface recession
 - Test case 3: 2D and 3D version of test case 1 and 2
- Since the release of Ablation Workshop cases, numerical tools have matured enough and require real experimental data for validation of the results
- Step 1: Validation test cases for non-charring ablators

Required well-characterized experimental data: flow environment and material response

Goals



- Focus on non-charring ablators (graphite, carbon-carbon, porous preforms, camphor, etc.)
- Identify experimental data from published literature and internal NASA sources
- Study the data by performing full cycle of numerical simulation (uncoupled)
 - Validate flow environment
 - Obtain boundary conditions at the material surface
 - Obtain material properties and ablation physics database
 - Simulate material response and compare to experimental data
- Propose validation test cases for ablation modeling community
- Requirements
 1. Non-charring surface ablator
 2. Arc-jet nozzle flow input parameters/equivalent freestream conditions
 3. Measurements of material response data
 - Surface temperature (Pyrometer/IR)
 - Surface recession (single point/profile)
 - In-depth temperature from thermocouples
- Constraints
 1. Non-ITAR
 2. Limited access to NASA Ames simulation tools (Icarus-DPLR-US3D)

Outline



- Short review of identified test cases
- Review of studied test cases
 - Graphite – sphere-cone (IHF)
 - FiberForm – capsule and flat-face cylinder (HyMETs)
 - Camphor – sphere-cone (low-enthalpy tunnel)
- Summary and proposed cases

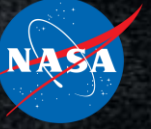
Identified Ablation Test Cases



- Around **12 identified test cases** of non-charring ablators
 - Graphite
 - FiberForm
 - Carbon-bonded carbon fiber (CBCF) composite
 - Camphor
 - Teflon
- About half, lack characterized enough flow environment or material response data
- **4 test cases fully studied** and compared to available data

Simulation tools

- Flow environment studied with DPLR (Data Parallel Line Relaxation Code – NASA Ames)
- Material response studied with KATS-MR (Kentucky Aerothermodynamics and Thermal-response System)
- Demonstrated performance with Icarus (NASA Ames)



Graphite Ablation

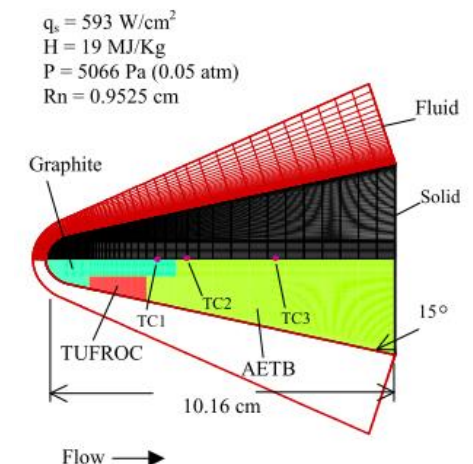
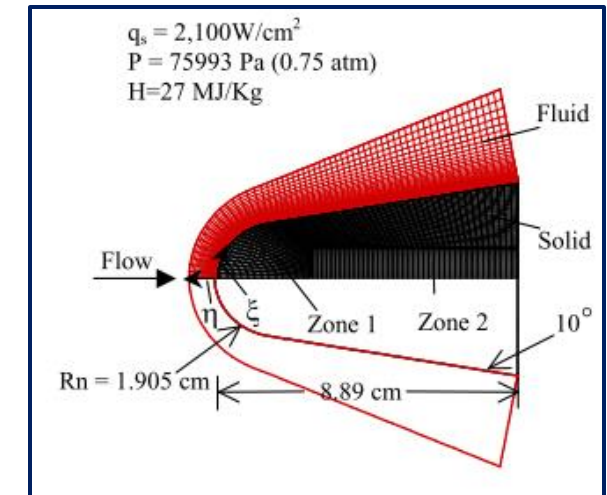
Graphite Test Case



Y. K. Chen et.al. Graphite ablation and thermal response simulation under arc-jet flow conditions. (2003)

- Graphite is crystalline form of carbon element
- High temperature ablator, used for reentry vehicles at high heat flux conditions
- Ablation occurs in two major regimes, oxidation > 800 K and sublimation > 3000 K
- 2 major experiments with graphite were conducted in Interactive Heating Facility (IHF) in air at two heat flux conditions: **2100** W/cm^2 and **593** W/cm^2
 - Test 1: POCO graphite (30 s duration), measured data: **pyrometer** and **IR** surface temperature and **recession** at two locations (0° and 45°) at several time points. **No thermocouple measurement**
 - Test 2: ATJ graphite (60 s duration), measured stagnation point **recession** and **3 thermocouple points**. **Included two insulators**. **Properties of the insulators are unknown** (Chen 07/12/2021)
- Studied in fluid-material coupled manner by several groups: chen2003, chen2005, Bianchi2010, Minyushkin2019

Studied case Test 1



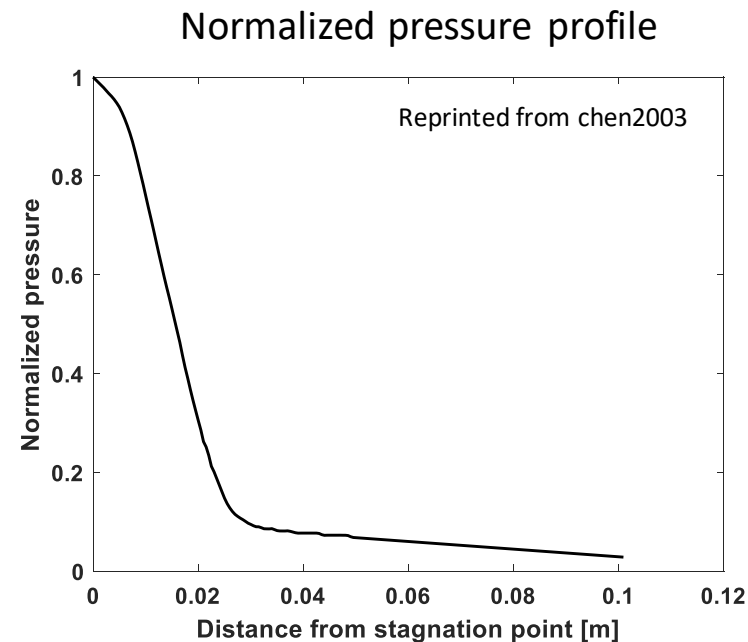
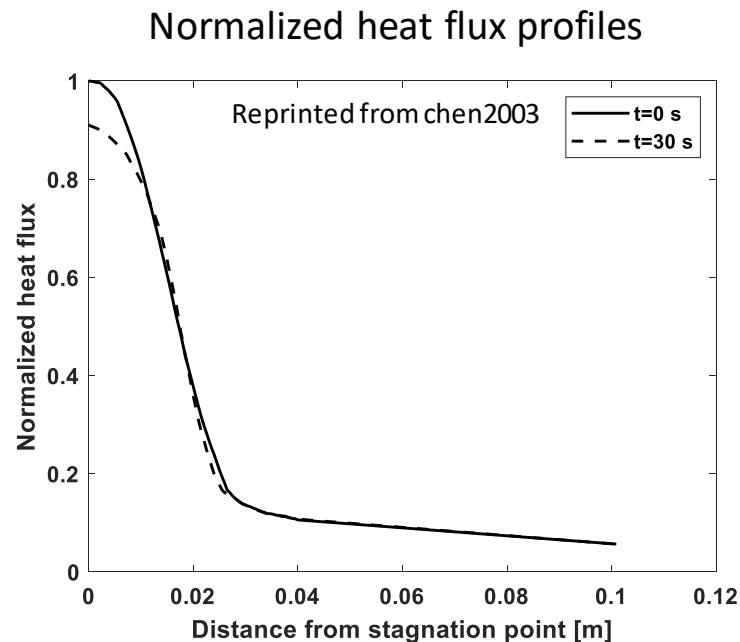
Chen et.al. (2003)

Flow Simulation Conditions

High heat flux case



- POCO graphite
- Heat flux 2100 W/cm^2 , pressure – 76 kPa, stagnation enthalpy – 27 MJ/kg
- Use of provided boundary conditions
- Linear interpolation between heat flux at $t=0 \text{ s}$ and $t=30 \text{ s}$



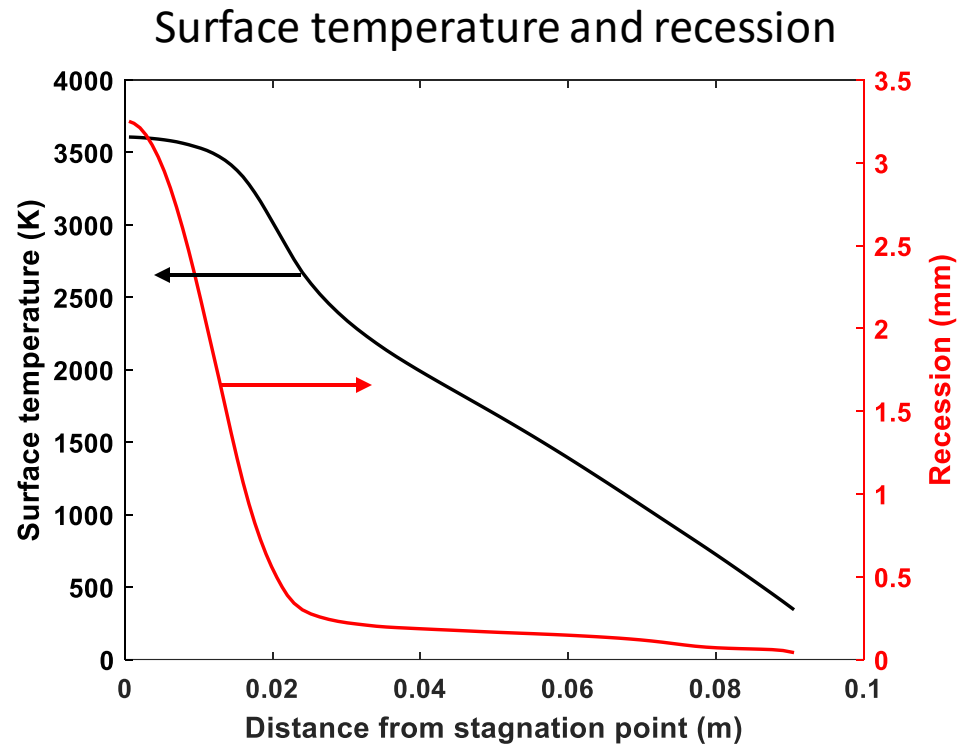
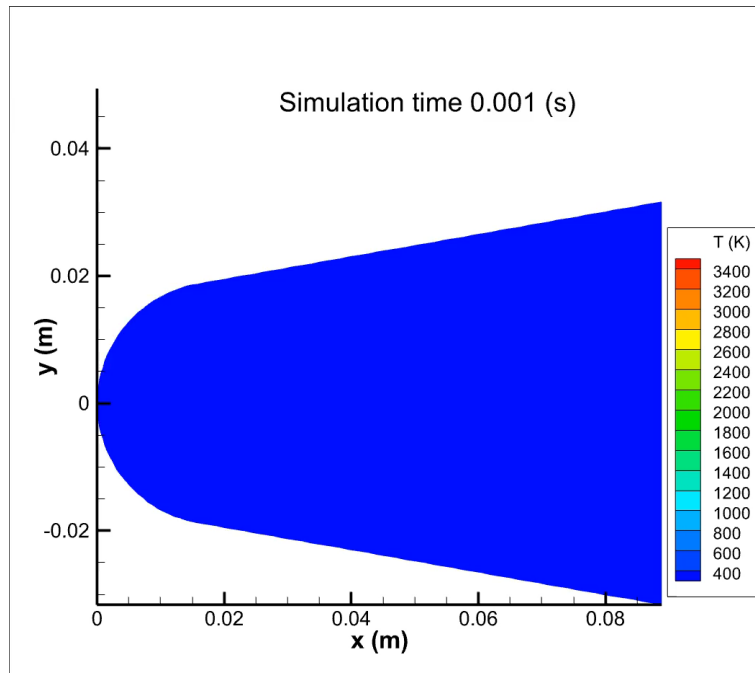
IHF Conditions	
$\dot{q}_{stag} \text{ (W/cm}^2\text{)}$	2100
$P_{stag} \text{ (kPa)}$	76
$H_{stag} \text{ (MJ/kg)}$	27
$T_{wall} \text{ (K)}$	312
Freestream conditions	
$T \text{ (K)}$	1428
$U \text{ (m/s)}$	5354
$\rho \text{ (kg/m}^3\text{)}$	0.003
$Y_{N_2} \text{ (kg/m}^3\text{)}$	0.6169
$Y_{O_2} \text{ (kg/m}^3\text{)}$	0
$Y_{NO} \text{ (kg/m}^3\text{)}$	0.0046
$Y_N \text{ (kg/m}^3\text{)}$	0.1212
$Y_O \text{ (kg/m}^3\text{)}$	0.2573

Material Response Simulation

Exposure time: 30 s; Total duration 30 s



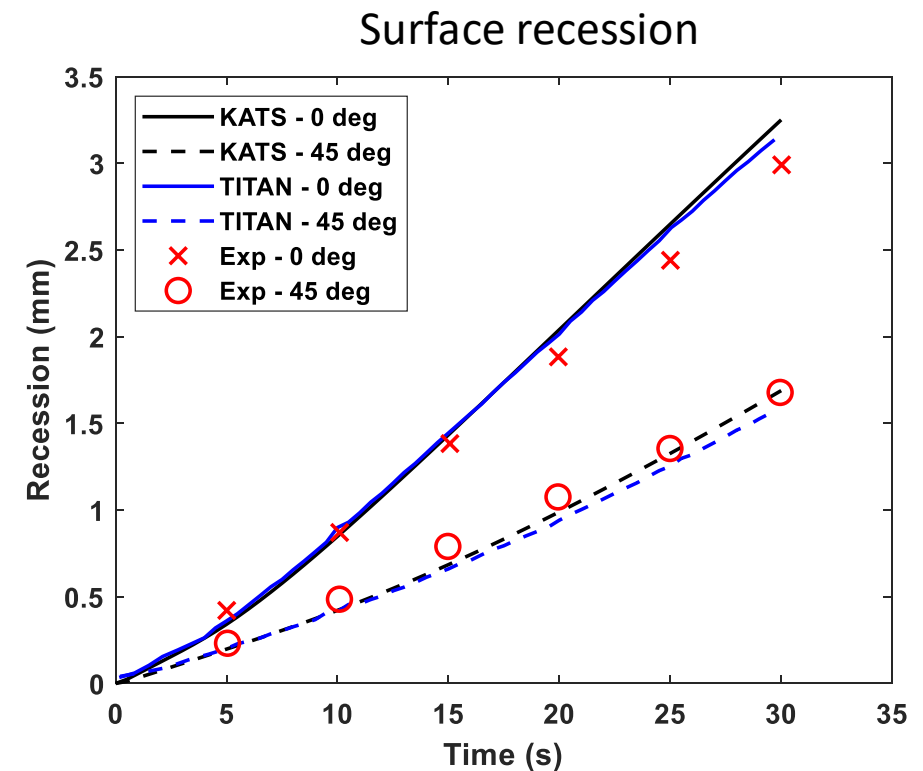
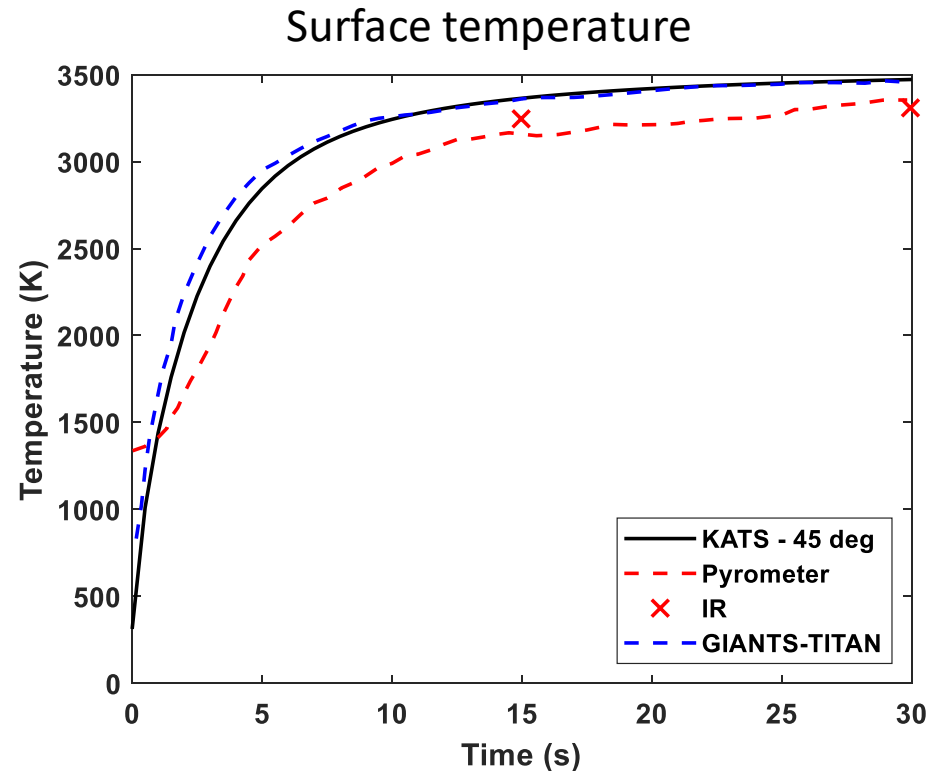
- Material thermal properties used from Touloukian1970 (provided in appendix)
- Ablation physics: Bprime for graphite in air, generated with Mutation++
- Peak temperature **3606 K**, max recession **3.25 mm**



Comparison to Experimental and Numerical Data



- **0° point:** overprediction of recession, likely due to shape change effect on heat flux reduction
- **45° point:** temperature overprediction (by $\sim 150^\circ\text{C}$), but perfect match of recession. Shape change effect on heat flux is minimal at this location.



Discussion



- Highlights:
 - Well defined freestream conditions
 - Measured pyrometer and IR surface temperature (only one location)
 - Recession history at two locations
 - Well established material properties database and ablation model
- Challenges:
 - Stagnation region ablation rate very sensitive to temperature (fully sublimation regime)
 - To fully capture the physics requires either multiple intermediate boundary condition profiles for interpolation or fully-coupled fluid-ablation simulation
- Missing data:
 - In-depth temperature response
 - Recession profile

Provides a good set of measurements for validation of high-temperature material response physics



FiberForm Ablation

Carbon FiberForm Ablation Test Cases Tested in HyMETs Facility - air



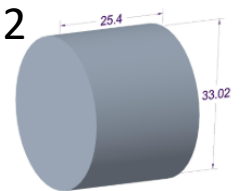
- FiberForm – porous low-density carbon material, made up of fibers that are about $15\ \mu\text{m}$ in diameter and 1.6 mm in length
- Used as a precursor for PICA material
- 4 test cases with provided conditions for nozzle flow
- Capsule data:
 - Pyrometer temperature
 - Surface profiles laser scan pre- and post-test
 - Thermocouples at 4 locations
- Flat-face cylinder, wedge, hemicylinder data:
 - Pyrometer temperature
 - Full sample laser scans

Test 1

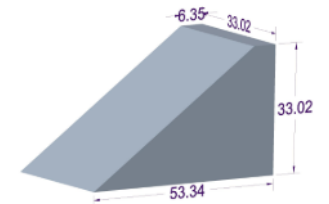


Capsule. Bessire2019

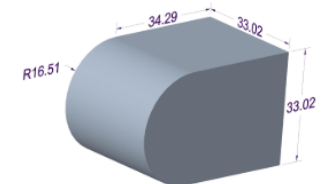
Test 2



Cylinder. Price2016



Wedge. Price2016

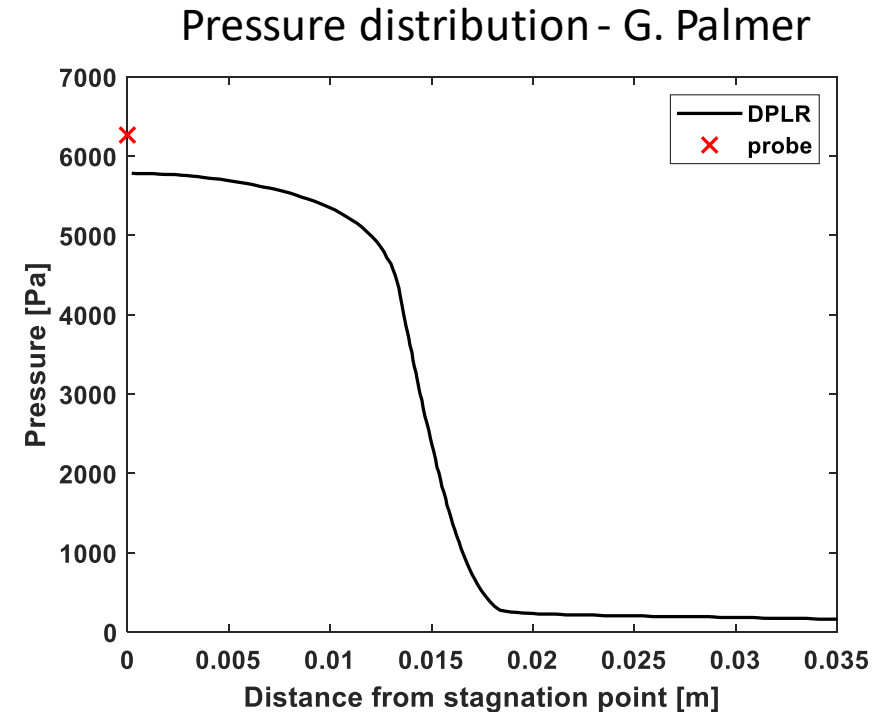
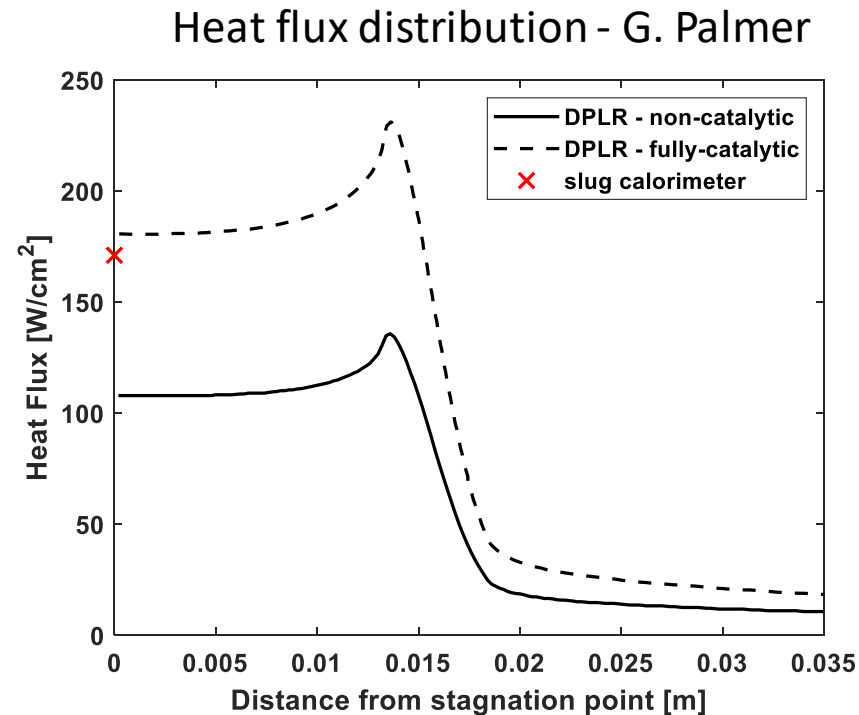


Hemicylinder. Price2016

DPLR Validation of Flow Solution HyMETS Facility



- DPLR simulation of HyMETS nozzle flow over flat face slug calorimeter probe. Conditions provided in appendix
- Fully catalytic solution
 - Heat flux 6% difference with measured value
 - Pressure 7.7 % difference with measured value

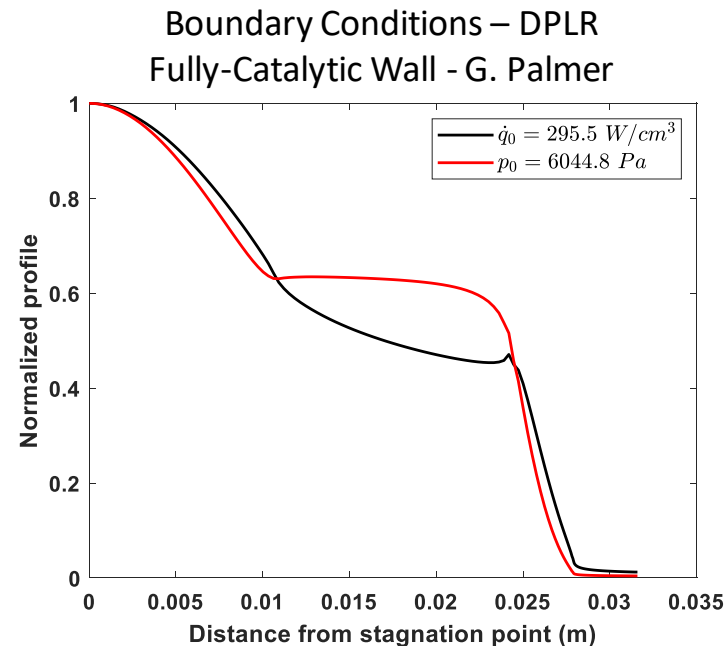
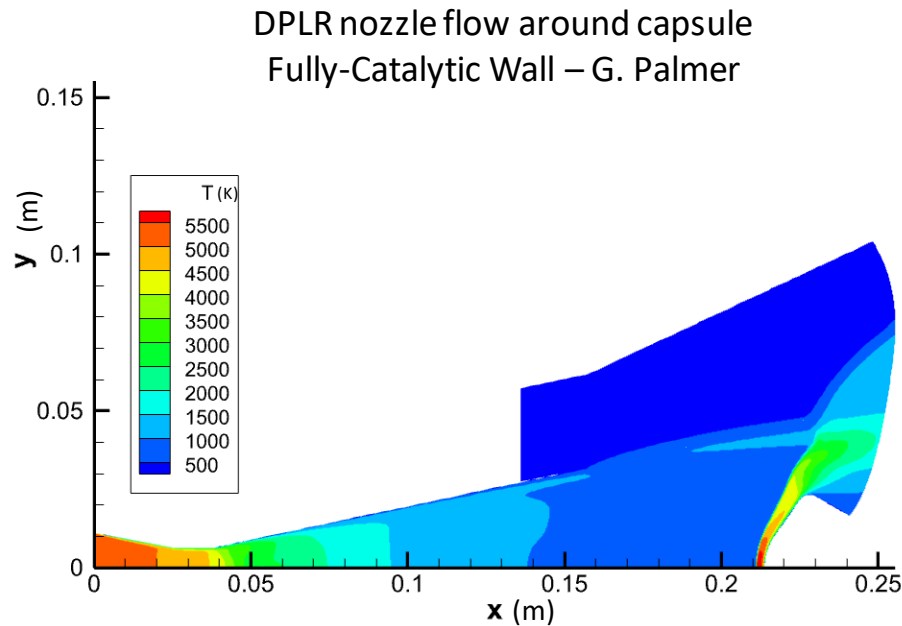


FiberForm Capsule Test Case - FS08 - Bessire2019

Flow Simulation Conditions



- Simulation of nozzle flow around the capsule geometry. Nozzle setup for simulation is provided in appendix
- Fully-catalytic heat flux - 295.5 W/cm^2 , pressure - 6044.8 Pa , stagnation enthalpy – 10.13 MJ/kg



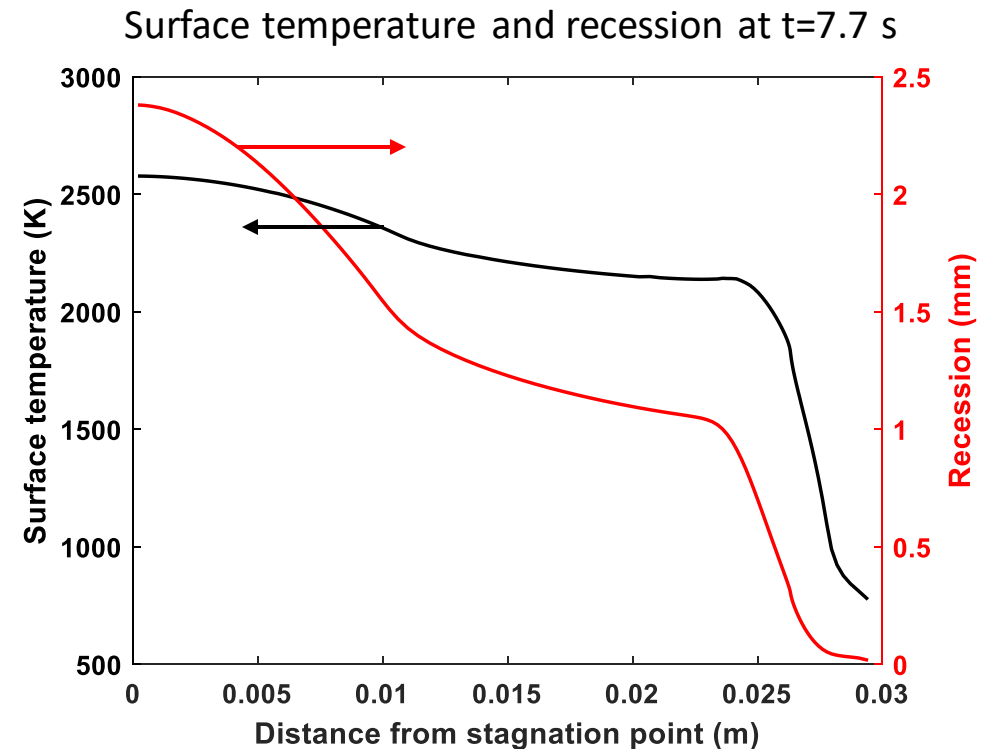
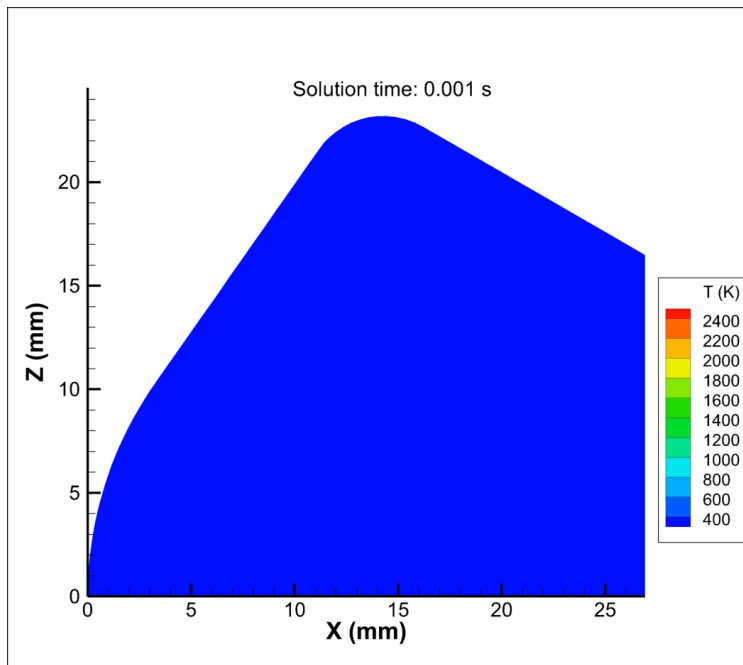
HyMETS - FS08	
$\dot{q}_{\text{slug}} \text{ (W/cm}^2\text{)}$	137
$P_{\text{stag}} \text{ (kPa)}$	5.592
$H_{\text{stag}} \text{ (MJ/kg)}$	10.13
$T_{\text{wall}} \text{ (K)}$	400
Nozzle inlet conditions	
$T \text{ (K)}$	5132.69
$U \text{ (m/s)}$	298.01
$\rho \text{ (kg/m}^3\text{)}$	0.07408
$Y_{N_2} \text{ (kg/m}^3\text{)}$	0.688092
$Y_{O_2} \text{ (kg/m}^3\text{)}$	0.002717
$Y_{NO} \text{ (kg/m}^3\text{)}$	0.022669
$Y_N \text{ (kg/m}^3\text{)}$	0.017530
$Y_O \text{ (kg/m}^3\text{)}$	0.215425
$\rho_{Ar} \text{ (kg/m}^3\text{)}$	0.053566

Material Response Simulation

Exposure time: 7.7 s; Total duration 20 s



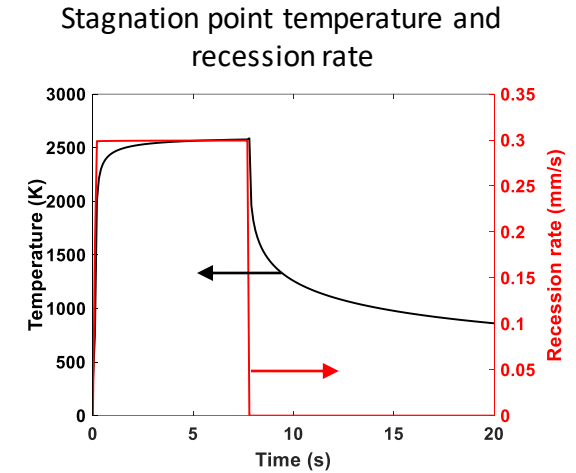
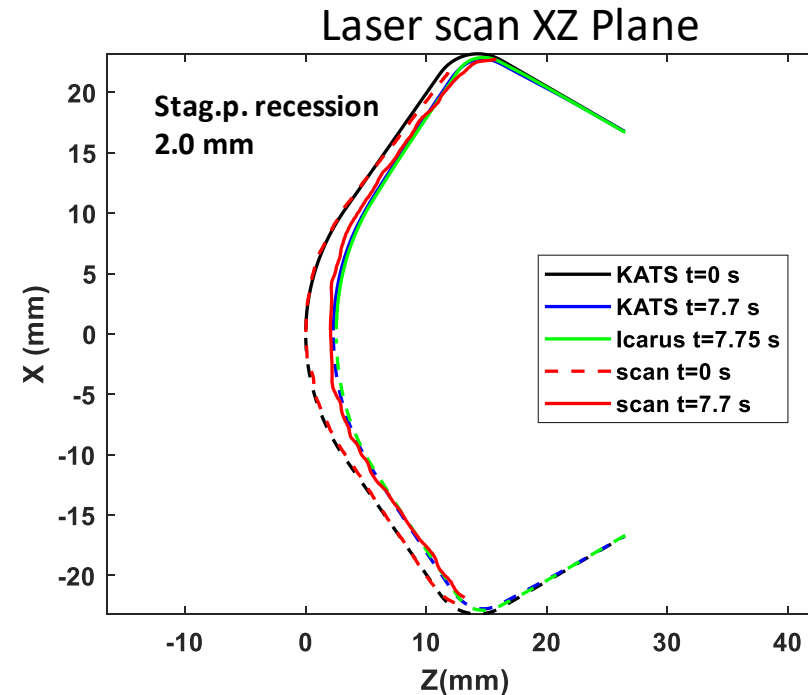
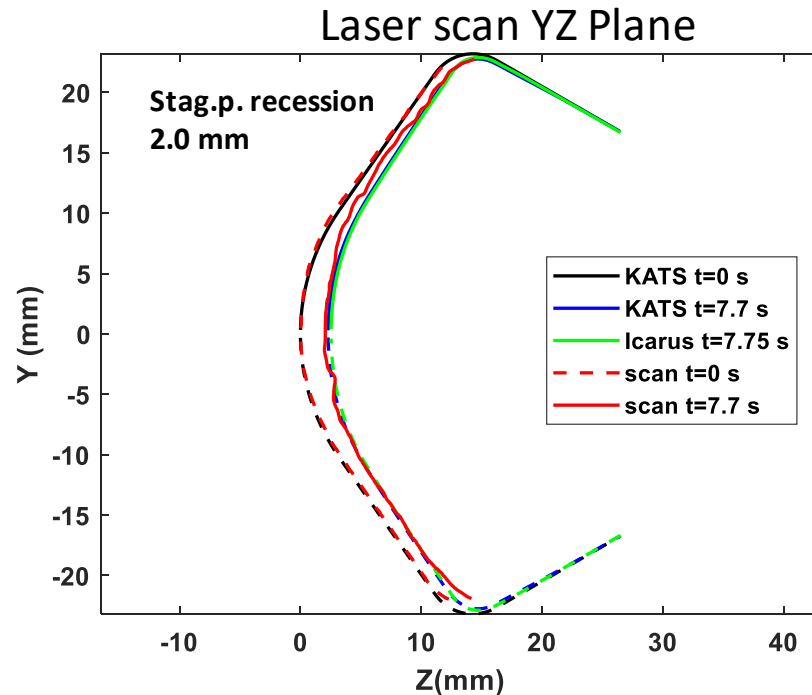
- FiberForm properties obtained from F. Panerai (provided in appendix)
- Simulation with isotropic conductivity (use of through-thickness direction)
- Ablation physics: Bprime for Graphite in air, generated with Mutation++
- Peak temperature **2588 K**, maximum recession **2.3 mm**



Comparison of Recession Profiles to Laser Scans and Icarus



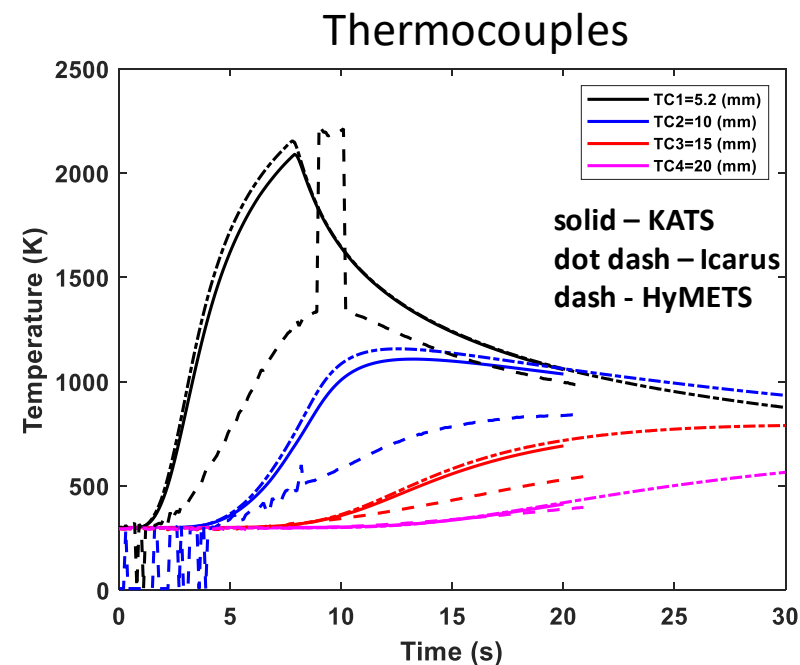
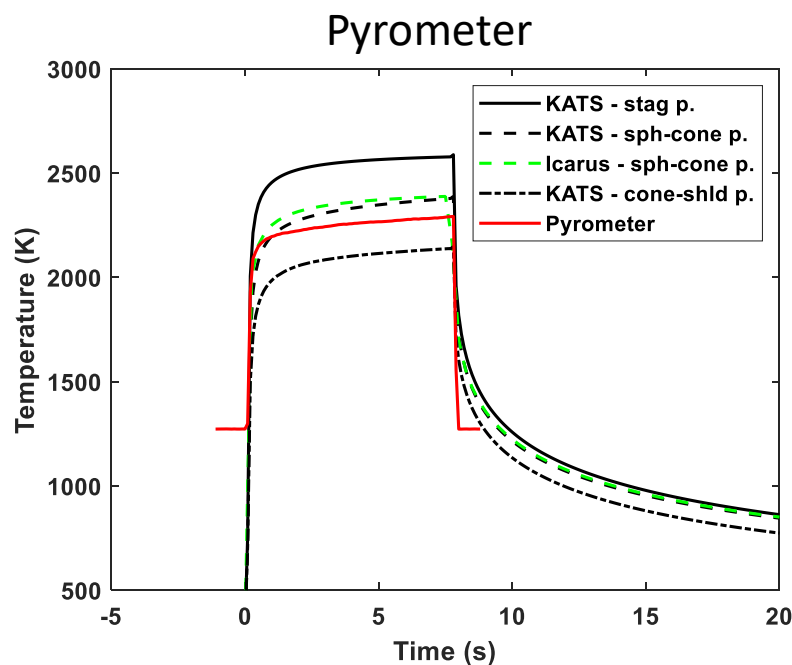
- Stagnation point recession 2.0 mm
- Few fractions of a millimeter difference with numerical results



Comparison of Temperatures: Pyrometer and Thermocouples



- **Pyrometer:**
 - Exact location of the measurement point is unknown (somewhere around sphere-cone junction). Solution sampled at three locations: stagnation, sphere-cone, cone-shoulder junctions
- **Thermocouples:** 5.2 mm, 10 mm, 15 mm, 20 mm from the surface
 - Icarus and KATS result overpredict thermocouple measurements
 - Possible misalignment of thermocouples with stagnation line

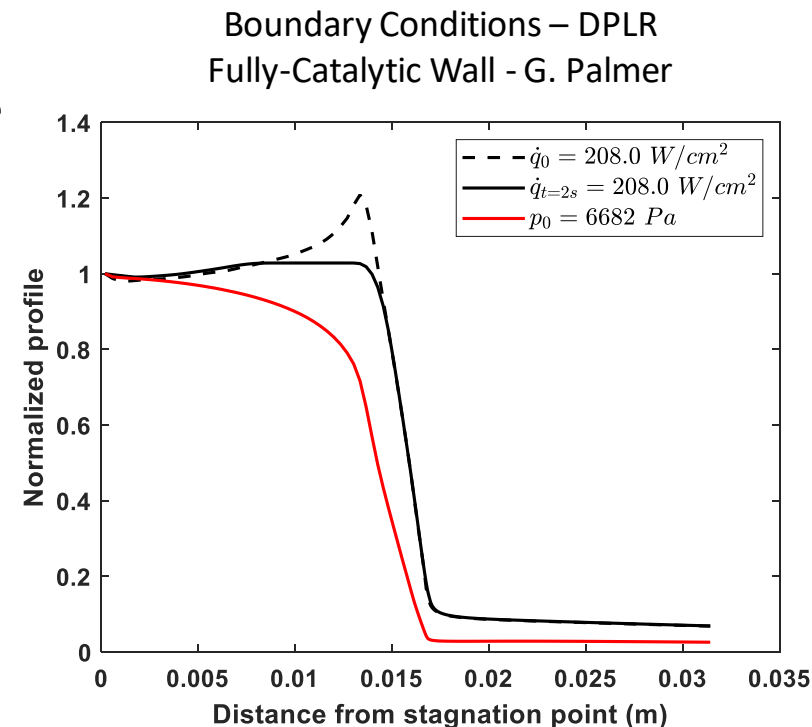


FiberForm Flat Face Cylinder - HyMETS – Run19 - Price2016

Flow Simulation Conditions



- Simulation of nozzle flow around flat face cylinder sample. (Nozzle setup for simulation is provided in appendix)
- Fully-catalytic heat flux – 208.0 W/cm^2 , pressure - 6682 Pa , stagnation enthalpy – 12.47 MJ/kg
- Smoothing of peak in initial heat flux profile to prevent unphysical recession
- Linear interpolation between two profiles over 2 s simulation time



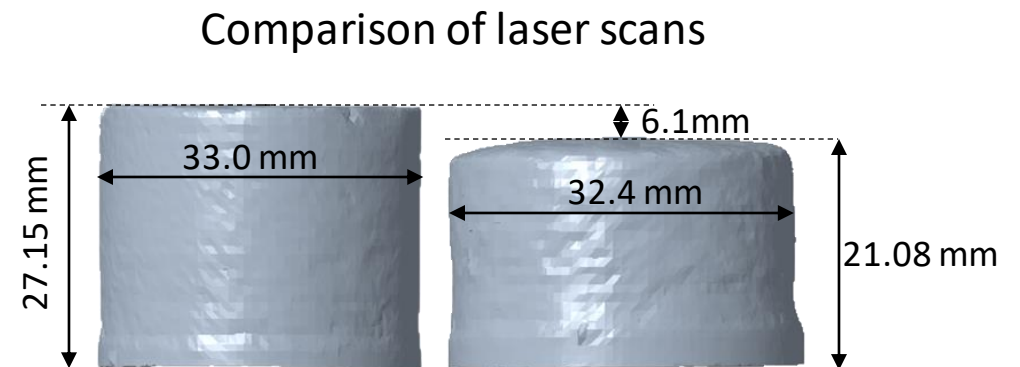
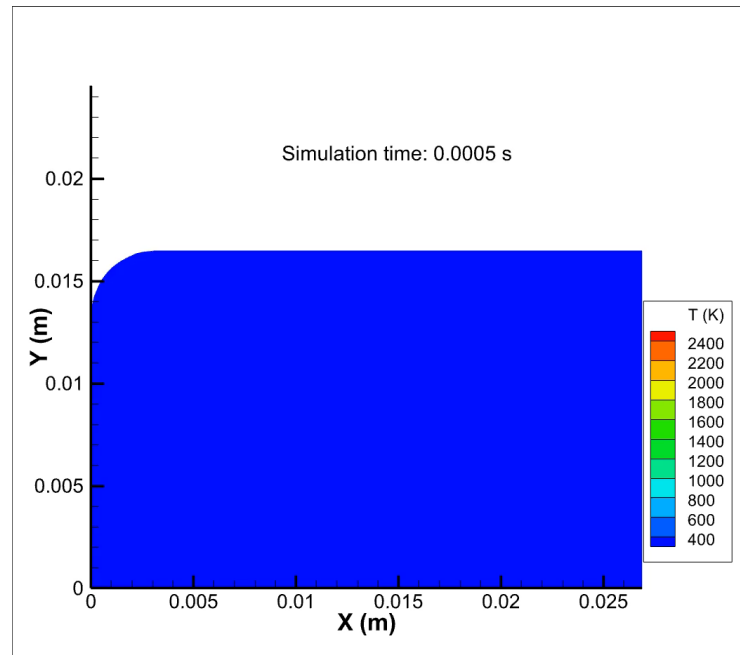
HyMETS – Run19	
$\dot{q}_{\text{slug}} \text{ (W/cm}^2\text{)}$	171
$P_{\text{stag}} \text{ (kPa)}$	6.266
$H_{\text{stag}} \text{ (MJ/kg)}$	12.47
$T_{\text{wall}} \text{ (K)}$	400
Nozzle inlet conditions	
$T \text{ (K)}$	5447
$U \text{ (m/s)}$	359.6
$\rho \text{ (kg/m}^3\text{)}$	0.069
$Y_{N_2} \text{ (kg/m}^3\text{)}$	0.674824
$Y_{O_2} \text{ (kg/m}^3\text{)}$	0.001242
$Y_{NO} \text{ (kg/m}^3\text{)}$	0.017079
$Y_N \text{ (kg/m}^3\text{)}$	0.033804
$Y_O \text{ (kg/m}^3\text{)}$	0.207025
$\rho_{Ar} \text{ (kg/m}^3\text{)}$	0.066026

Material Response Simulation

Exposure time: 30.6 s; Total duration 30.6 s



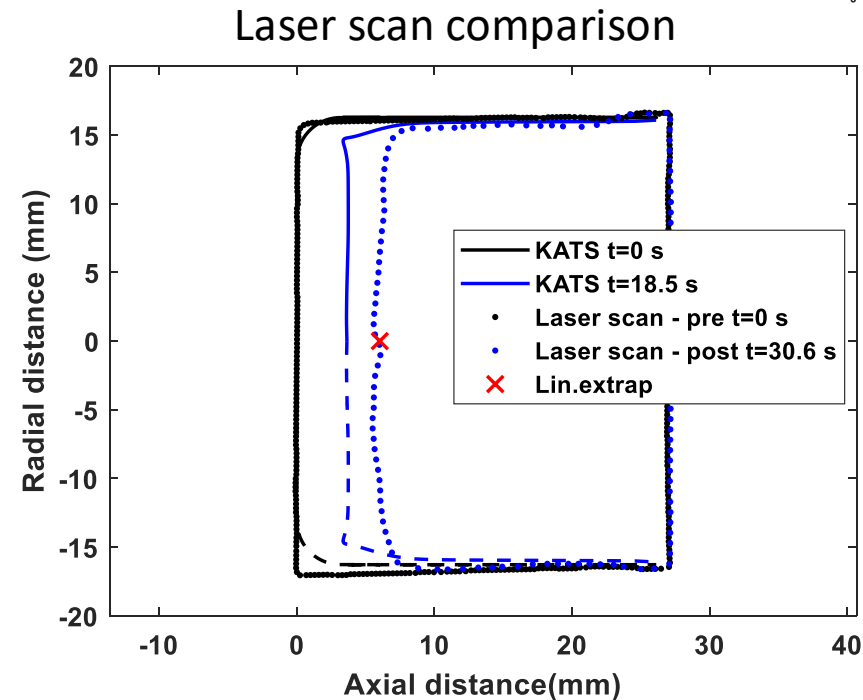
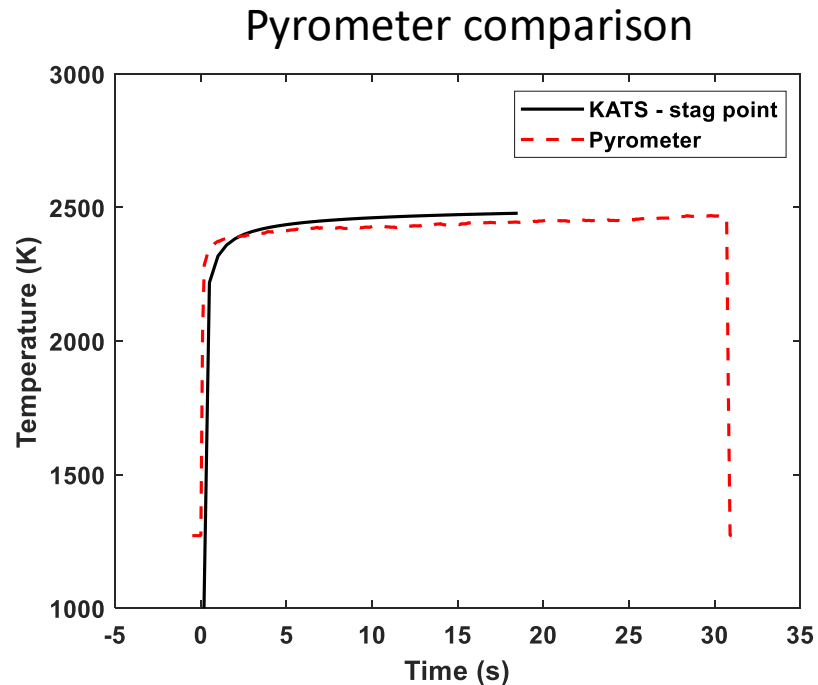
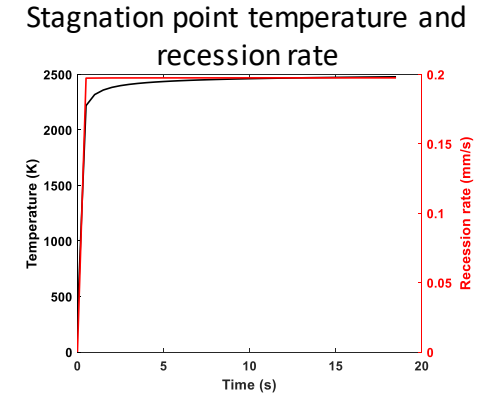
- Material properties and ablation physics are the same as in the previous case
- Peak temperature **2495 K** (near shoulder); stagnation point recession (extrapolated) - **6 mm**
- Unphysical deformation of shoulder region due to:
 - No adaptation of heat flux to shape change
 - Challenges of current moving mesh algorithm (RBF) in shoulder regions with low curvature
- Crash of KATS simulation after 16.5 s possibly due to too skewed mesh in shoulder region



Comparison to Pyrometer and Laser Scan



- **Pyrometer:**
 - Close comparison of measured and numerical data
- **Laser scan:**
 - Linear extrapolation of stagnation point recession matches the measured value



Discussion



- Highlights:
 - Provided laser scan and surface temperature data in every case
 - Good overall comparison
 - Surface temperature
 - Recession
- Challenges:
 - Flat face cylinder is a challenging case due to geometry shape and changing boundary conditions as the material recesses
 - To fully capture the physics requires either multiple intermediate boundary condition profiles for interpolation or fully-coupled fluid-ablation simulation
- Uncertainty in location of thermocouple junctions in capsule case

Flat-face cylinder test provides a good case for challenging mesh motion problem and opens a way for coupled simulation



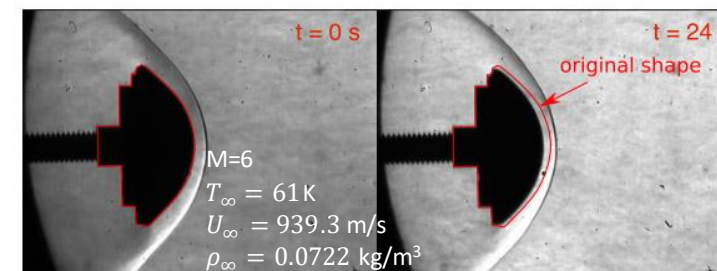
Camphor Ablation

Camphor Ablation

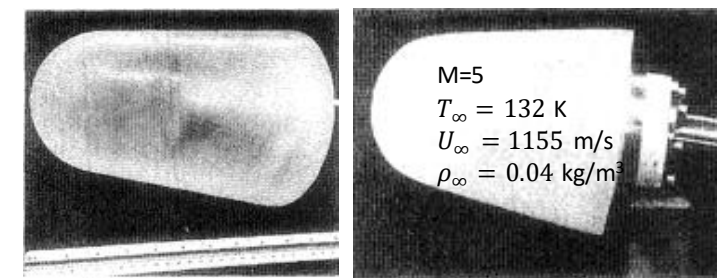


- Camphor – low conductivity, flammable solid material
- Relatively simple ablation physics – sublimation in a wide temperature and pressure range
- Use for testing mesh motion algorithm in codes
- Two major experimental test cases
 - Turchi2019:
 - Phoebus capsule shape
 - Relatively small recession (~2 mm at stag point – 20 s)
 - Effect of copper base structure on material thermal behavior after 10 s
 - Baker1972:
 - Sphere-cone shape
 - Long experiment (320 s)
 - Significant recession (~5 cm) at stag point)

Camphor Phoebus capsule (Turchi 2019)



Camphor Sphere-cone (Baker1972)



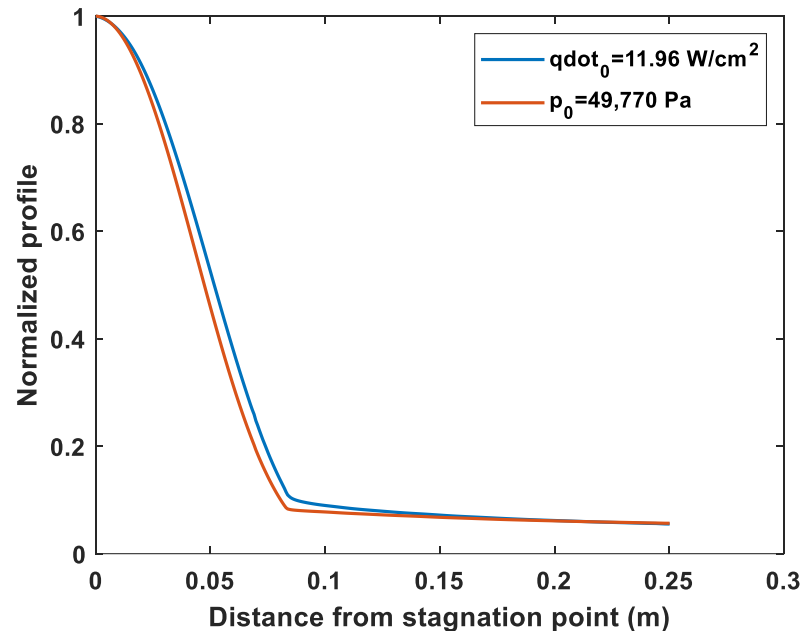
Flow Simulation Conditions

Baker1972 sphere-cone

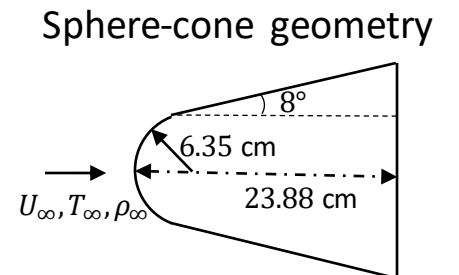


- Freestream conditions: Mach 5, $P_0=807$ kPa, $T_0=797$ K
- Heat flux – 11.96 W/cm², pressure – $49,770$ Pa, stagnation enthalpy – 0.5 MJ/kg

Boundary Conditions
DPLR – G. Palmer



Tunnel conditions	
Mach	5
P_0 (kPa)	807
T_0 (K)	797
Simulation conditions	
T_∞ (K)	132
U_∞ (m/s)	1155
ρ_∞ (kg/m ³)	0.04
T_w (K)	400

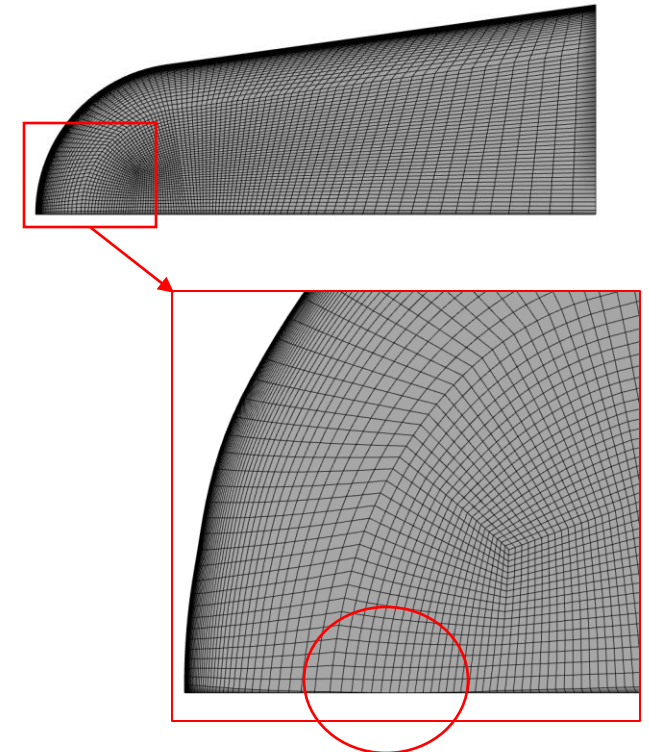
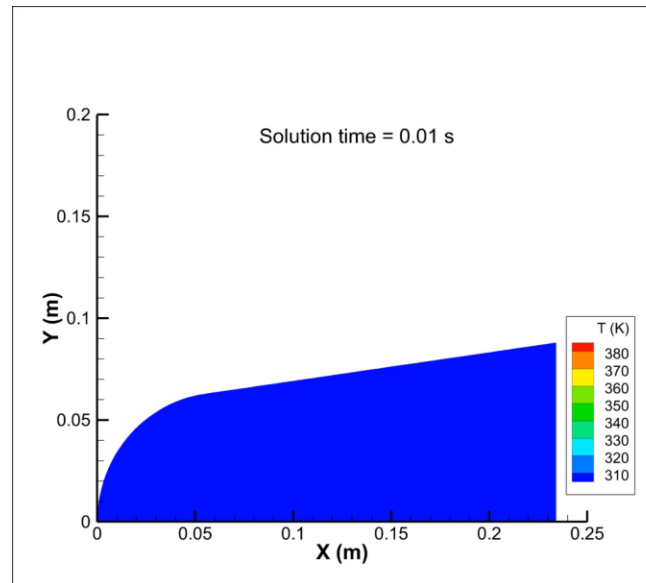
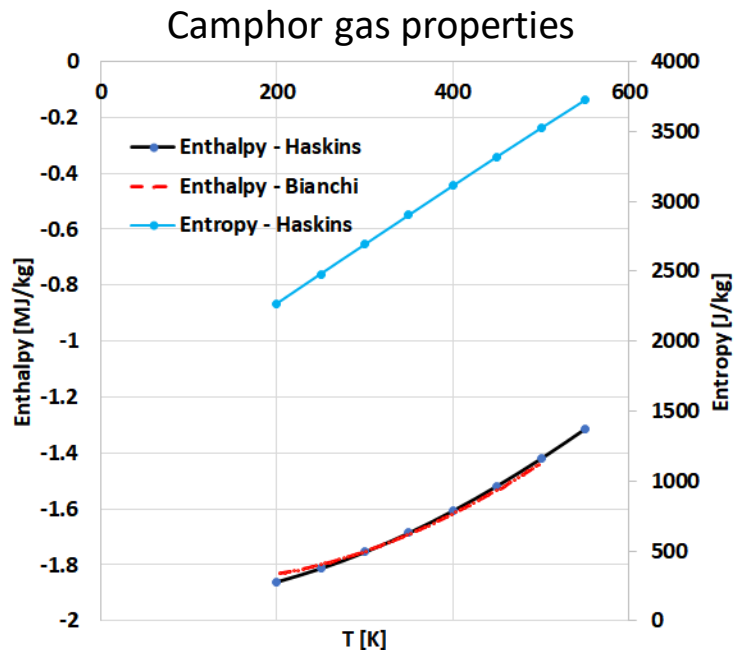


Material Response Simulation

Exposure time 320 s; Simulation duration 90 s



- Constant solid properties
- Gas properties evaluated with molecular dynamic simulation (J. Haskins) and added in NASA-7 format to Mutation++
- Ablation physics:
 - Bprime curves obtained from the work of Bianchi2019
 - Mixture enthalpy at the wall obtained using relation: $Y_w = \frac{B'_c}{1+B'_c}$ and mixture rule: $h_w = (1 - Y_w)h_{air} + Y_w h_c$



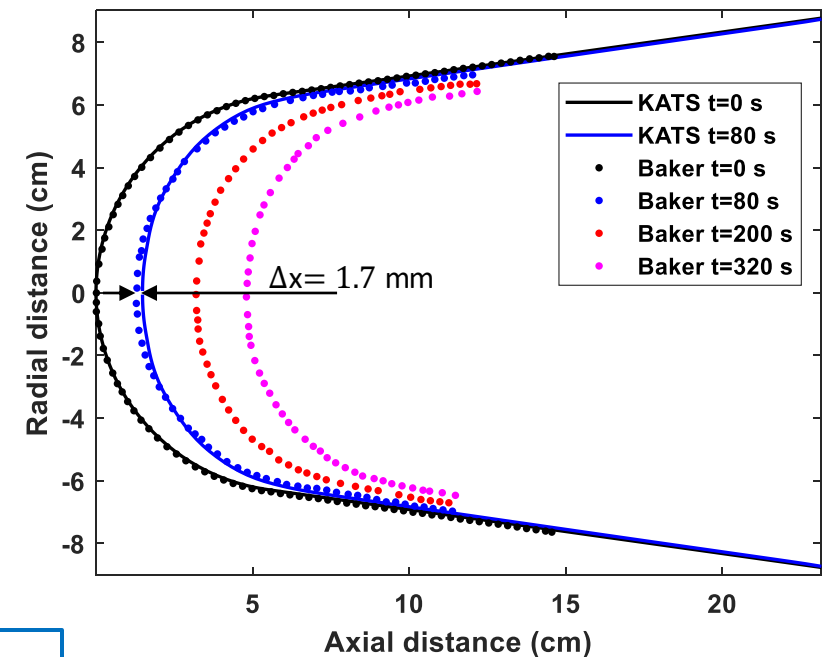
Comparison of Recession Profile



- Comparison of recession profiles at $t=80$ s
- Small discrepancy in recession is likely due to heat flux decrease due to blunter nose tip
- Highlights:
 - Long duration experiment with significant recession
 - Geometry shape is relatively simple for recession modeling
- Challenges:
 - Shape change effect on heat flux – requires either multiple boundary conditions profiles or coupled simulation
- No temperature measurement

Relatively simple mesh motion problem and ablation physics.
Long enough experiment to be studied with coupled tools

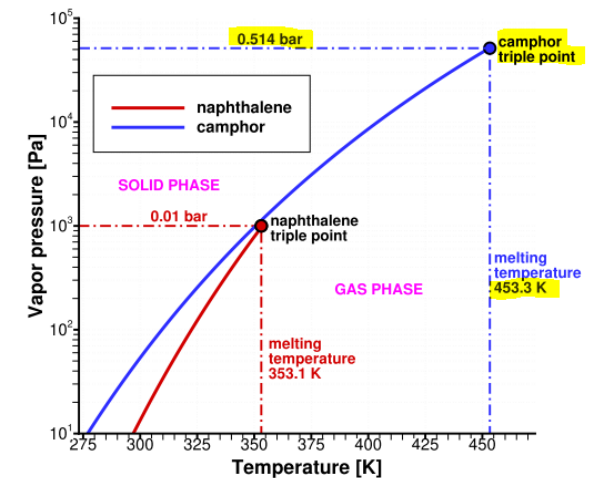
Comparison of recession profiles



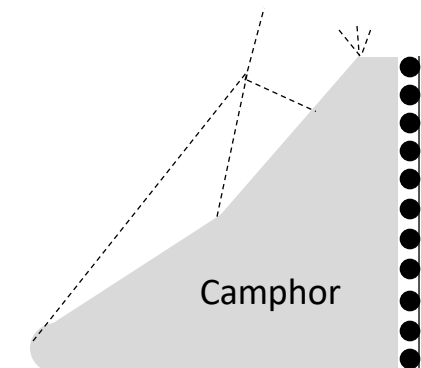
Proposal of Low Temperature Ablation Experiment

- Material – Camphor (sublimation in wide temperature range – up to 453.3 K)
Previous experiments:
 - Baker1972 - sphere-cone 23.9 cm long mounted on sting, ($t=320$ s); Mach 5, $p_0=8$ bar, $T_0=797$ K. $\dot{s}\sim 0.15$ mm/s
 - Turchi2019 - capsule 2.2 mm thick camphor layer, ($t=20+$ s); Mach 6, p_0 : 15:25 bar, T_0 : 487-524 K. $\dot{s}\sim 0.11$ mm/s
- NASA Ames Unitary Plan Wind Tunnel
 - 11x11 ft Transonic tunnel, M: 0.2-1.4; P_0 : 0.2-2.2 bar, T_0 max = 338.7 K
 - 9x7 ft supersonic tunnel, M: 1.55-2.5; P_0 : 0.3-2 bar, T_0 max = 333 K
- Model Shapes
 - Not too sharp, to prevent breaking of the sample
 - Not too simple, since there is quite a good sphere-cone experimental data
 - Possible challenging case: Double wedge with rounded leading edge
- Model preparation
 - Vacuum sintering: Heating and compressing – would require a mold and preparation close to the experiment time or storing at proper conditions to prevent shape change

Camphor phase diagram



Double wedge Camphor sample



Summary



- **Total 12** identified ablation test cases (not all shown here)
- **4 out of 7** test cases that included enough information for simulation were extensively studied, showing good comparison with experimental data in most cases
- Each studied test case can be released to ablation modeling community
- **Proposed test cases for Ablation Workshop 2022**
 - **Graphite sphere-cone (chen2003)** – a warm-up test case. Sensitive to temperature ablation physics
 - **Camphor sphere-cone (Baker1972)/newly performed experiment** – test case for mesh motion validation
 - **FiberForm flat-face cylinder (Price2016)** – challenging boundary conditions and mesh motion, which would require more sophisticated simulation with flow-ablation coupling/multiple CFD simulations
- Still no “perfect” test case for complete validation of TPS material thermal response aspects
 - Well-characterized flow environment
 - Surface temperature
 - In-depth temperature
 - Recession profiles
 - Spectroscopy

Acknowledgments



- My biggest gratitude to all the people who helped, guided and supported me during this internship.
- Special thanks to my mentor Eric Stern, Grant Palmer, Georgios Bellas, Joseph Schultz, Brody Bessire, Justin Haskins, Khalil Bensassi, Olivia Schroeder and many others!



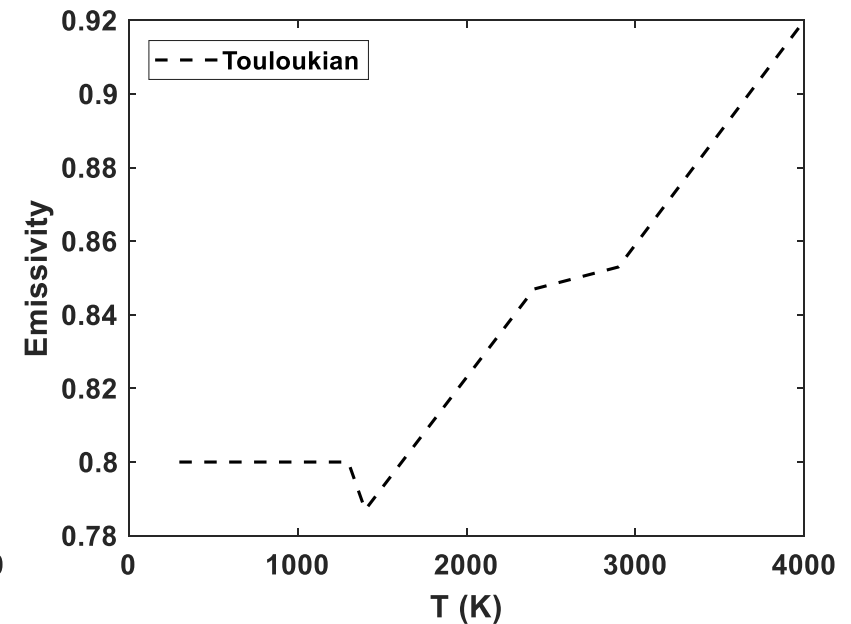
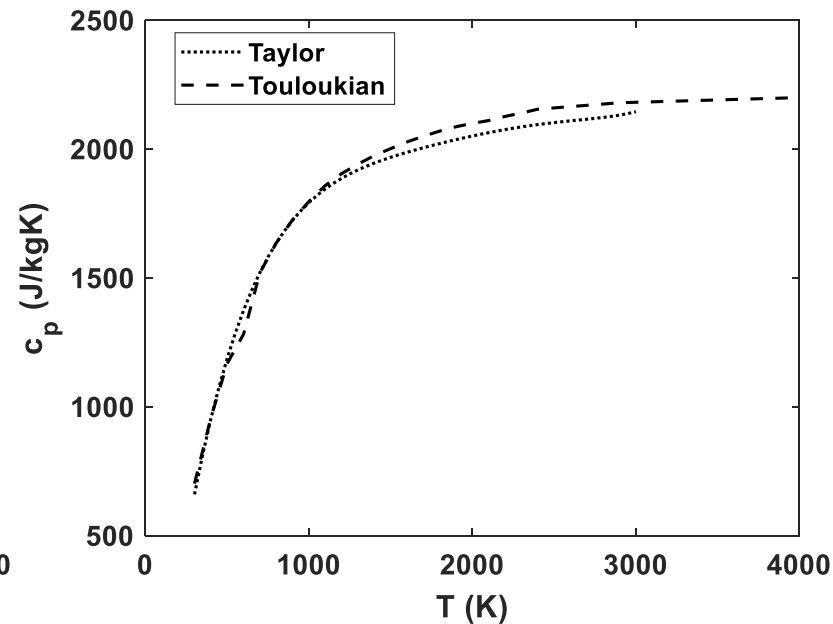
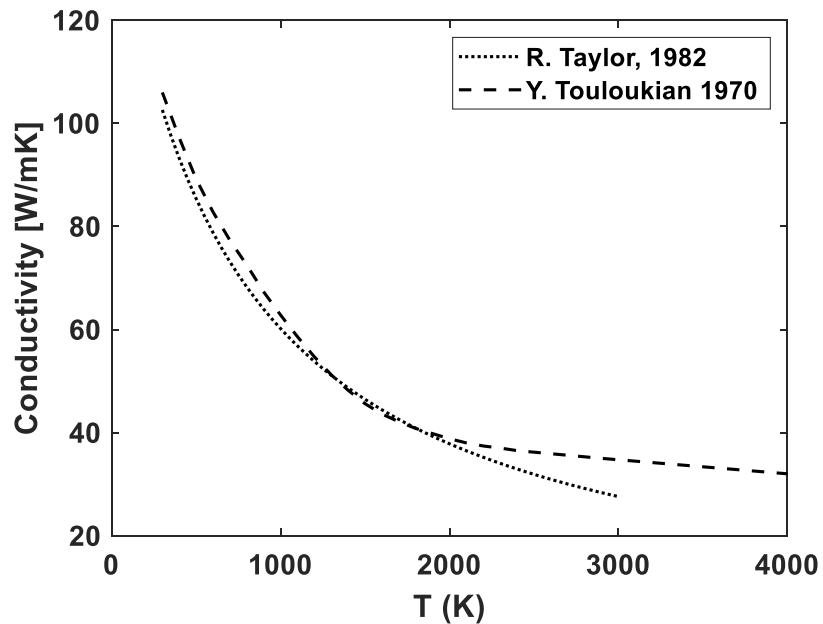
Thanks!

Questions?

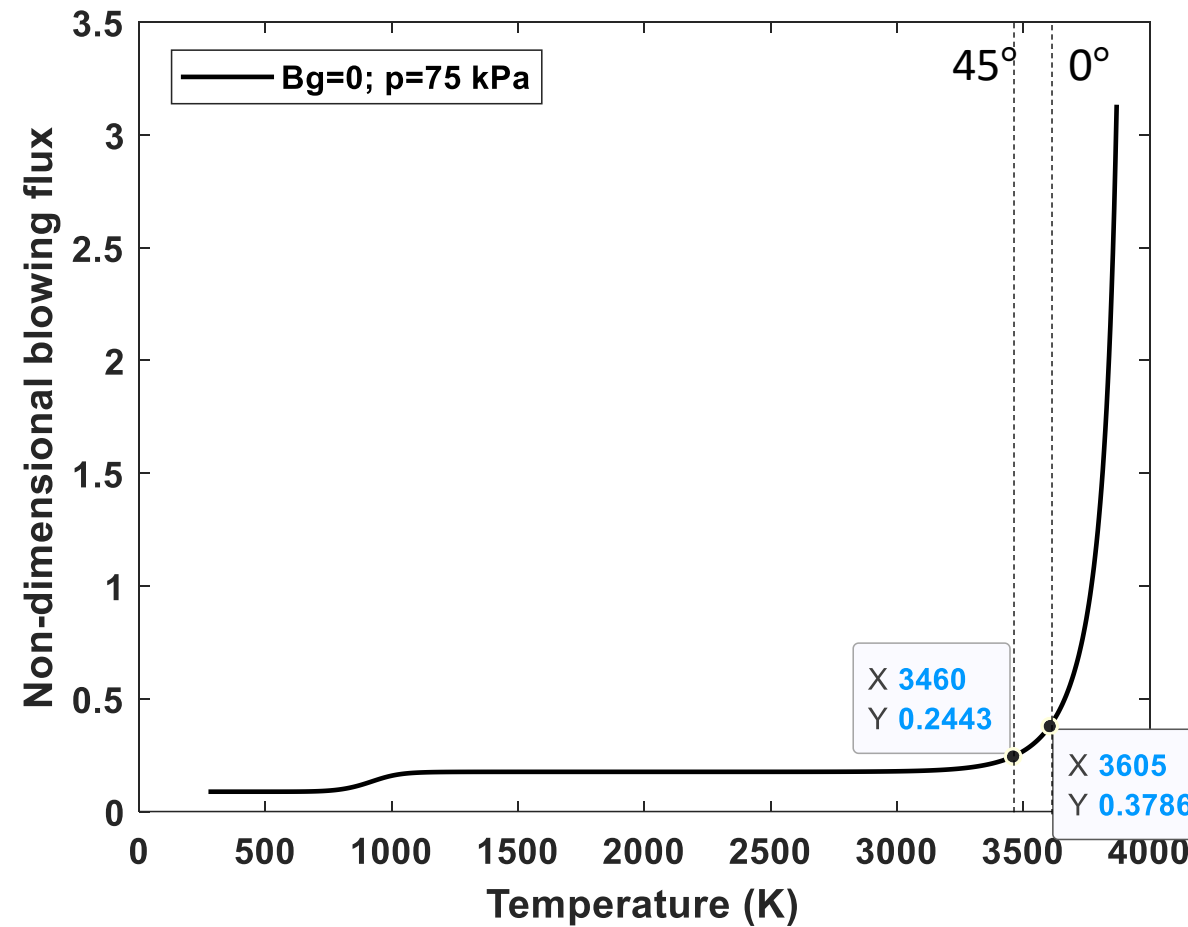
Graphite Properties



- Thermal properties obtained from Touloukian1970 and Taylor1982
- Taylor1982 has shorter temperature range for conductivity and specific heat, unsuitable for high heat flux simulation



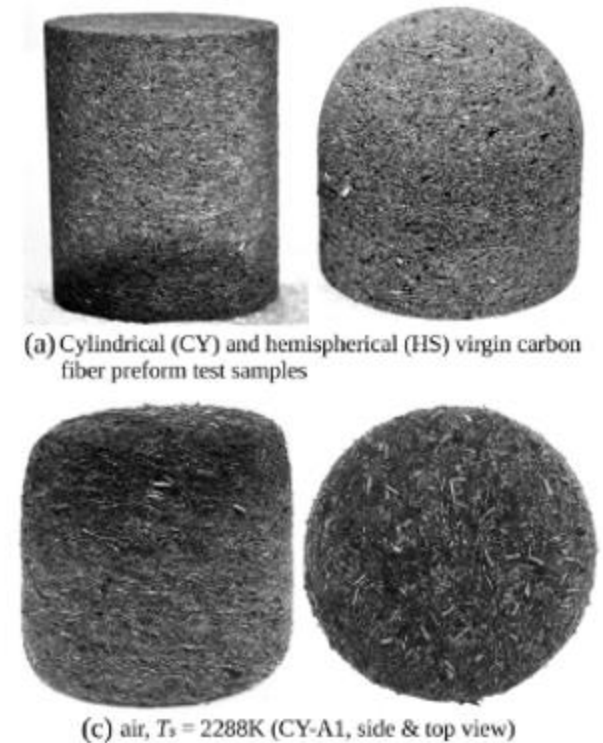
Graphite Bprime Curve



Test Cases



- FiberForm – porous low-density carbon material, made up of fibers that are about $15\ \mu\text{m}$ in diameter and 1.6 mm in length
- Used as a precursor for PICA TPS material
- Several experimental campaigns
 - D. Driver, D. Olson, M. Barnhardt, M. MacLean, 2010. Understanding high recession rates of carbon ablators seen in shear tests in an arc jet
 - B. Helber, O. Chazot, A. Hubin, T. Magin 2015. Microstructure and gas-surface interaction studies of a low-density carbon-bonded carbon fiber composite in atmospheric entry plasmas
 - K. Price, J. Hardy, C. Borchetta, S. Bailey and A. Martin. 2020. Analysis of spallation products using arc-jet experiments
 - B. Bessire, HyMETs campaign. Studying Ablation of FiberForm and FiberForm – N in air, N_2 and CO_2 environments



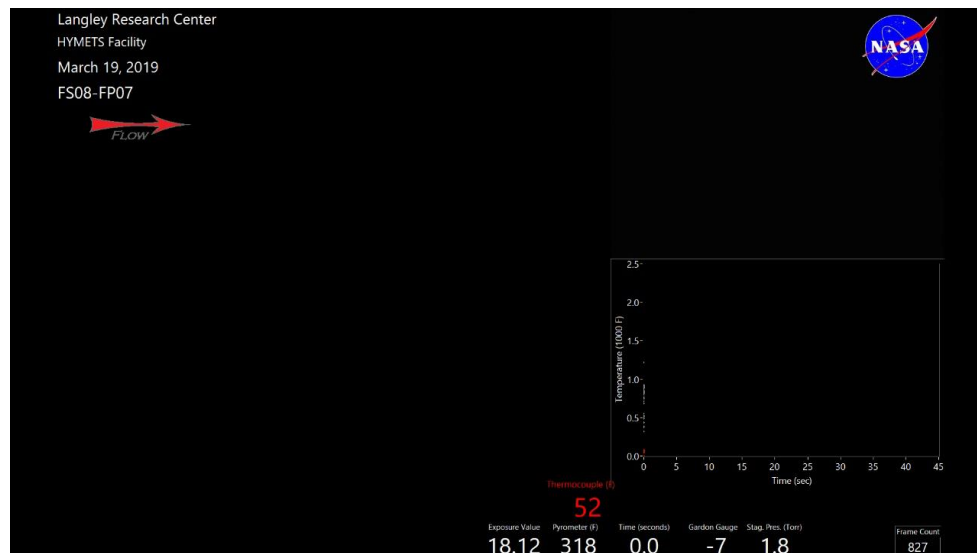
Helber2015. Pre- and post photographs of carbon preform (similar to FiberForm) tested in VKI

Brody2019 - HyMETs - FS08

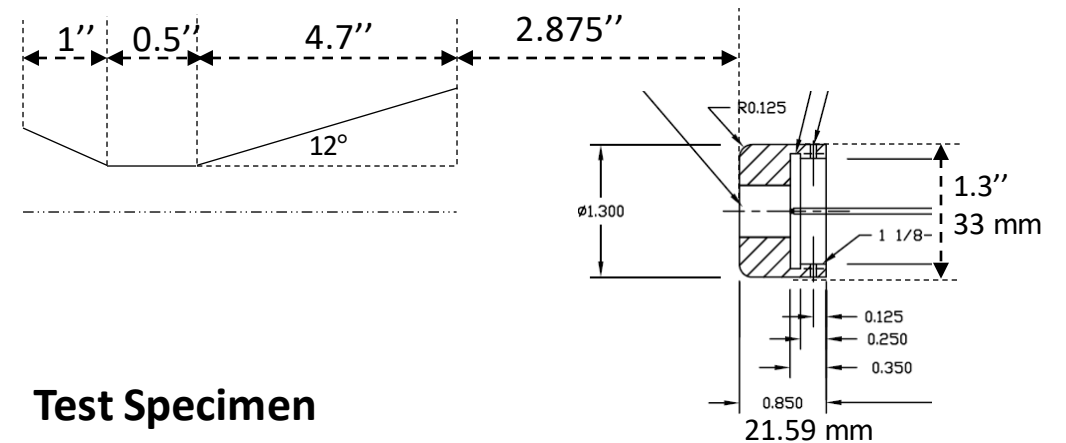
Capsule Shape - Duration 7.7 sec



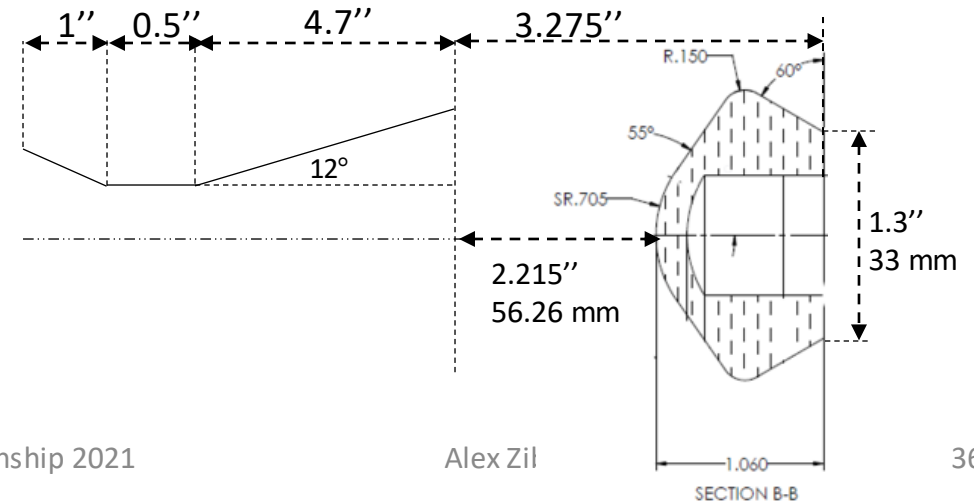
Exposure of the test specimen



Slug calorimeter

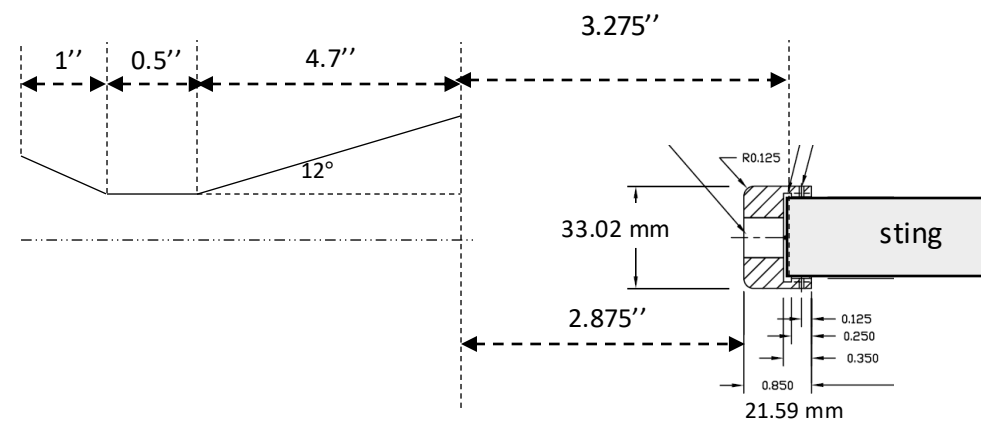


Test Specimen



- Simulation parameters

HyMETS – Run19	
$\dot{q}_{\text{slug}}$ (W/cm ²)	171
P_{stag} (kPa)	6.266
H_{stag} (MJ/kg)	12.47
T_{wall} (K)	400
Nozzle inlet conditions	
T (K)	5447
U (m/s)	359.6
ρ (kg/m ³)	0.069
Y_{N_2} (kg/m ³)	0.674824
Y_{O_2} (kg/m ³)	0.001242
Y_{NO} (kg/m ³)	0.017079
Y_N (kg/m ³)	0.033804
Y_O (kg/m ³)	0.207025
ρ_{Ar} (kg/m ³)	0.066026

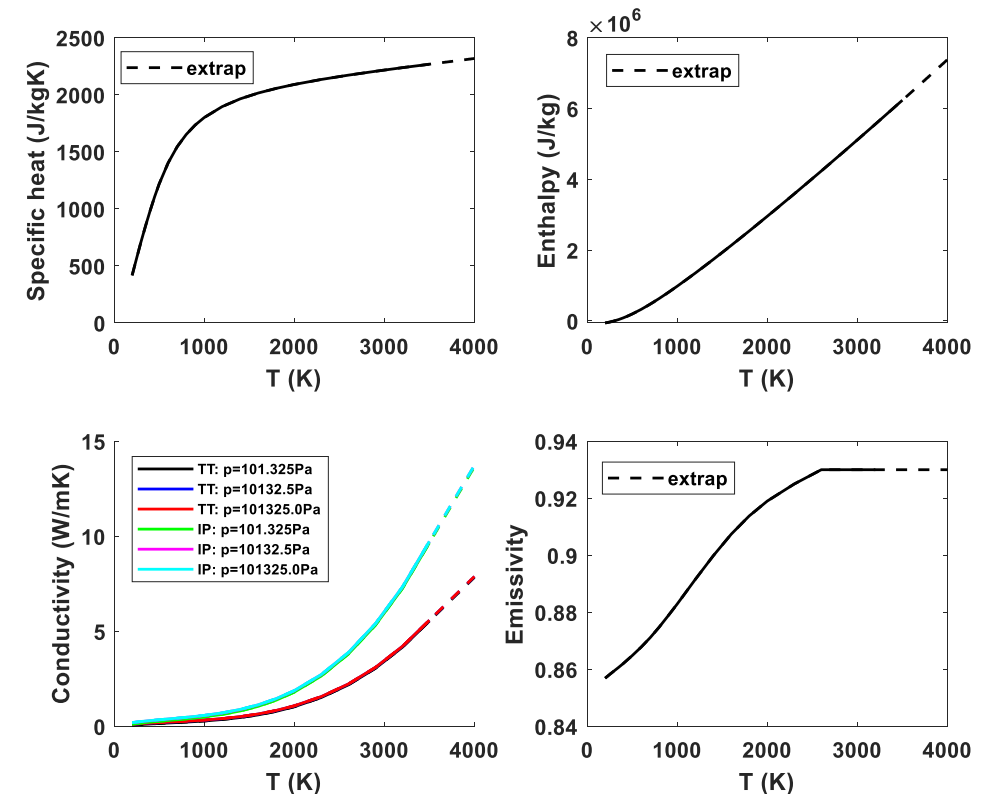


Material Simulation Conditions



- FiberForm properties from F. Panerai
- In simulation, use of isotropic conductivity (through-thickness)
- Ablation physics: Bprime for Graphite in air, generated with Mutation++

Fiber Form properties - F. Panerai



FiberForm Flat Face Cylinder - HyMETS – Run19 - Price2016

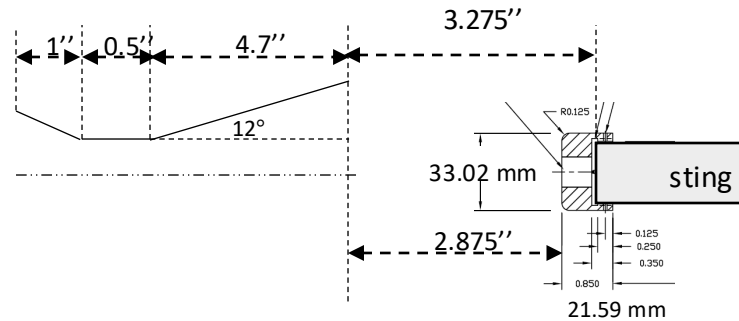
Flow Simulation Conditions



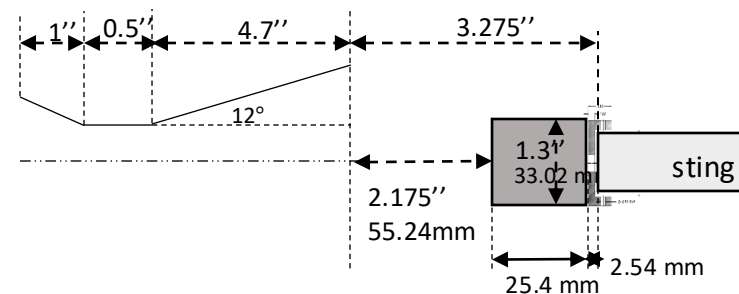
- Smoothing of initial heat flux profile
- Linear interpolation between two heat flux profiles over 2 s time

HyMETS – Run19	
$\dot{q}_{\text{slug}}$ (W/cm ²)	171
P_{stag} (kPa)	6.266
H_{stag} (MJ/kg)	12.47
T_{wall} (K)	400
Nozzle inlet conditions	
T (K)	5447
U (m/s)	359.6
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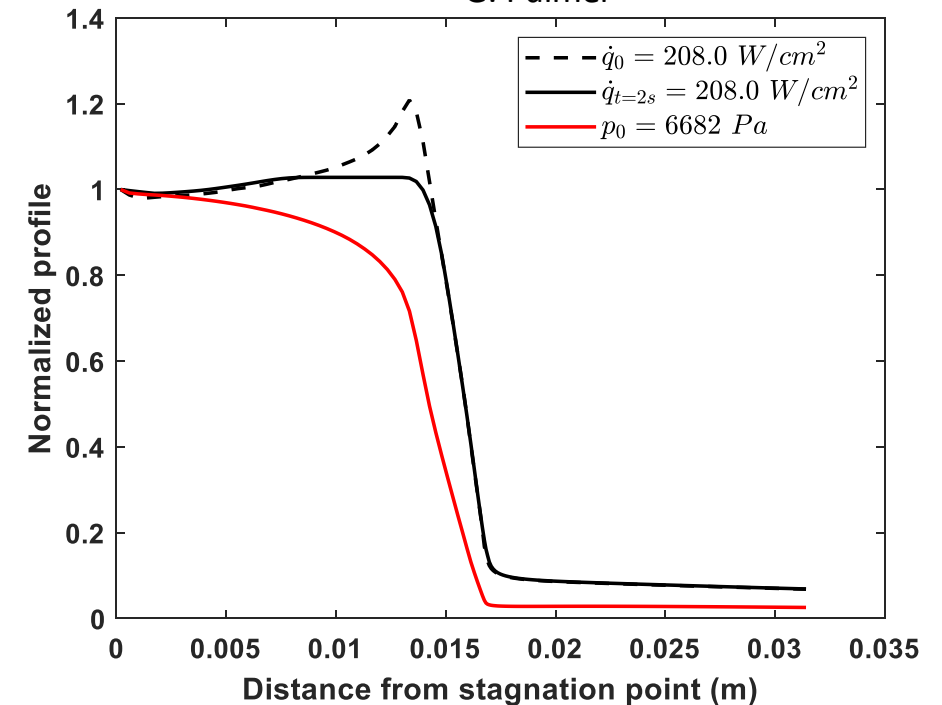
Slug calorimeter



Test specimen



Boundary Conditions – DPLR Fully-Catalytic Wall
G. Palmer



Material Response Simulation

Exposure time 320 s; Simulation duration 80 s



- Constant solid properties
- Gas properties evaluated with molecular dynamic simulation (J. Haskins) and added in NASA-7 format to Mutation++
- Ablation physics:
 - Bprime curves obtained from the work of Bianchi2019
 - Mixture enthalpy at the wall obtained using relation: $Y_w = \frac{B'_c}{1+B'_c}$ and mixture rule: $h_w = (1 - Y_w)h_{air} + Y_w h_c$

Camphor properties	
M_w (g/mol)	152.23
ρ_s (kg/m ³)	990
$c_{p,s}$ (J/kg-K)	1781
k (W/m ² -K)	0.2
ϵ	0.88
T_{melt} (K)	453.3
P_{triple} (bar)	0.514
$\Delta h_{f,s}$ (MJ/kg)	-2.1
$\Delta h_{f,g}$ (MJ/kg)	-1.756

