Thickness and Fuel Preheating Effects on Material Flammability in Microgravity from the BASS Experiment

Paul V. Ferkul, National Center for Space Exploration Research

Sandra L. Olson, NASA Glenn Research Center

Fumiaki Takahashi, National Center for Space Exploration Research

Makoto Endo, Case Western Reserve University

Michael C. Johnston, Case Western Reserve University

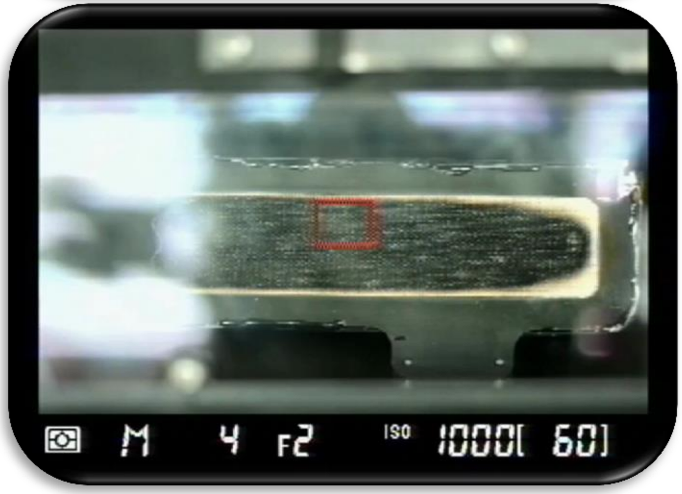
James S. T’ien, Case Western Reserve University

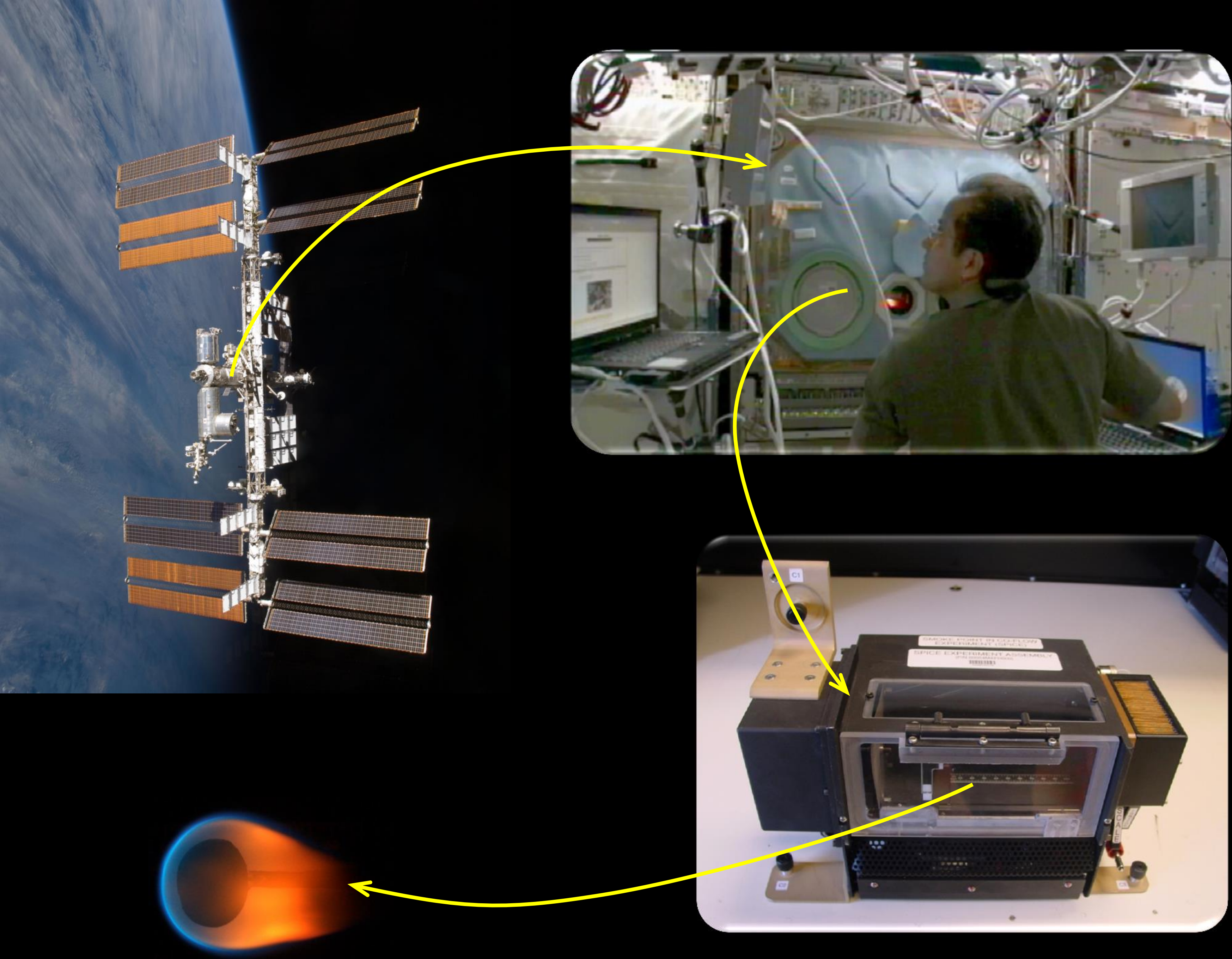
This work was supported by the NASA Space Life and Physical Sciences Research and Applications Division (SLPSRA).

Presented at the American Society for Gravitational and Space Research 2013 Annual Meeting
Orlando, Florida

Approach:

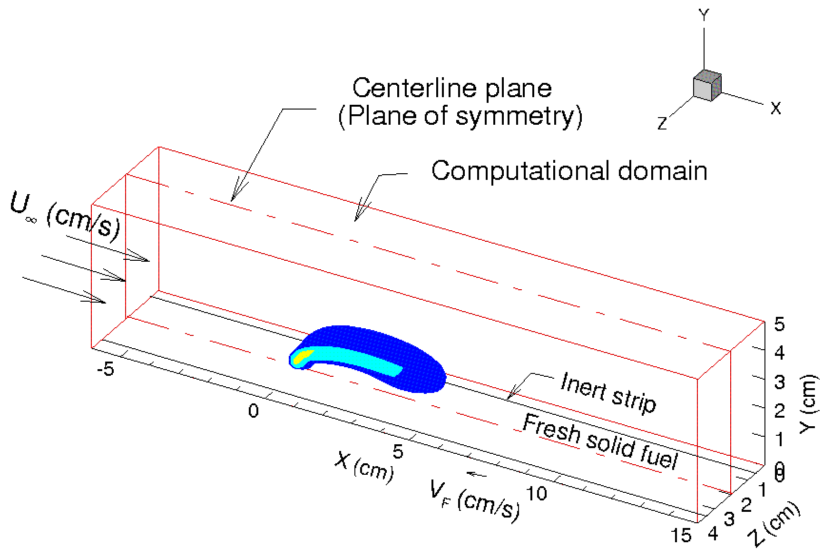
- Microgravity combustion tests were performed aboard the International Space Station using the BASS (Burning and Suppression of Solids) hardware.
- The wind tunnel was installed in the Microgravity Science Glovebox which supplied power, imaging, and a level of containment.
- Fuel samples were mounted inside a small wind tunnel which could impose airflow speeds up to 40 cm/s.
- The effects of airflow speed on flame appearance, flame growth, and extinction were determined in both the opposed and concurrent flow.
- Ambient oxygen atmospheres 17% to 21.5% (cabin air).

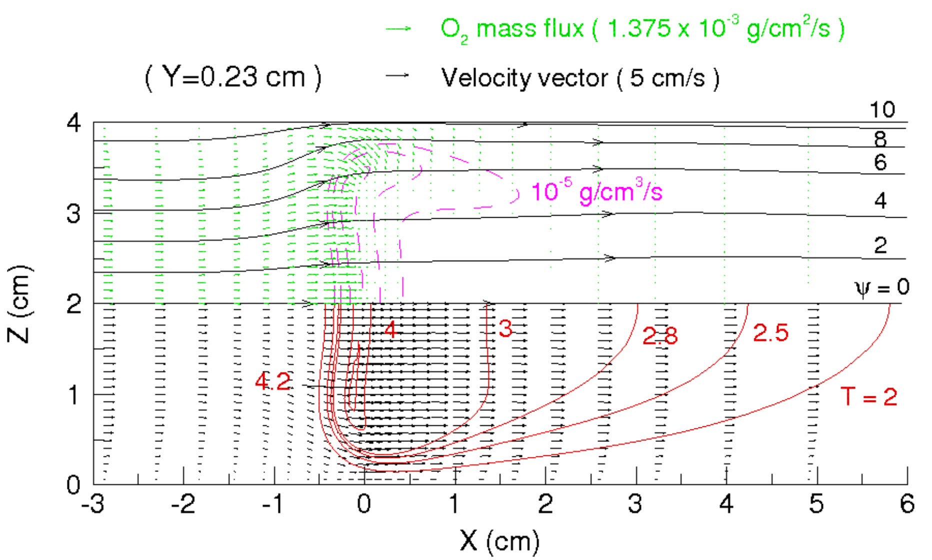



C1
SMOKE POINT IN CO-FLOW
EXPERIMENT (SPICE)
SPICE EXPERIMENT ASSEMBLY

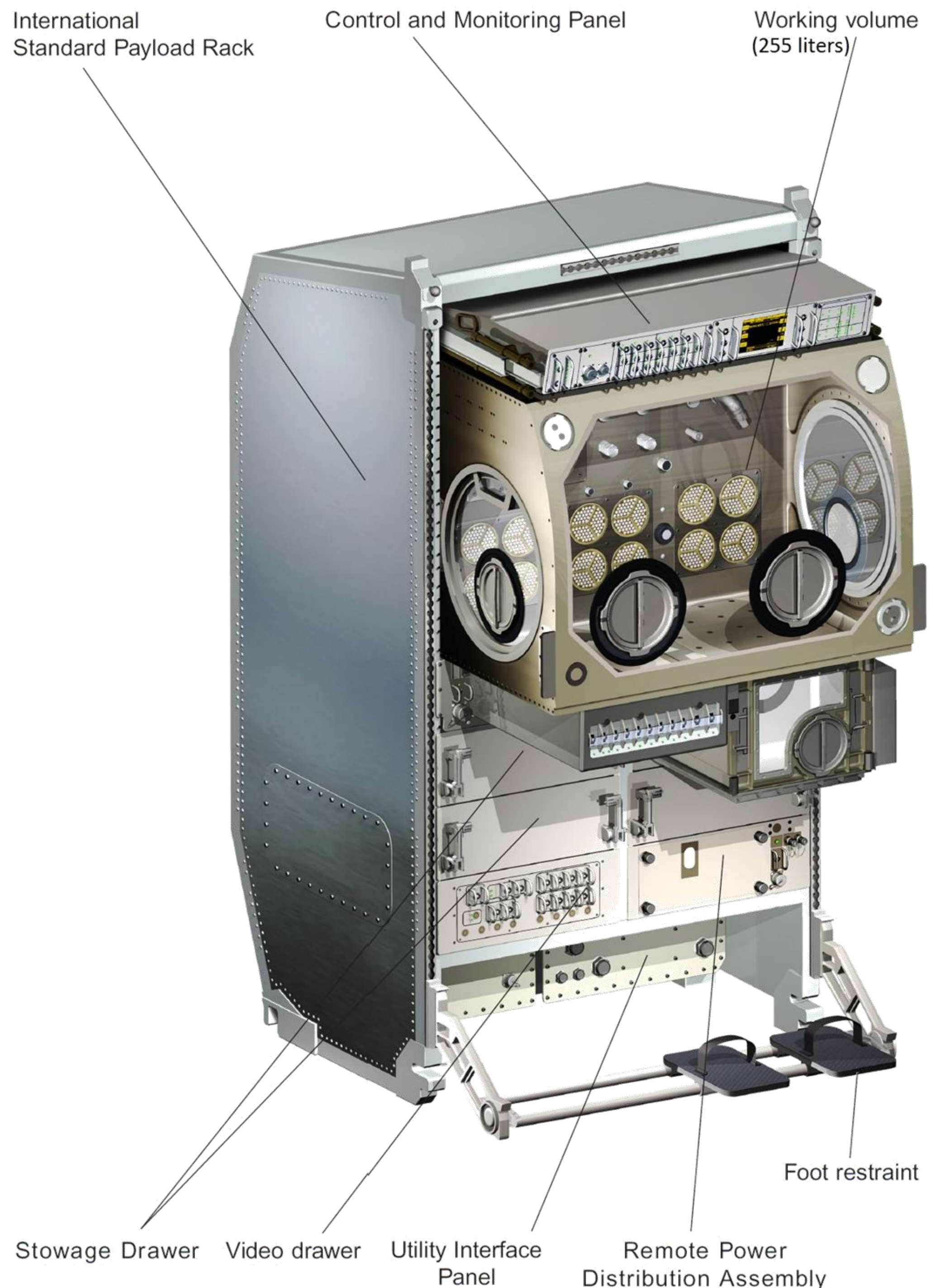
Science Applications:

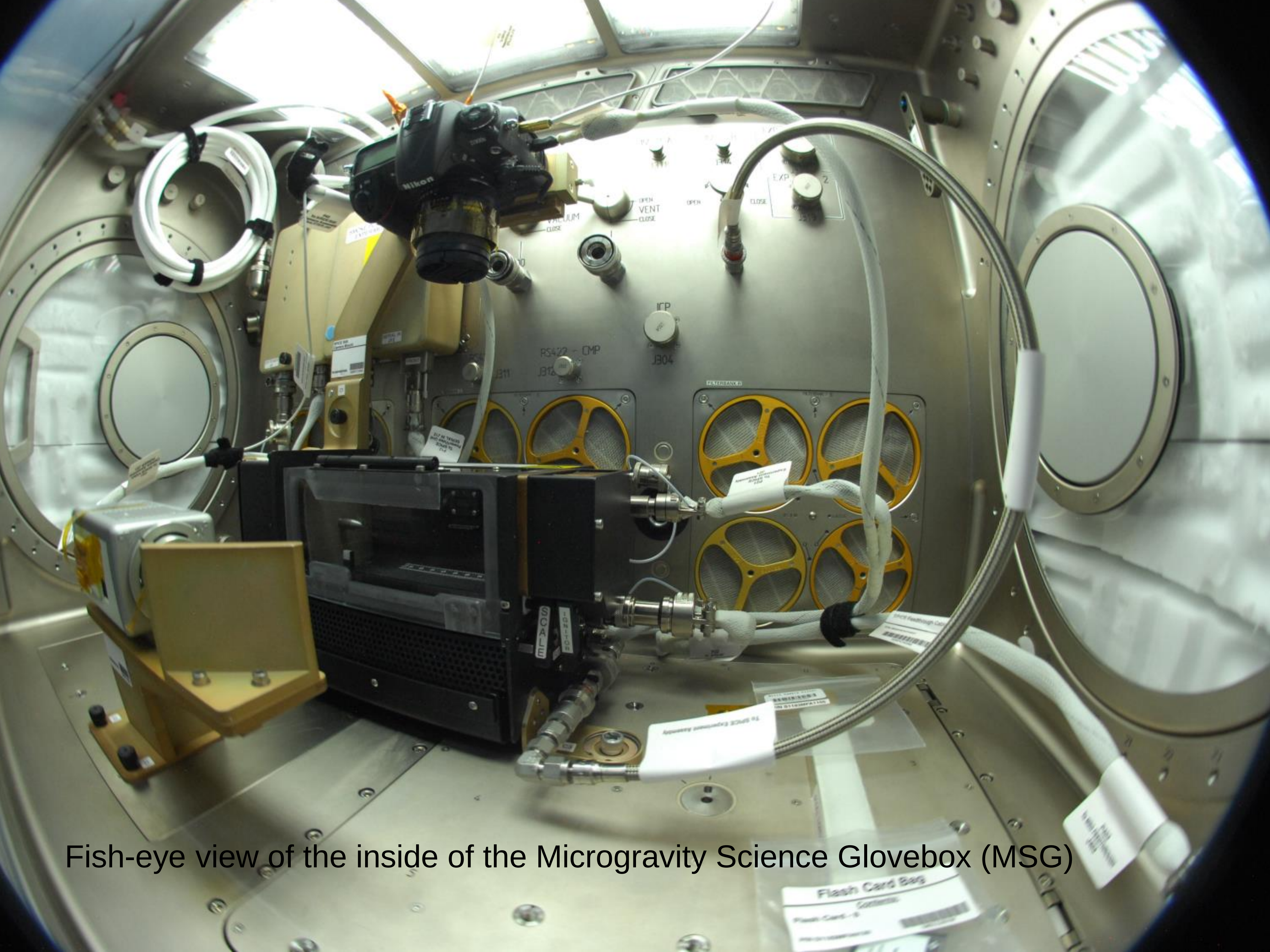
- Understanding of long-duration microgravity solid material burning and extinction
- Improved strategies for NASA spacecraft materials selection; link actual burn behavior in microgravity to Earth-based selection methods
- Improved combustion computational models used in the design of fire detection and suppression systems in microgravity and on Earth
- Validated detailed combustion models in the simpler flow environment of microgravity build more complex combustion models needed to capture the important details of flames burning in normal gravity; models have wide applicability to the general understanding of many terrestrial combustion problems.





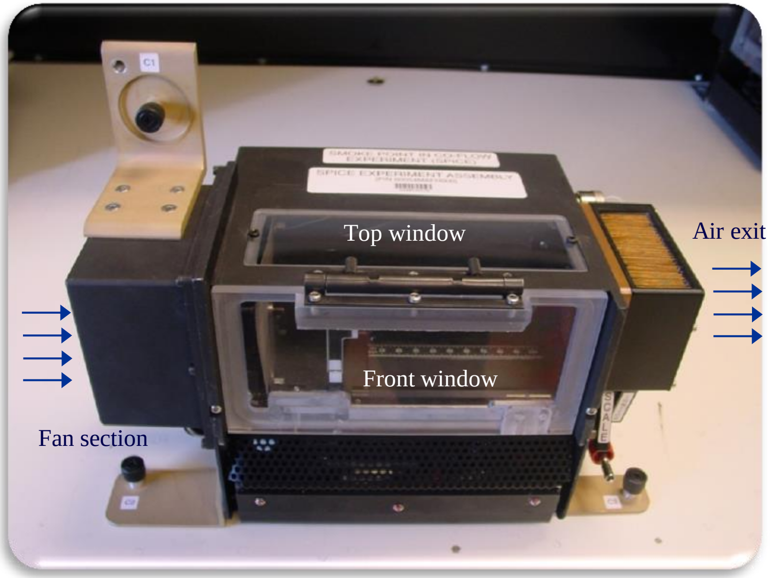
Microgravity Science Glovebox (MSG)



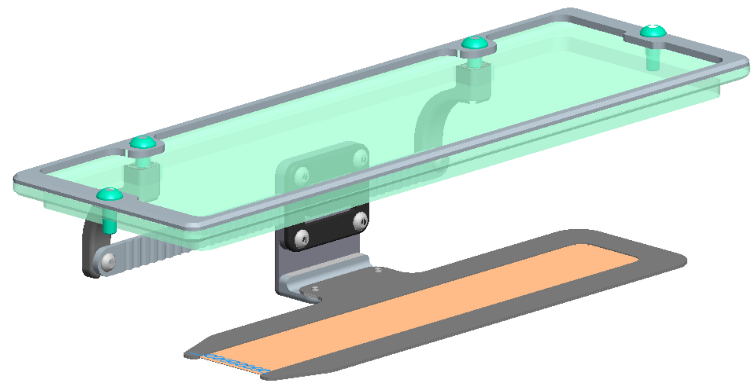


Fish-eye view of the inside of the Microgravity Science Glovebox (MSG)

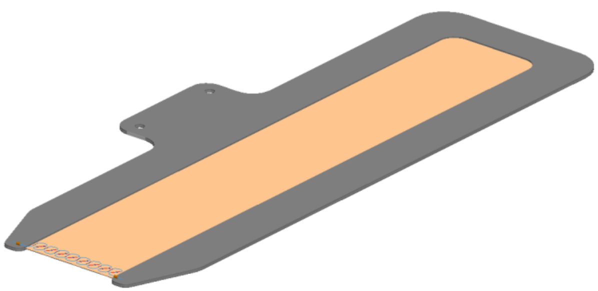
Hardware Details



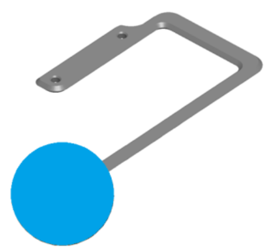
Top window



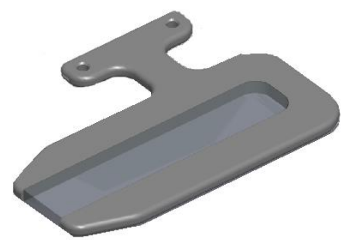
Permits variety of solid samples to be mounted, ignited, and burned:



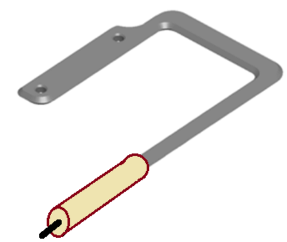
Thin, flat (17)



Spheres (12)



Thick, flat (4)

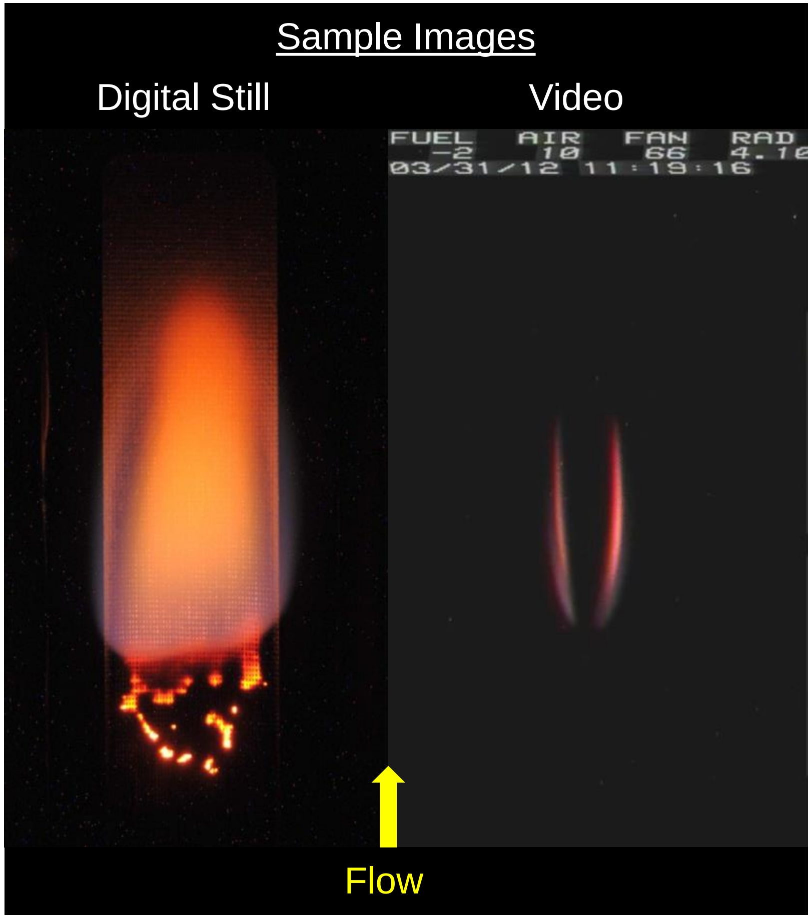


Candles (8)

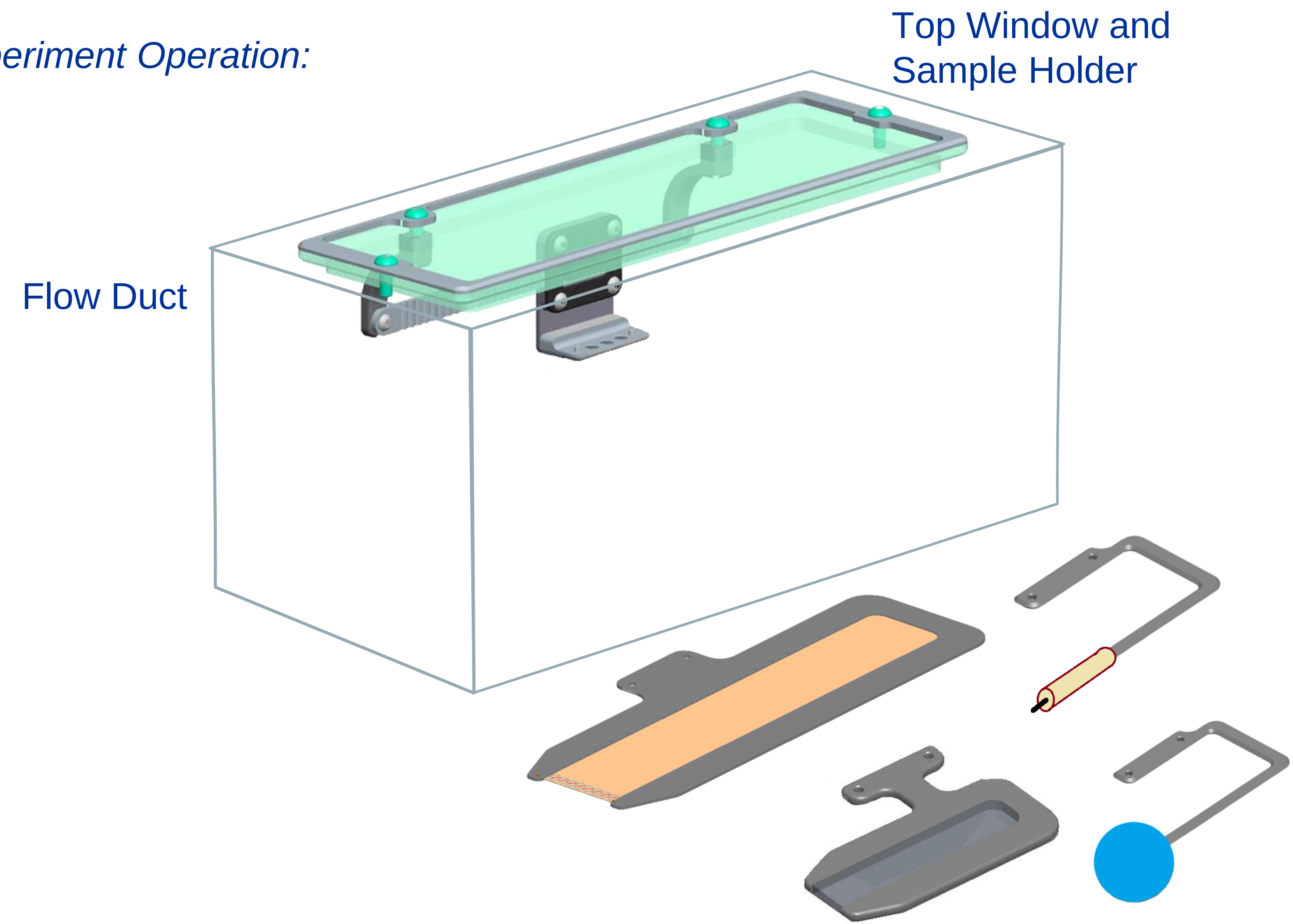
(Note: samples are not to scale; samples can be flipped 180 degrees if desired)

Hardware Summary:

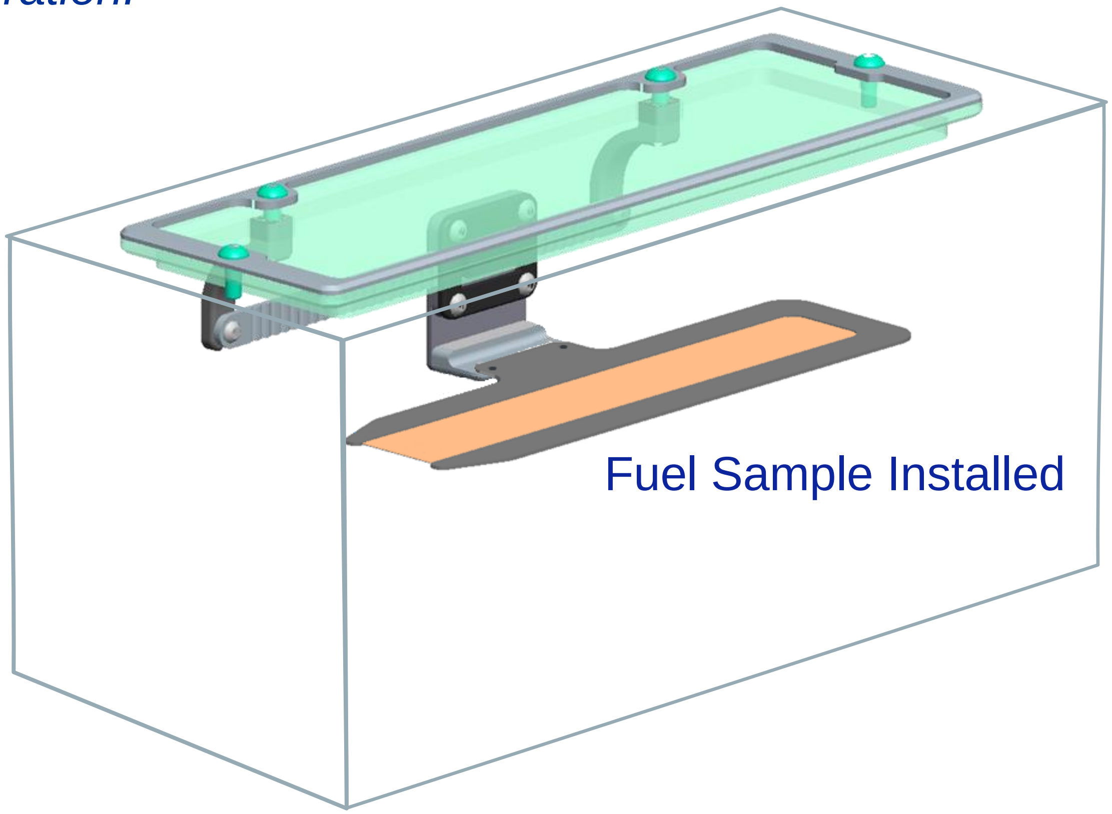
- BASS utilized the on-orbit SPICE hardware; minor modifications were made to burn solid samples
- Small flow tunnel
- Solid samples were installed, ignited, extinguished, and recorded
- Video and digital still camera provided bulk of the data. Flame appearance, behavior, spread rate, and extinction dynamics were measured
- Airflow speed was the main variable
- 41 samples, 115 burns completed



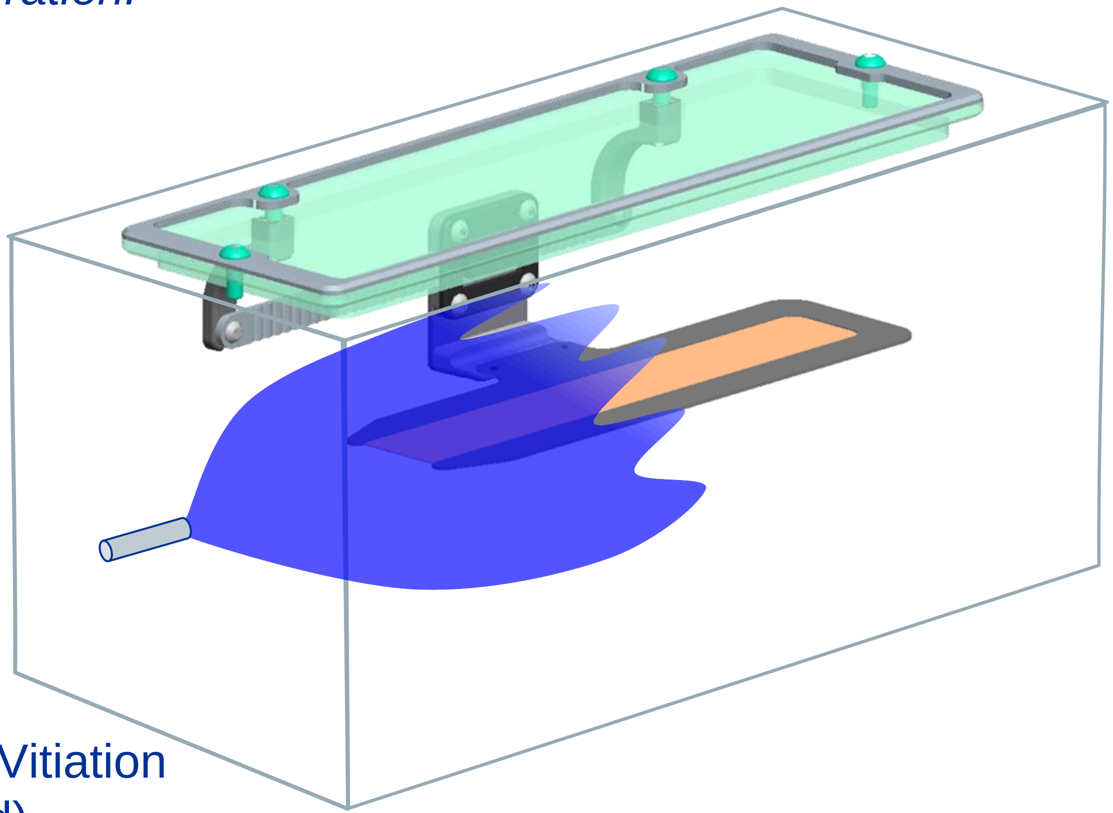
Experiment Operation:



Experiment Operation:

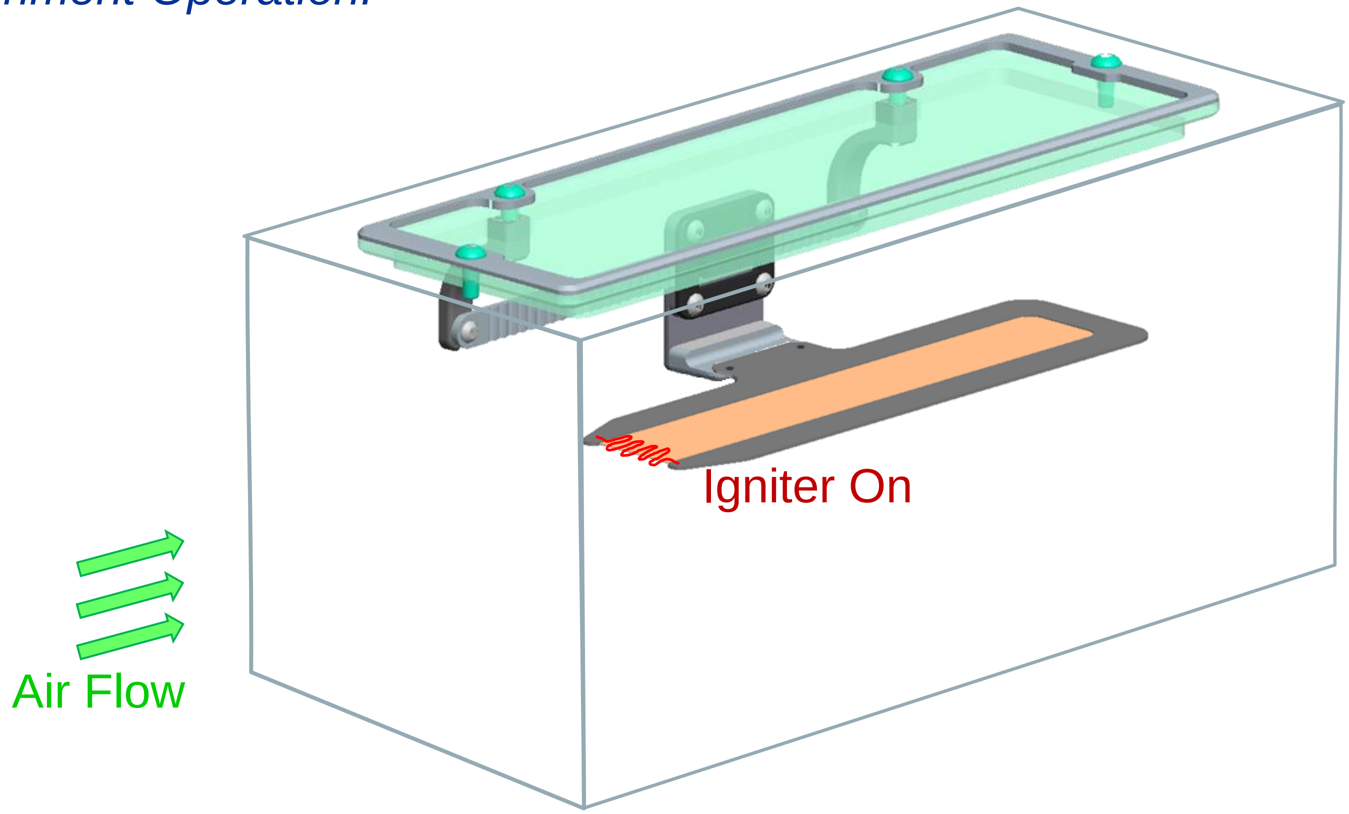


Experiment Operation:

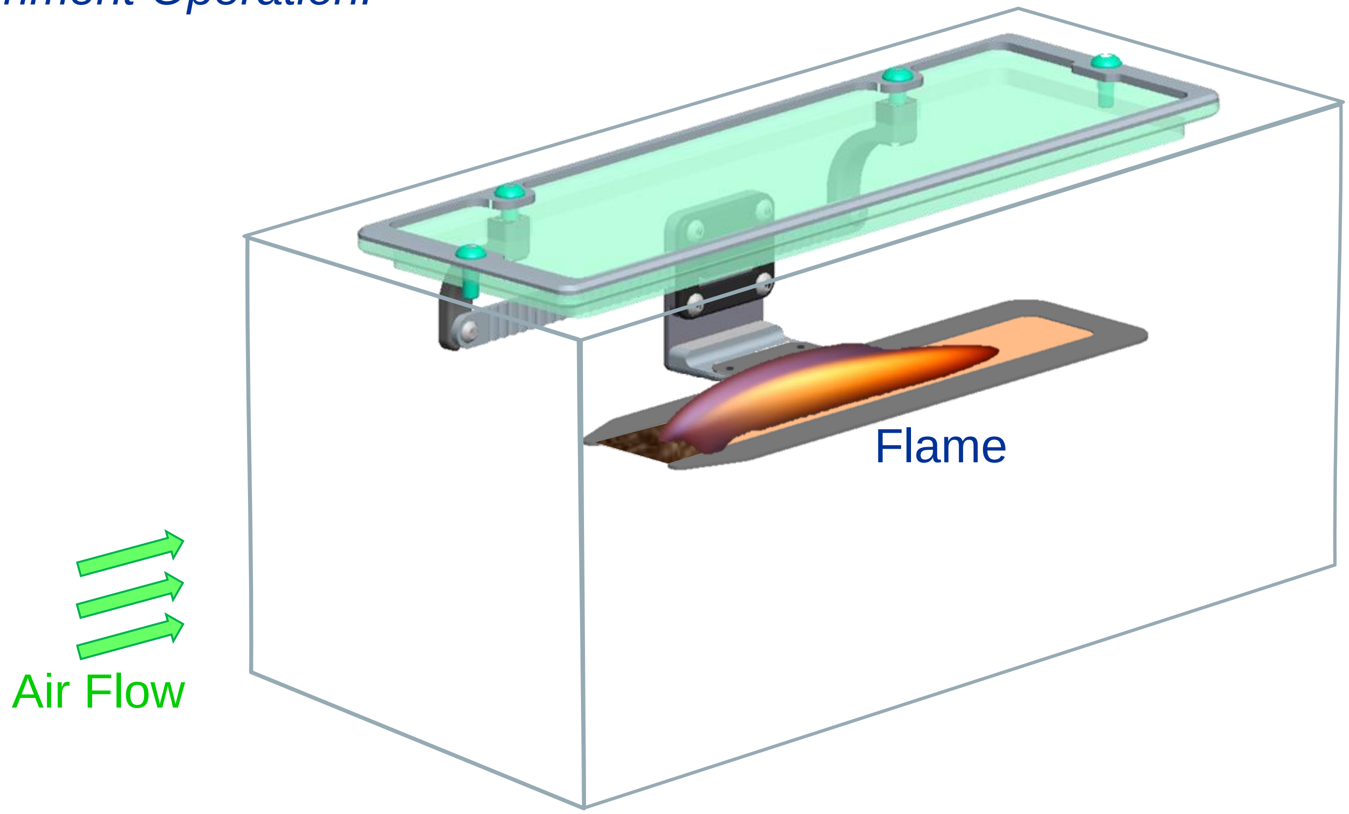


Nitrogen Vitiation
(if desired)
Down to 16% O_2

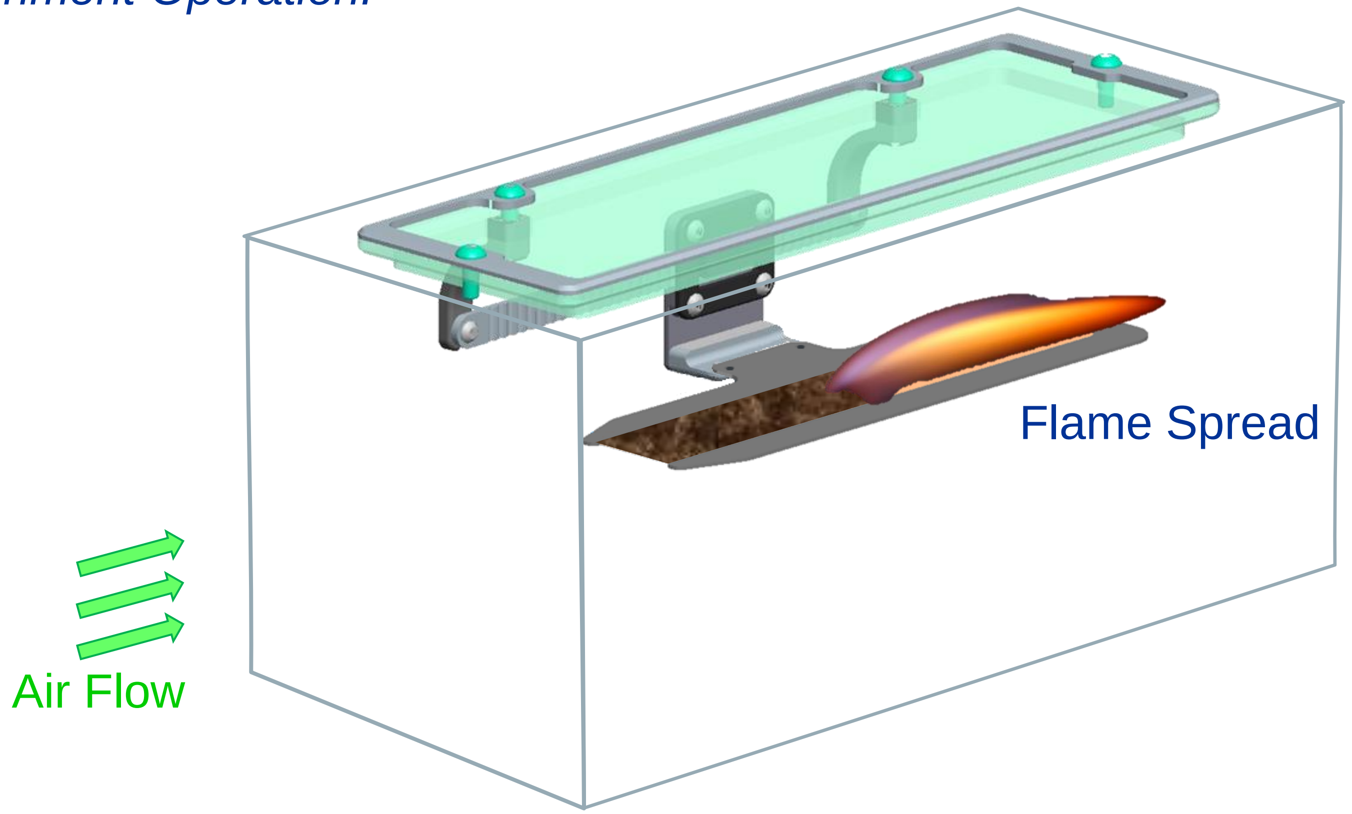
Experiment Operation:



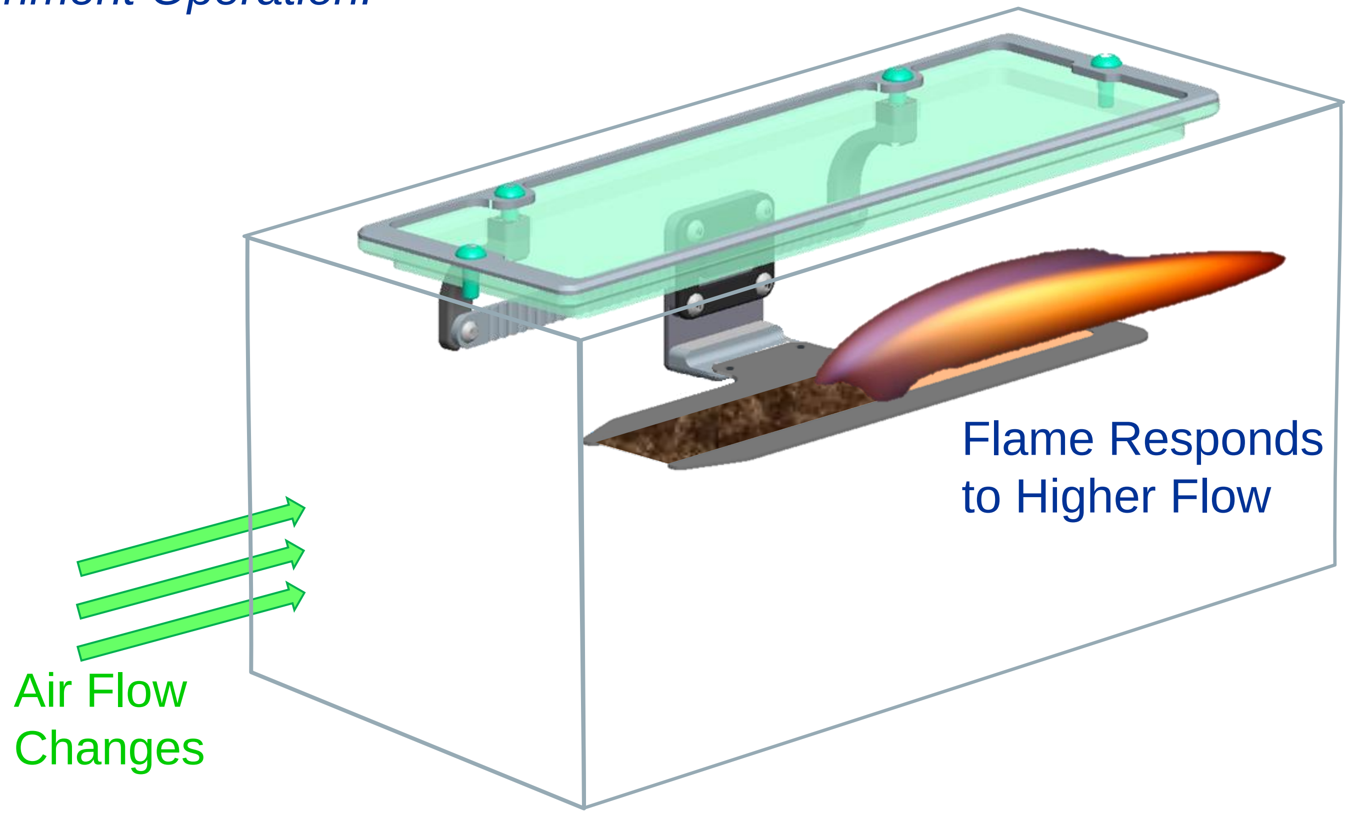
Experiment Operation:



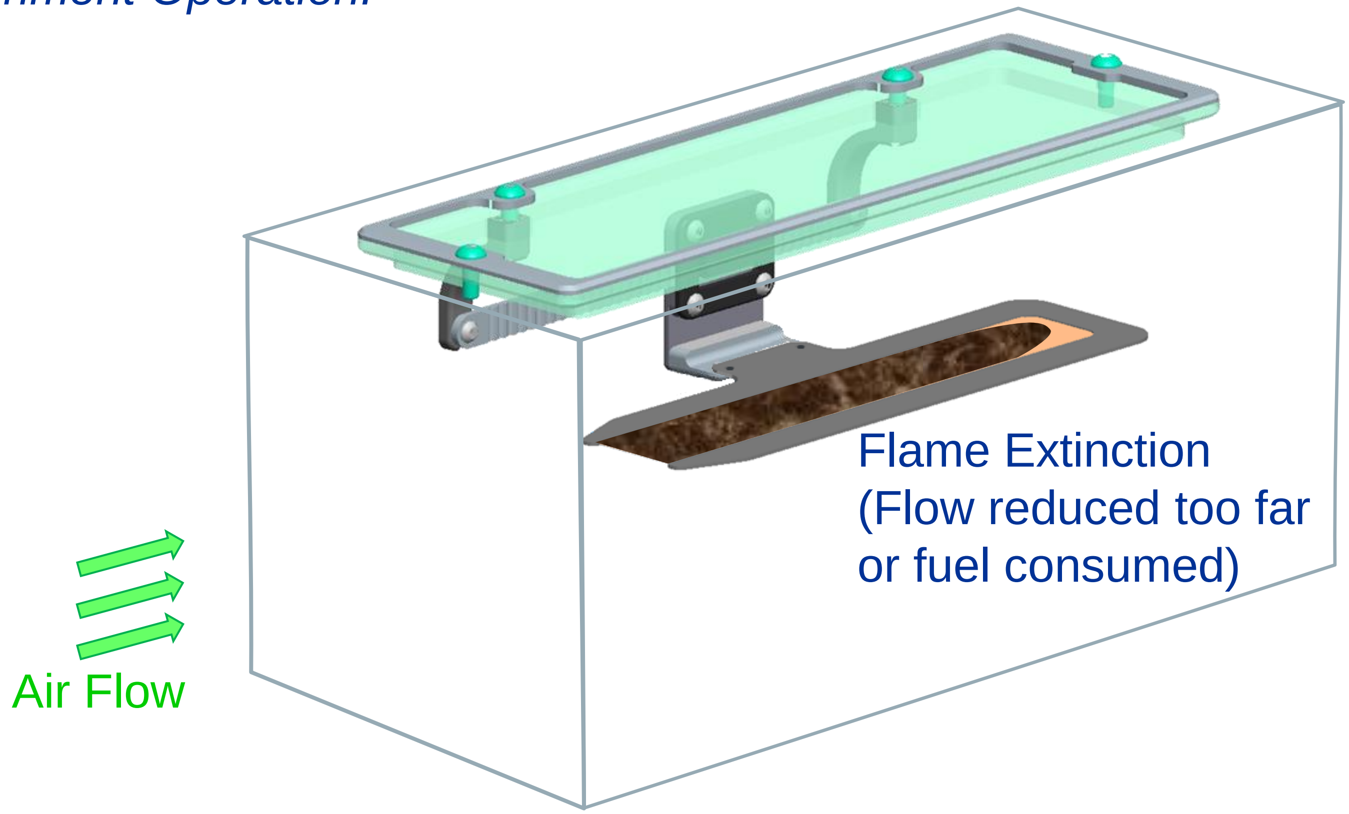
Experiment Operation:



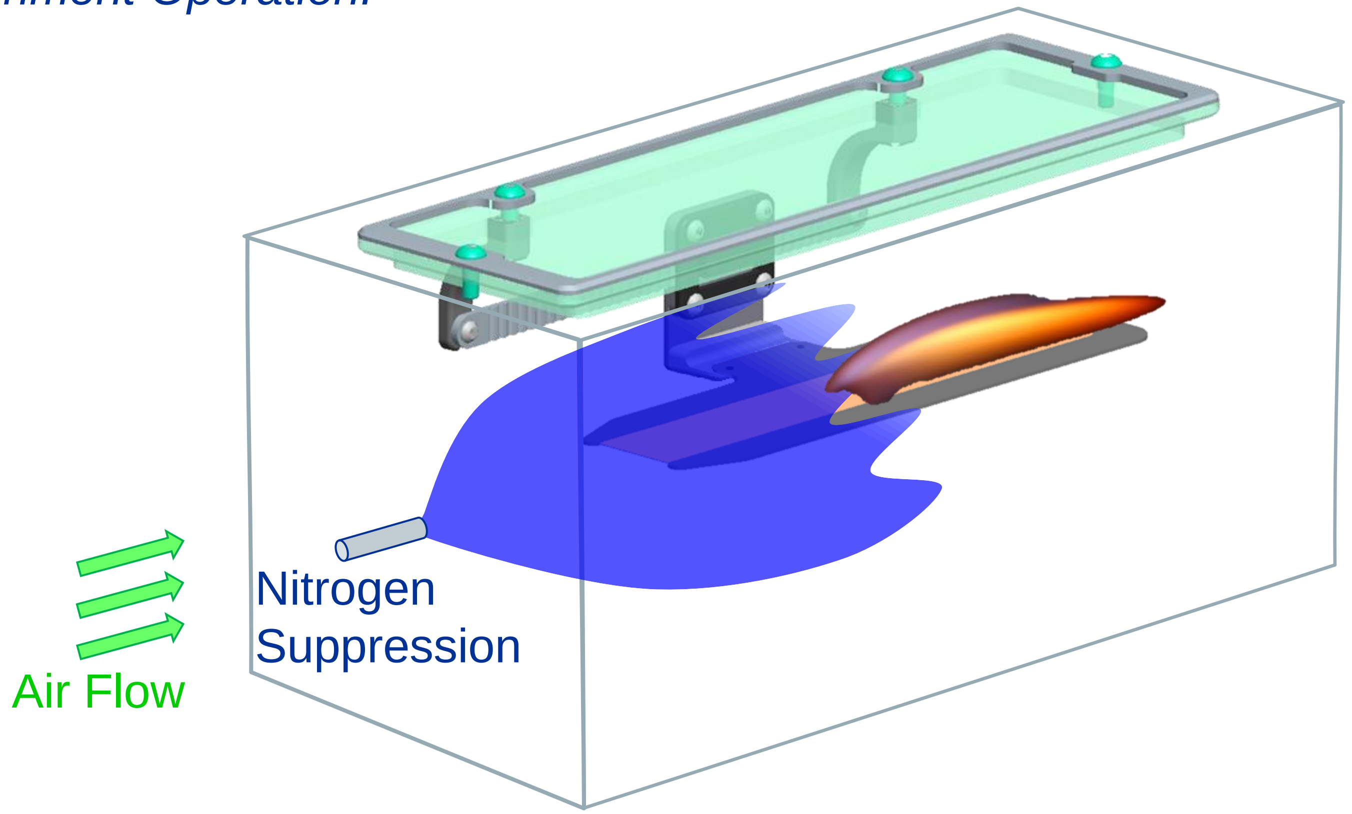
Experiment Operation:



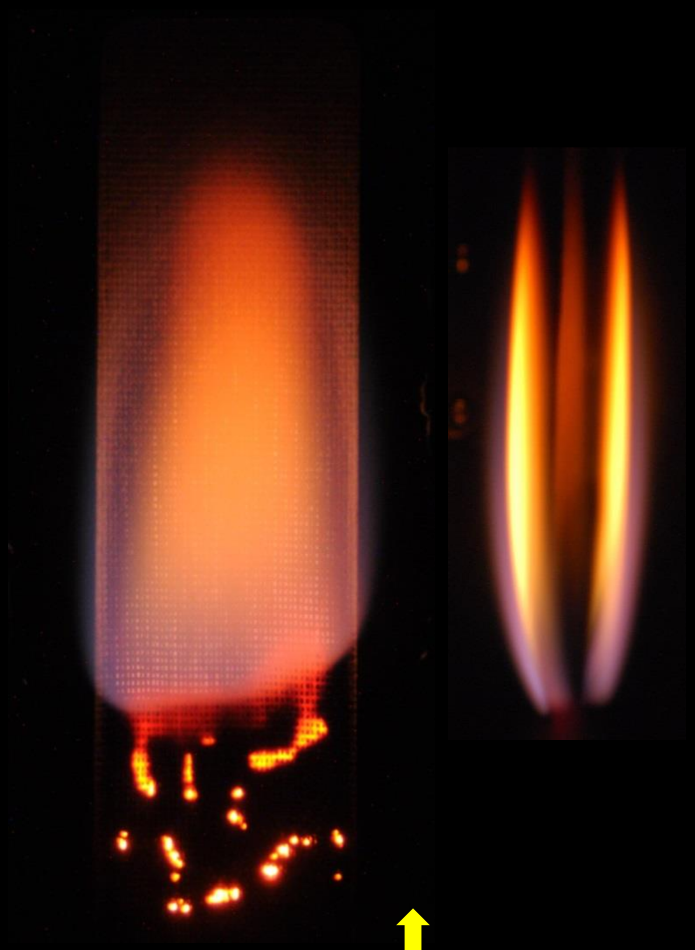
Experiment Operation:



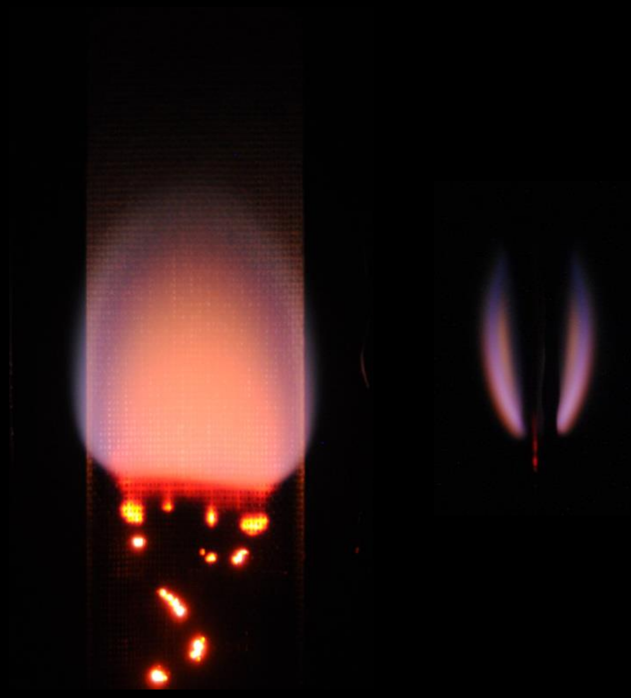
Experiment Operation:



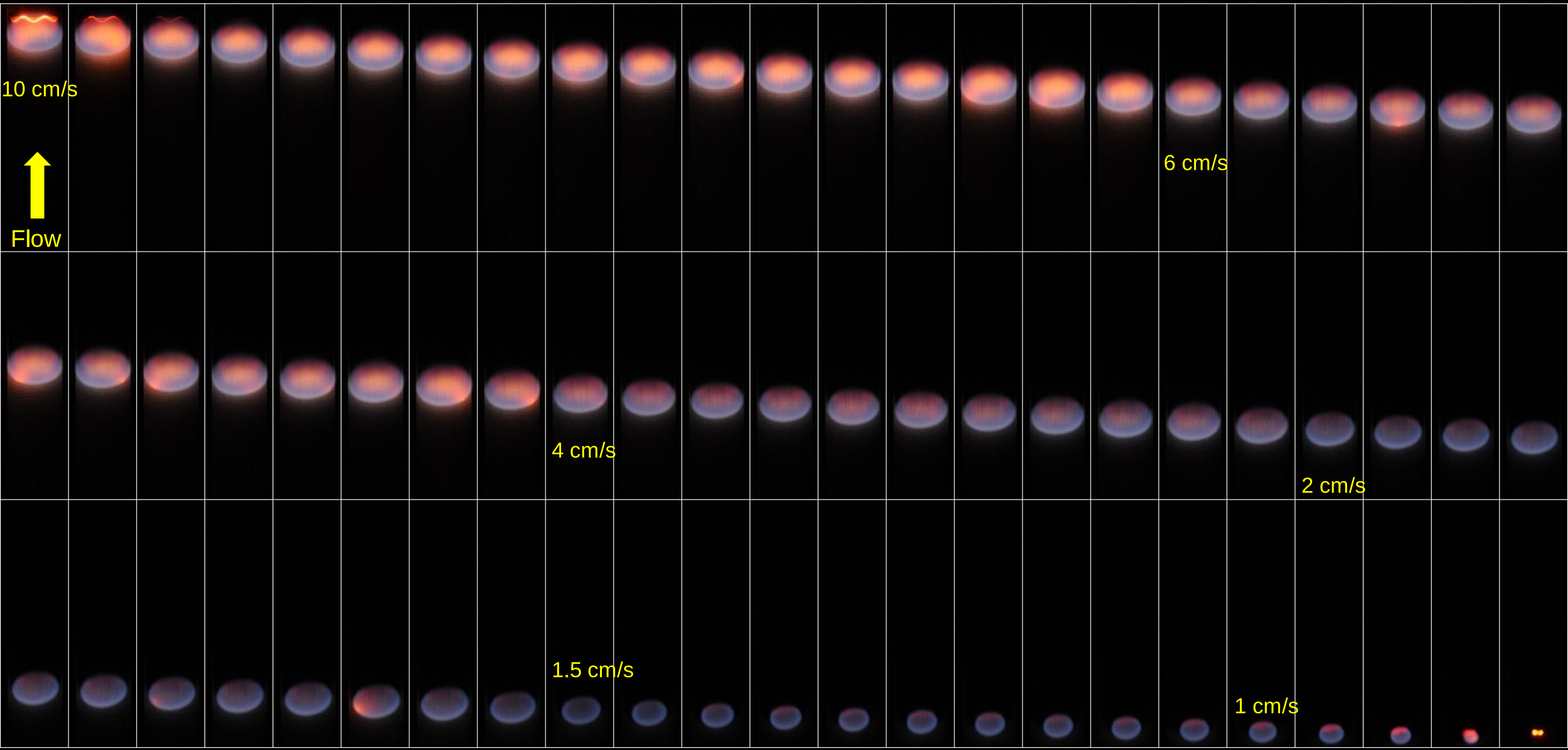
1. Thin Fuel (Cotton / fiberglass fabric) – Review



10 cm/s Flow

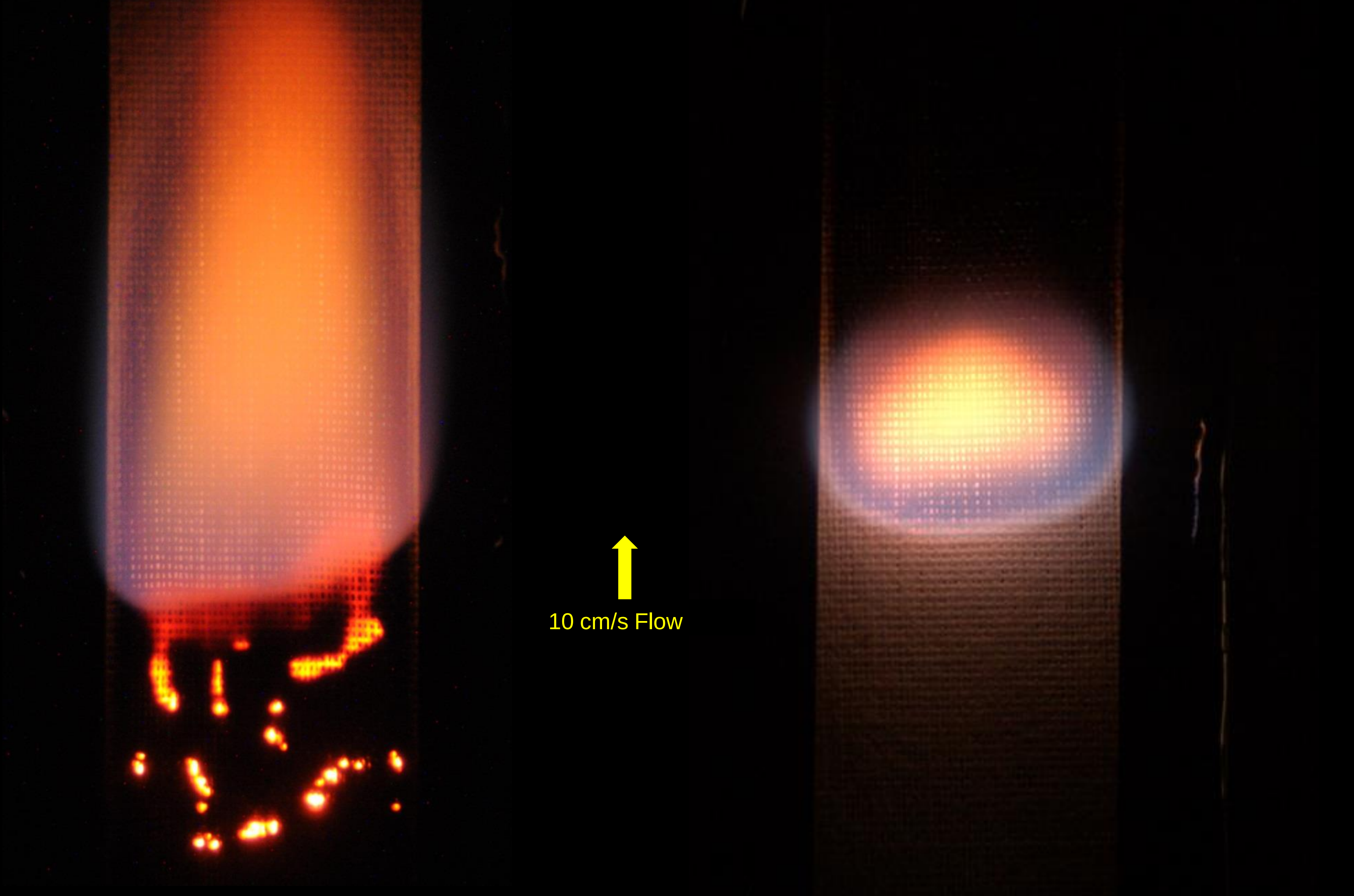


5 cm/s Flow

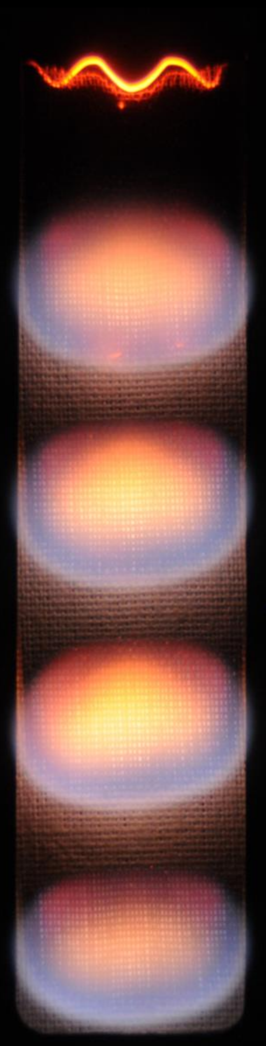


Digital still camera images showing a flame burning a 2-cm wide cotton-fiberglass fabric in opposed flow. Images are taken every 1.25 sec (starting at top and moving from left to right). The flow is decreased in discrete steps from 10 cm/s all the way down to about 1 cm/s. The flame response to flow changes is very rapid, and the flow effects on the flame and its spread rate are dramatic. Total burn time is 90 sec. Flow changes are indicated by numbers.

Concurrent and Opposed Spread at ~ 10 cm/s
2.55 mm/s versus 1.21 mm/s



Comparison of 0-g and 1-g Opposed Flow Flames



0-g with flow (10 cm/s)
Steady flame size and spread
Convex base
Extended blue zone

1-g
Flame does not propagate downward

Results: Thin Fuel Flame Spread and Extinction

- Opposed flow:
  - flame quickly reached steady spread
  - spread rate was fastest at an intermediate value of flow speed
- Concurrent flow:
  - Flame spread rate increased linearly with increasing flow.
  - Quenching extinction was observed (around 1 cm/s)
- This is the first time that detailed transient flame growth data was obtained in purely forced flows in microgravity.
- Long-duration experiments validate a number of theoretical predictions and also provide the data for a transient flame growth model under development.

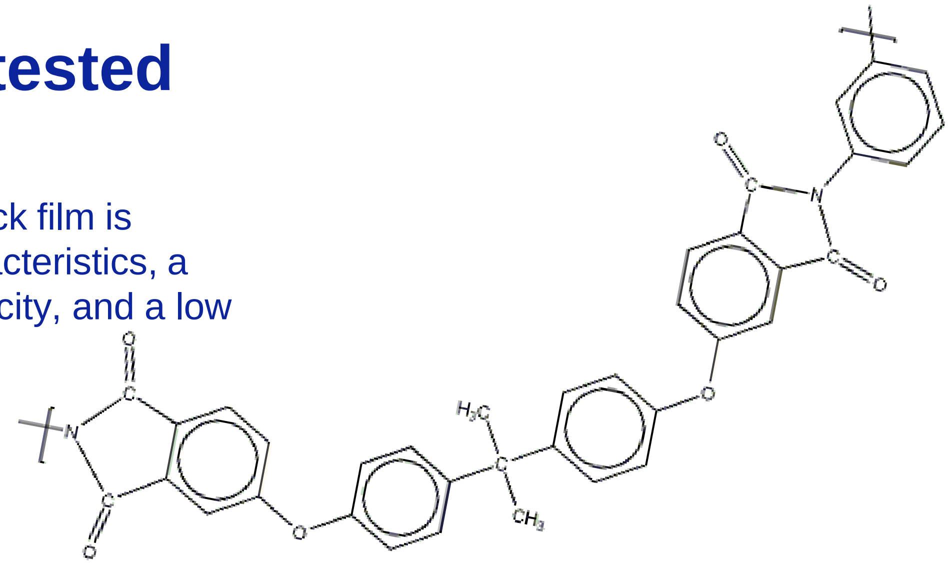
2. Material Flammability Comparison: 0-g / 1-g

Fuels tested

- **Ultem® 1000** $C_{37}H_{24}O_6N_2$

  Fire retarded polyetherimide (PEI) in 10 mil thick film is inherently flame-retarding, with ***charring*** characteristics, a very low smoke signature, very low smoke toxicity, and a low heat-release rate.

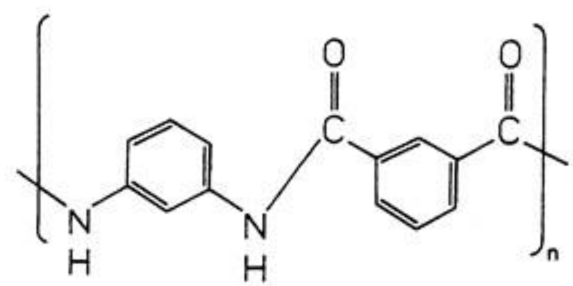
  ULOI: 23.5% O_2



- **Nomex®** $(C_{14}H_{12}O_2N_2)_n$

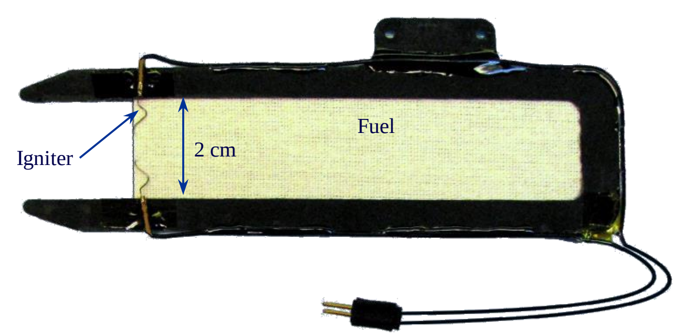
  <u>HT90-40</u> fabric is a 12 mil thick fire retarded aromatic nylon ***fabric*** which does not melt or drip as it burns. When exposed to a heat source, the Nomex fibers swell and seal the spaces between the fibers, stopping air movement through the fabric and thus inhibiting heat transfer through the fabric.

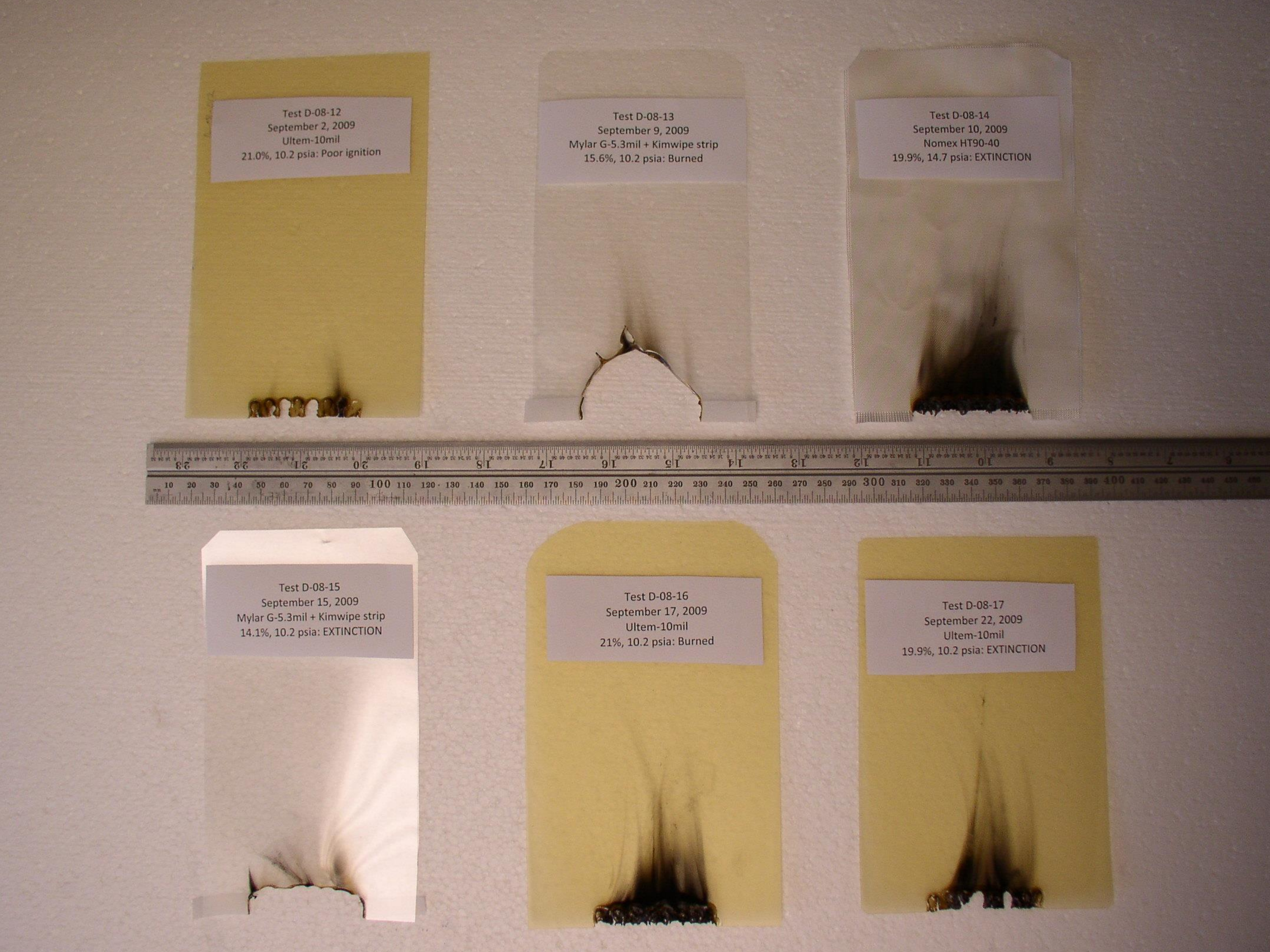
  ULOI: 23.5% O_2



- **Nomex-III ®**

  ULOI: 22% O_2




Test D-08-12
September 2, 2009
Ultem-10mil
21.0%, 10.2 psia: Poor ignition
Test D-08-13
September 9, 2009
Mylar G-5.3mil + Kimwipe strip
15.6%, 10.2 psia: Burned
Test D-08-14
September 10, 2009
Nomex HT90-40
19.9%, 14.7 psia: EXTINCTION
Test D-08-15
September 15, 2009
Mylar G-5.3mil + Kimwipe strip
14.1%, 10.2 psia: EXTINCTION
Test D-08-16
September 17, 2009
Ultem-10mil
21%, 10.2 psia: Burned
Test D-08-17
September 22, 2009
Ultem-10mil
19.9%, 10.2 psia: EXTINCTION

Results: Material Flammability

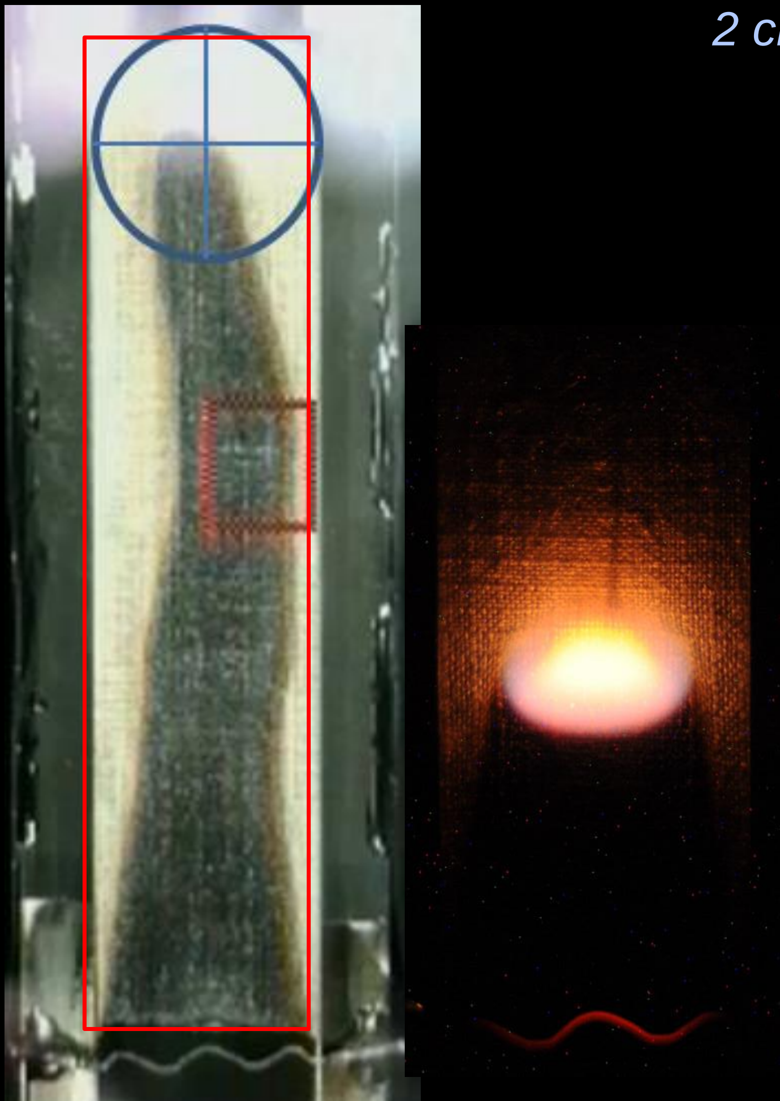
Ultem and Nomex HT90-40 samples did not burn on ISS atmosphere

- 21% to 22% O_2
- Flow speeds around 15 cm/s
- Similar to 1-g (Note: samples narrower on ISS)

Nomex-III sample did burn

NOMEX – III, 22% O_2, 1 atm 14 cm/s (0g)

2 cm wide sample

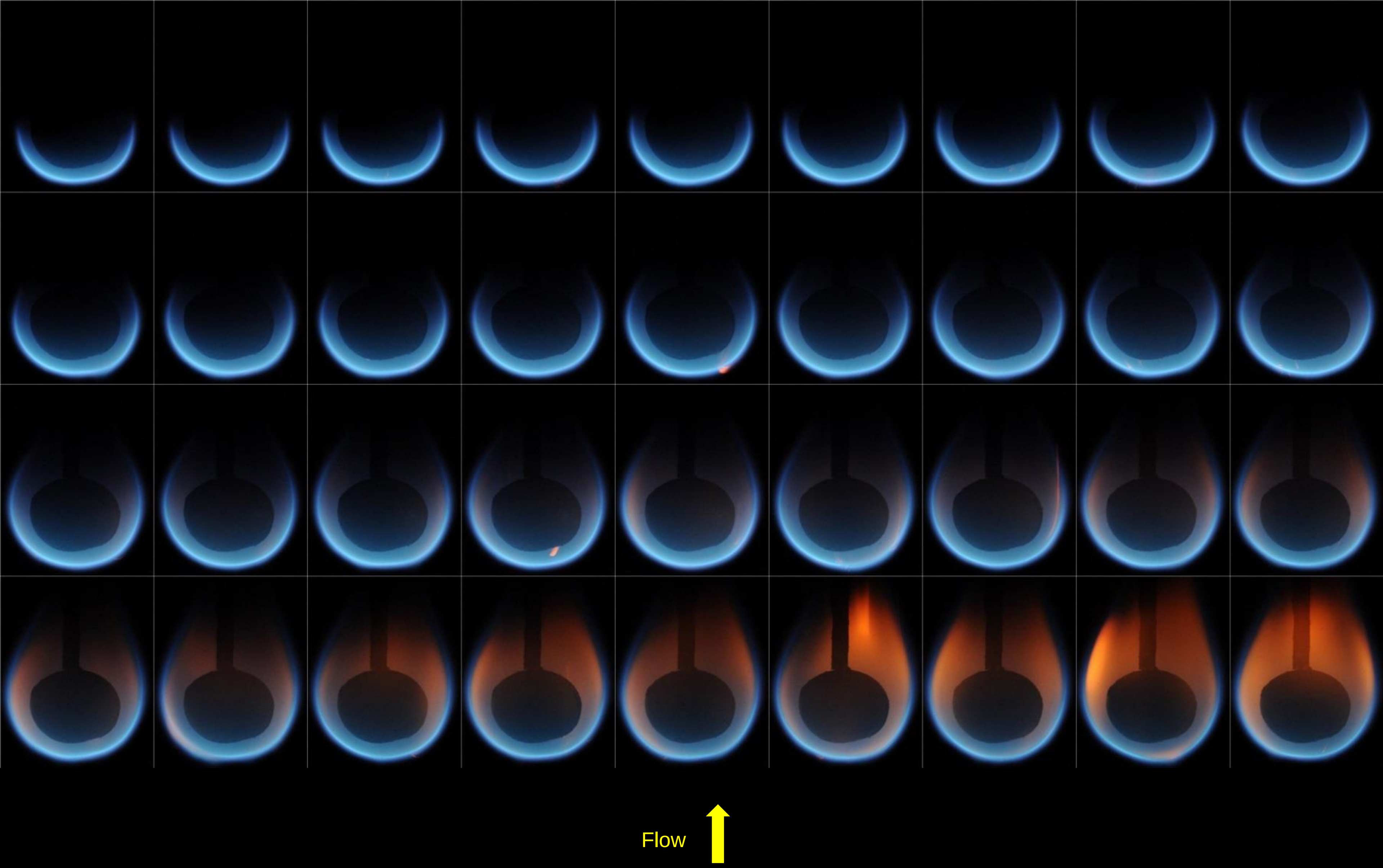


At 1g ULOI, but narrower sample

Nomex III sample residue after nearly complete concurrent propagation at 15 cm/s on ISS. Flame was shrinking in width until it extinguished within 1 cm of the end of the sample, as its width became smaller than ~ 1 cm, which is on the scale of a fingering flamelet.

Flow

3. Spherical PMMA samples

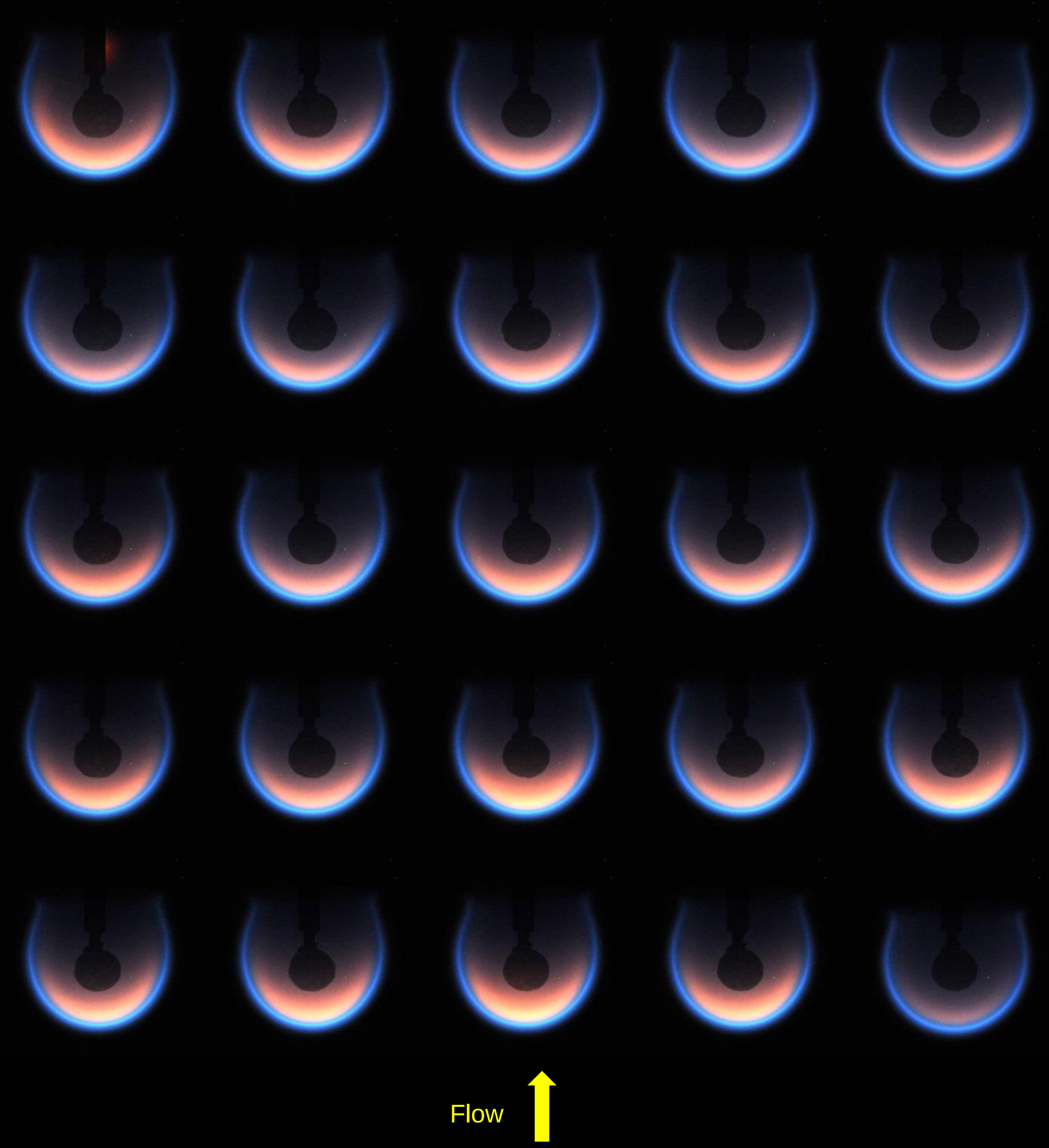


Flame sequence of a burning 2-cm diameter PMMA sphere at 17% oxygen and 12 cm/s flow. The images are about 1.5 sec. apart. The high resolution images allow model comparison of flame growth rate, flame-to-fuel distance, and the solid regression rate.

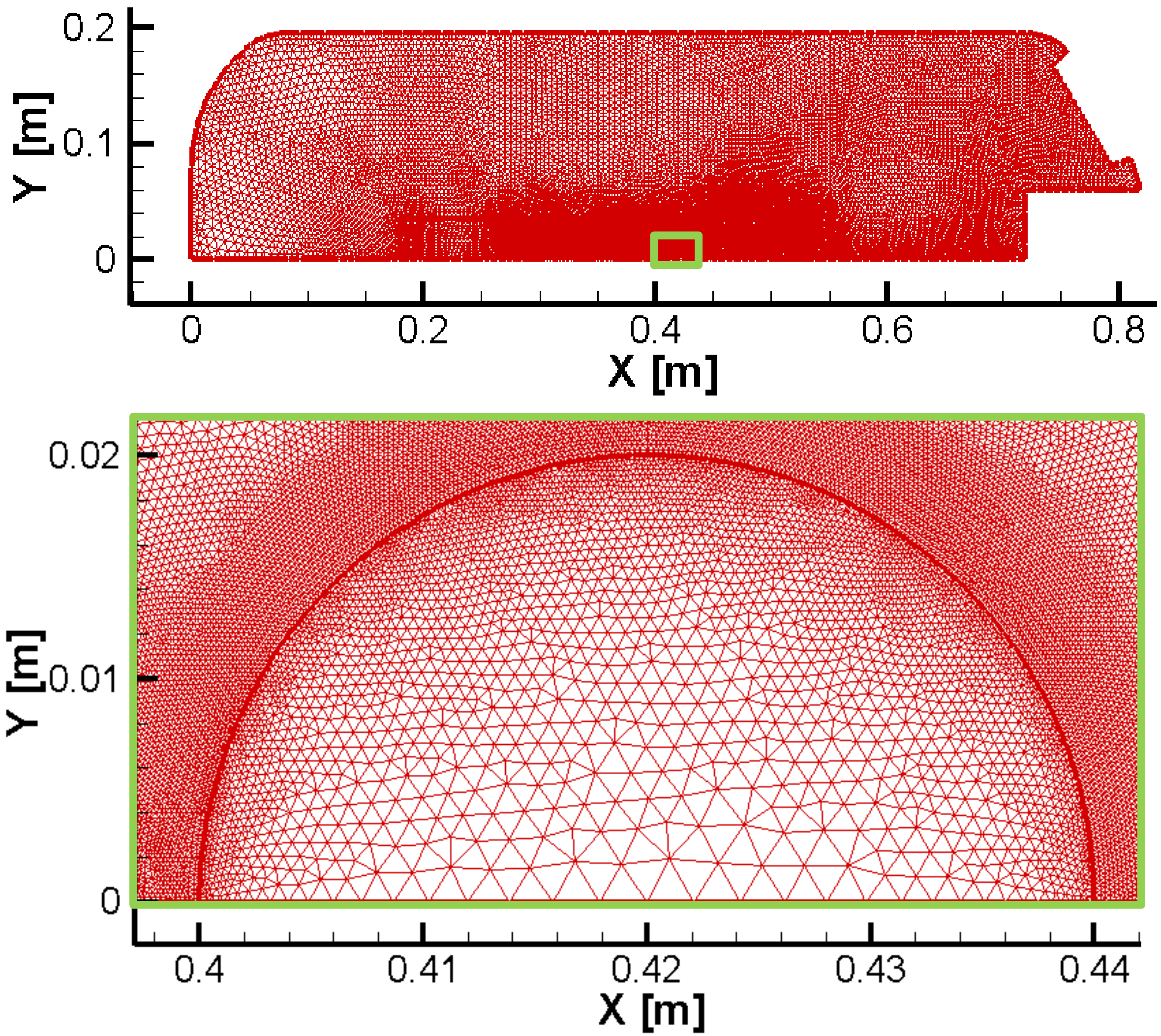
Flame sequence of a burning PMMA sphere (1-cm diameter) at 17% oxygen and less than 1 cm/s.

(Images are 1.3 sec. apart)

The fuel itself is clearly visible in this contrast-enhanced montage. This enables us to get an accurate measure of the fuel burning rate which is an important parameter to characterize the system for comparison to the model.

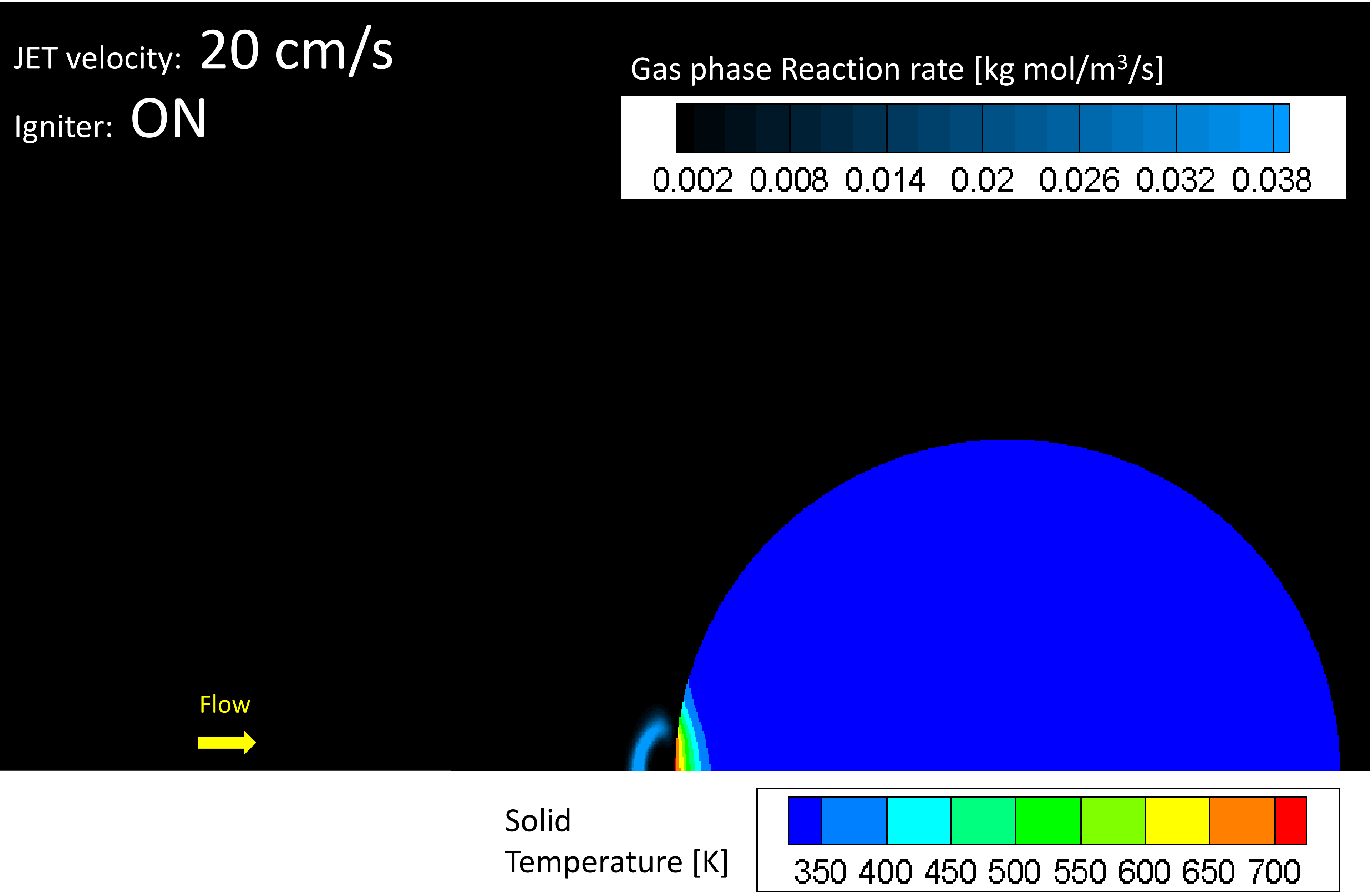


Mesh

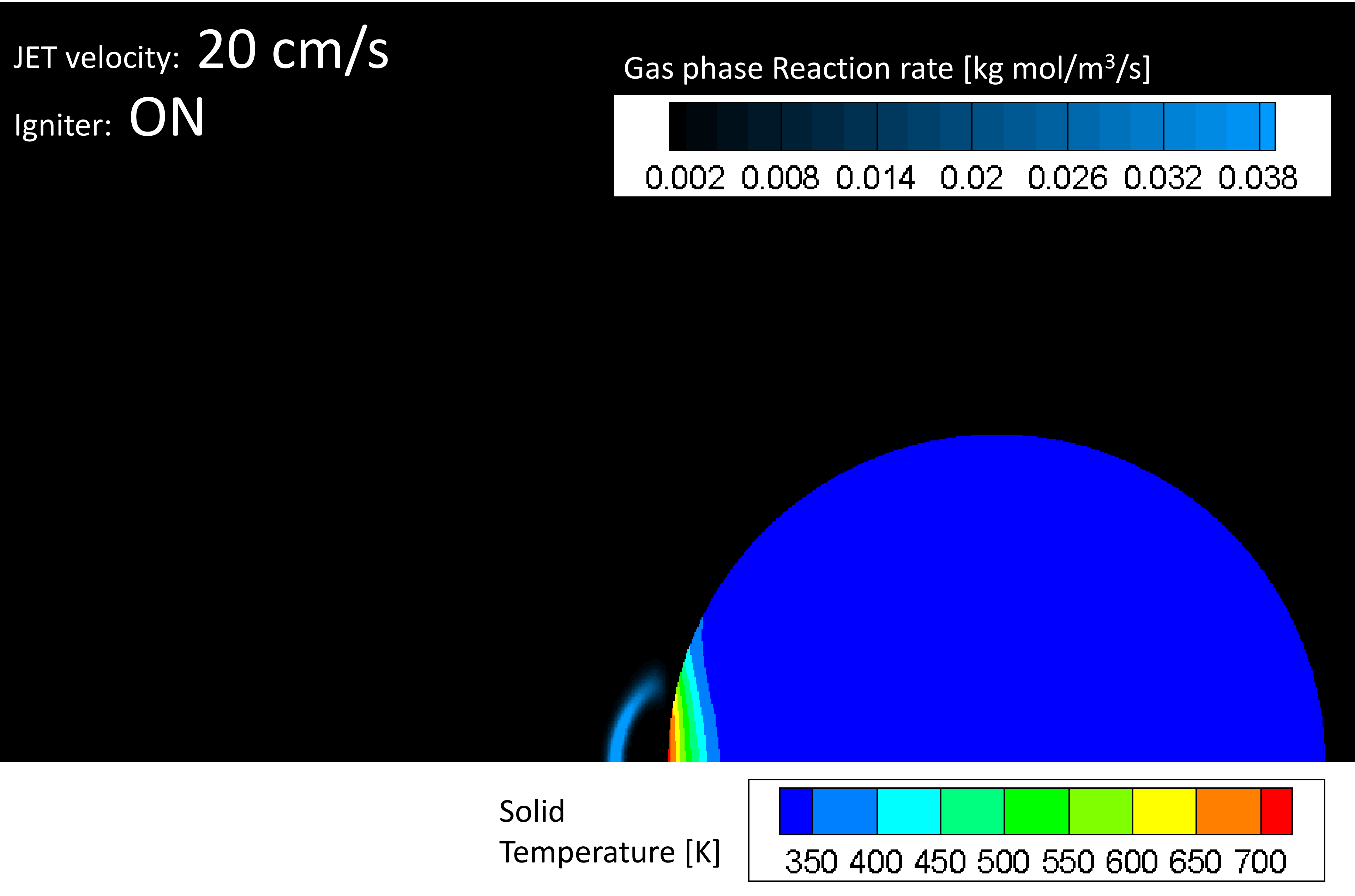


Having 33930 points total, Using quad-core CPU (4 processors) with 16GB memory, it takes 2.7 hours to compute one second in the computation (with capability of shape change due to solid surface regression).

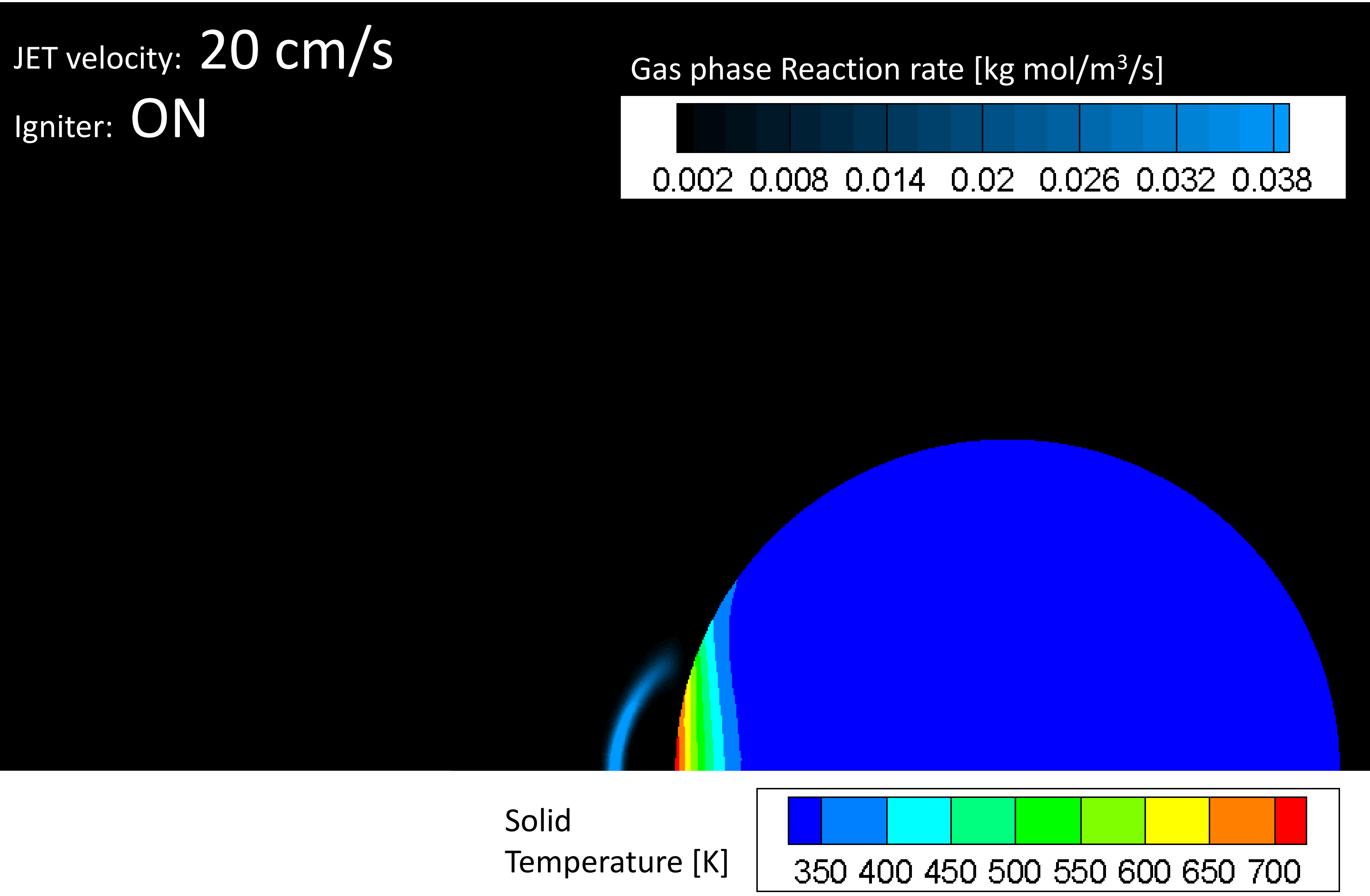
Flame spread (10sec.)



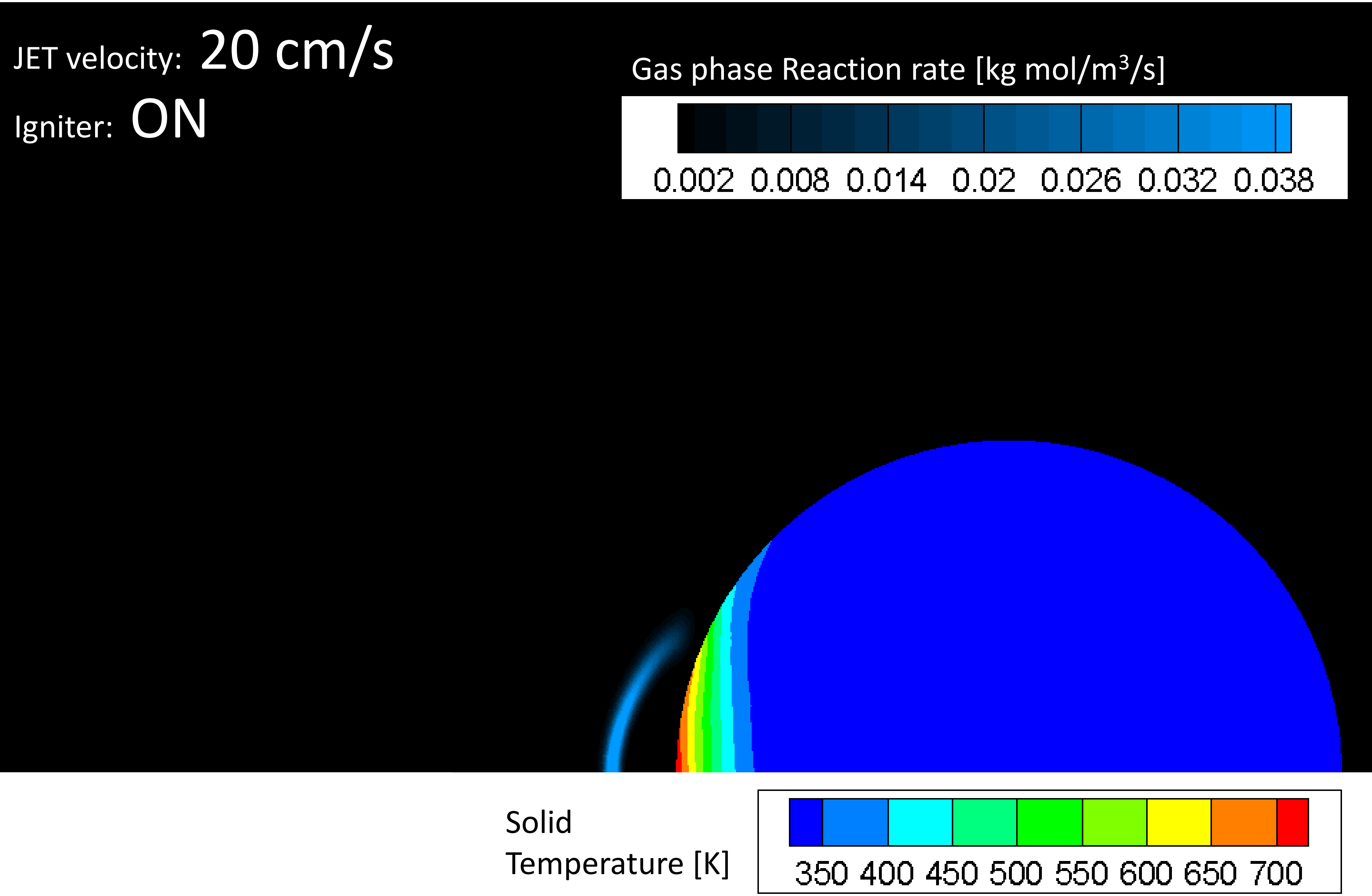
Flame spread (20sec.)



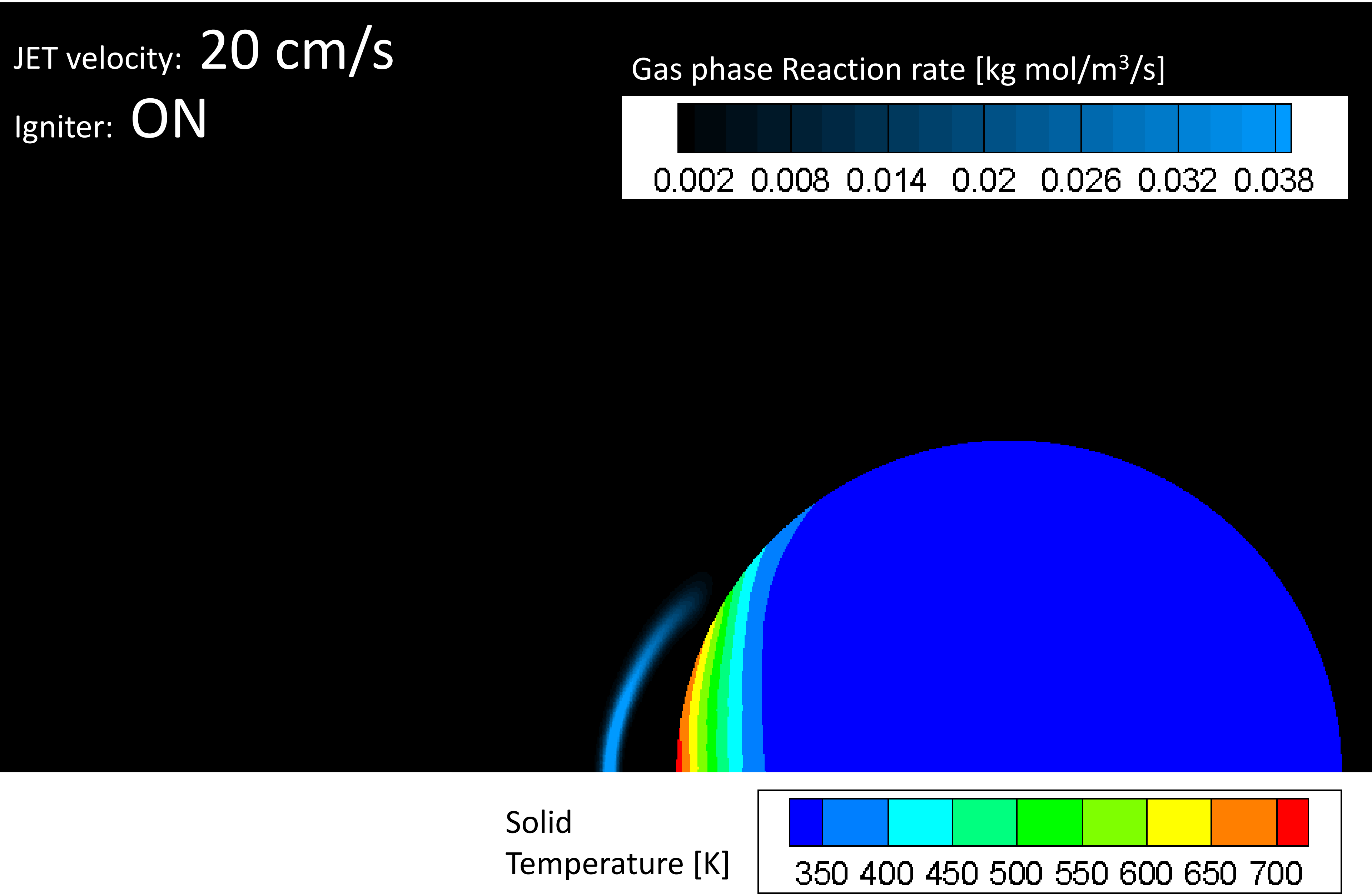
Flame spread (30sec.)



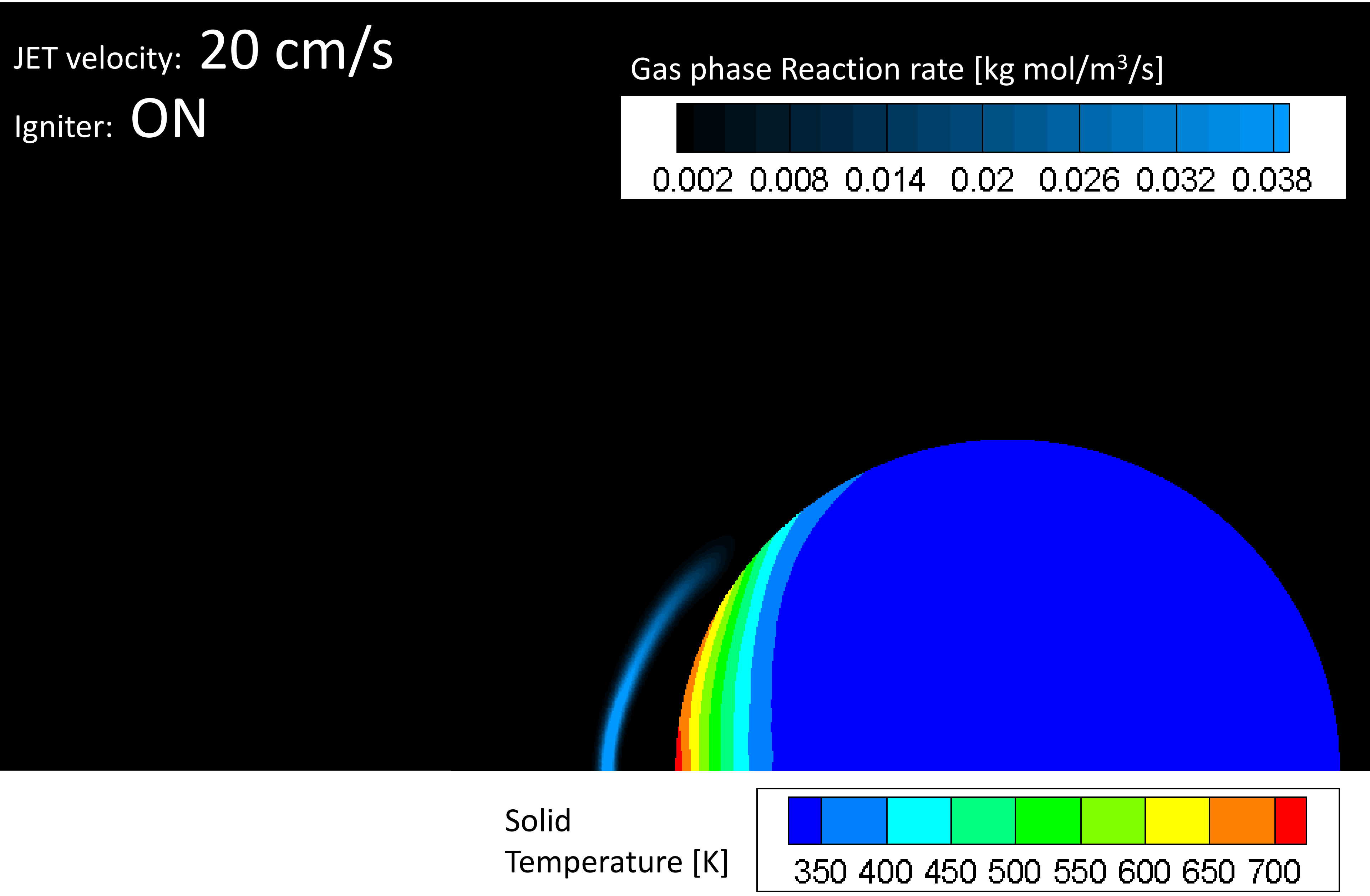
Flame spread (40sec.)



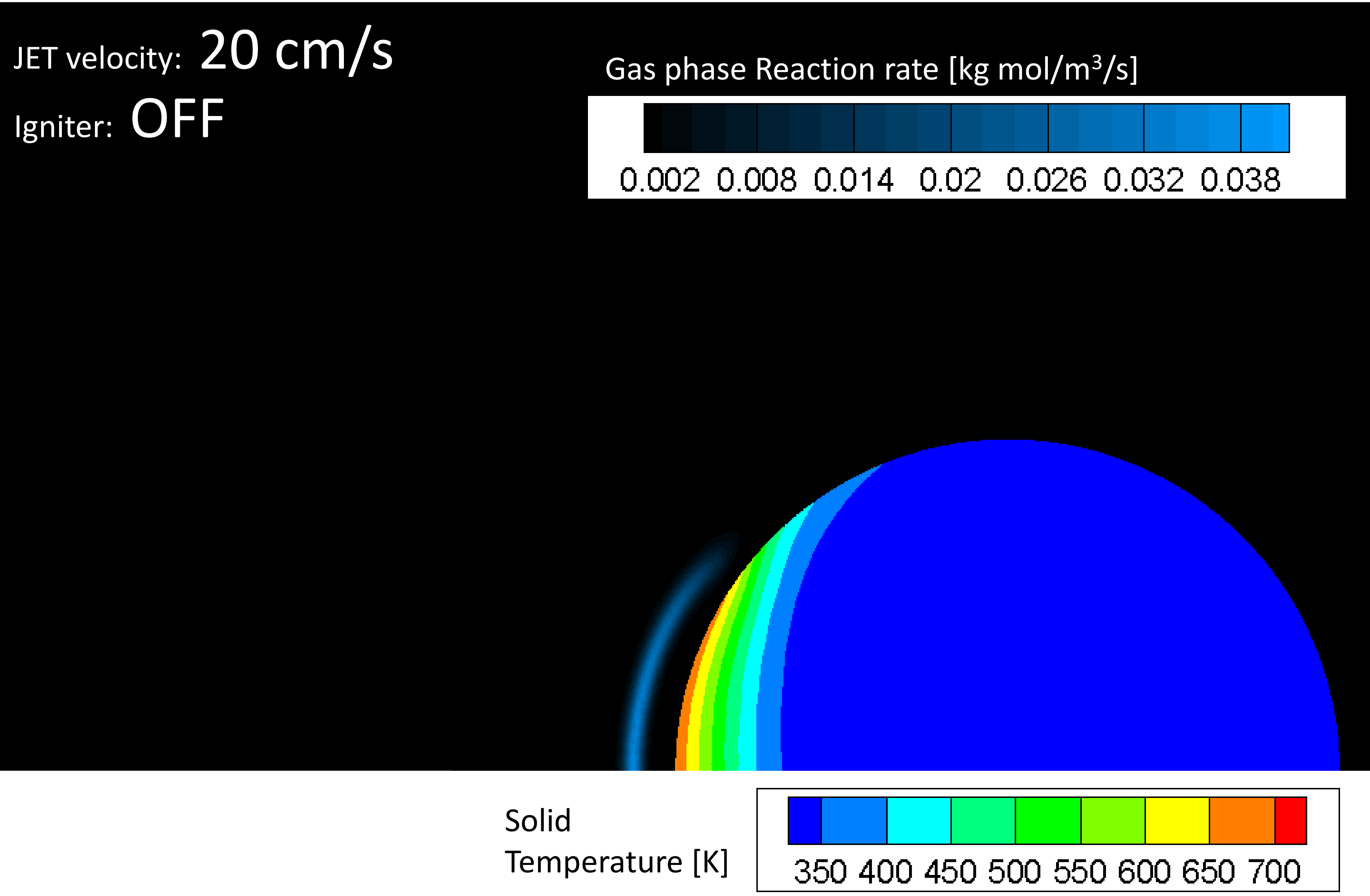
Flame spread (50sec.)



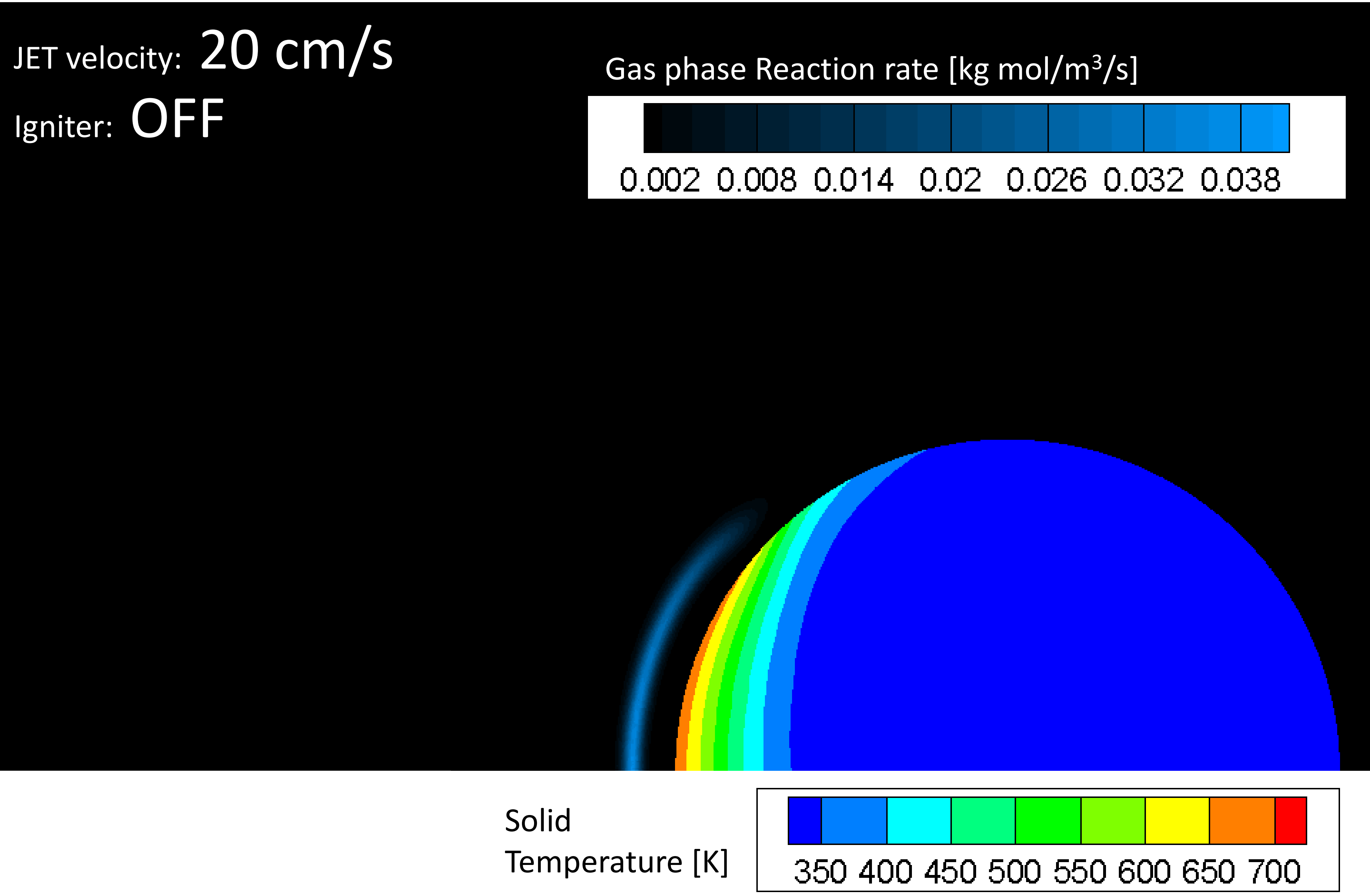
Flame spread (60sec.)



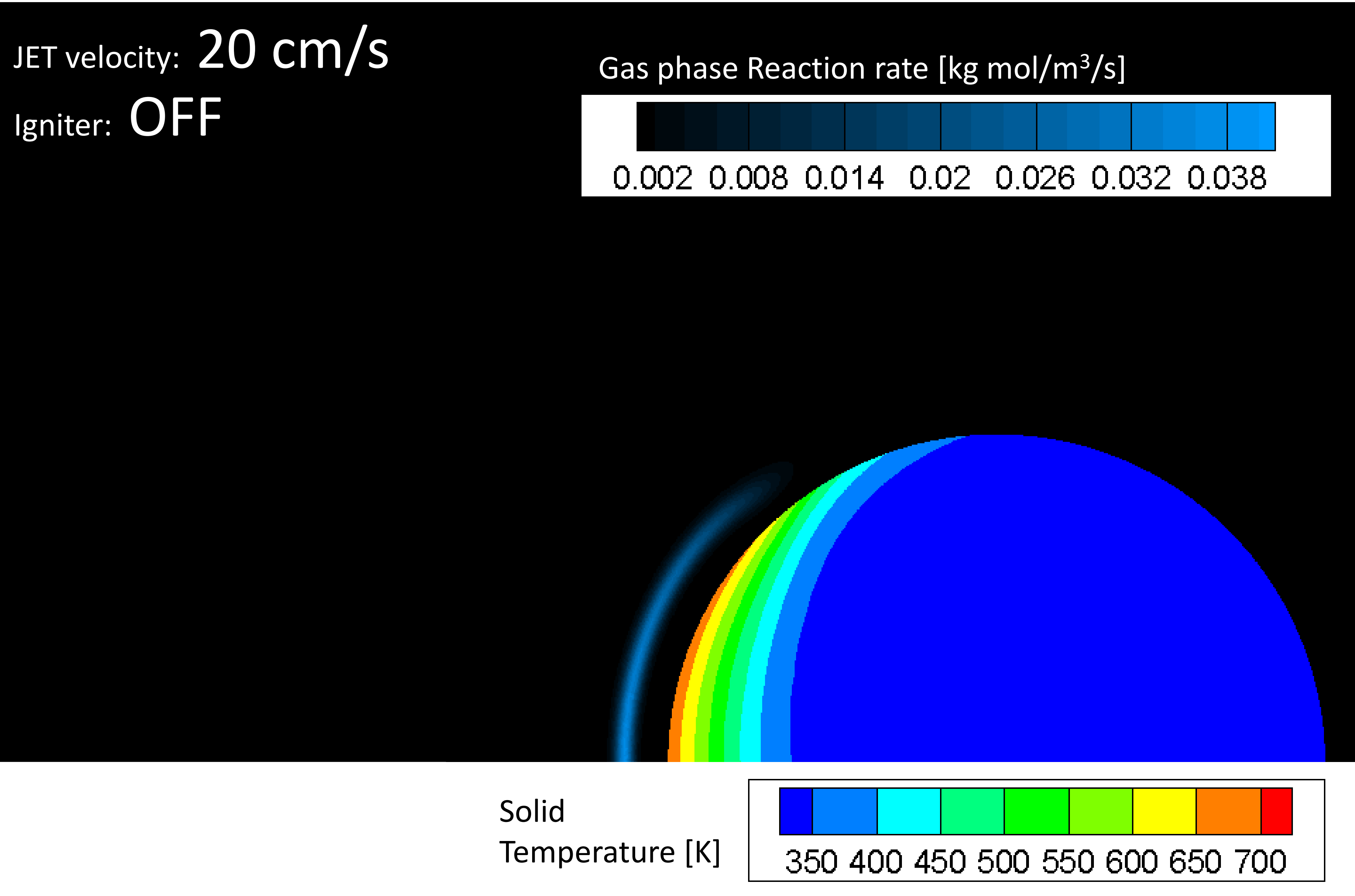
Flame spread (70sec.)



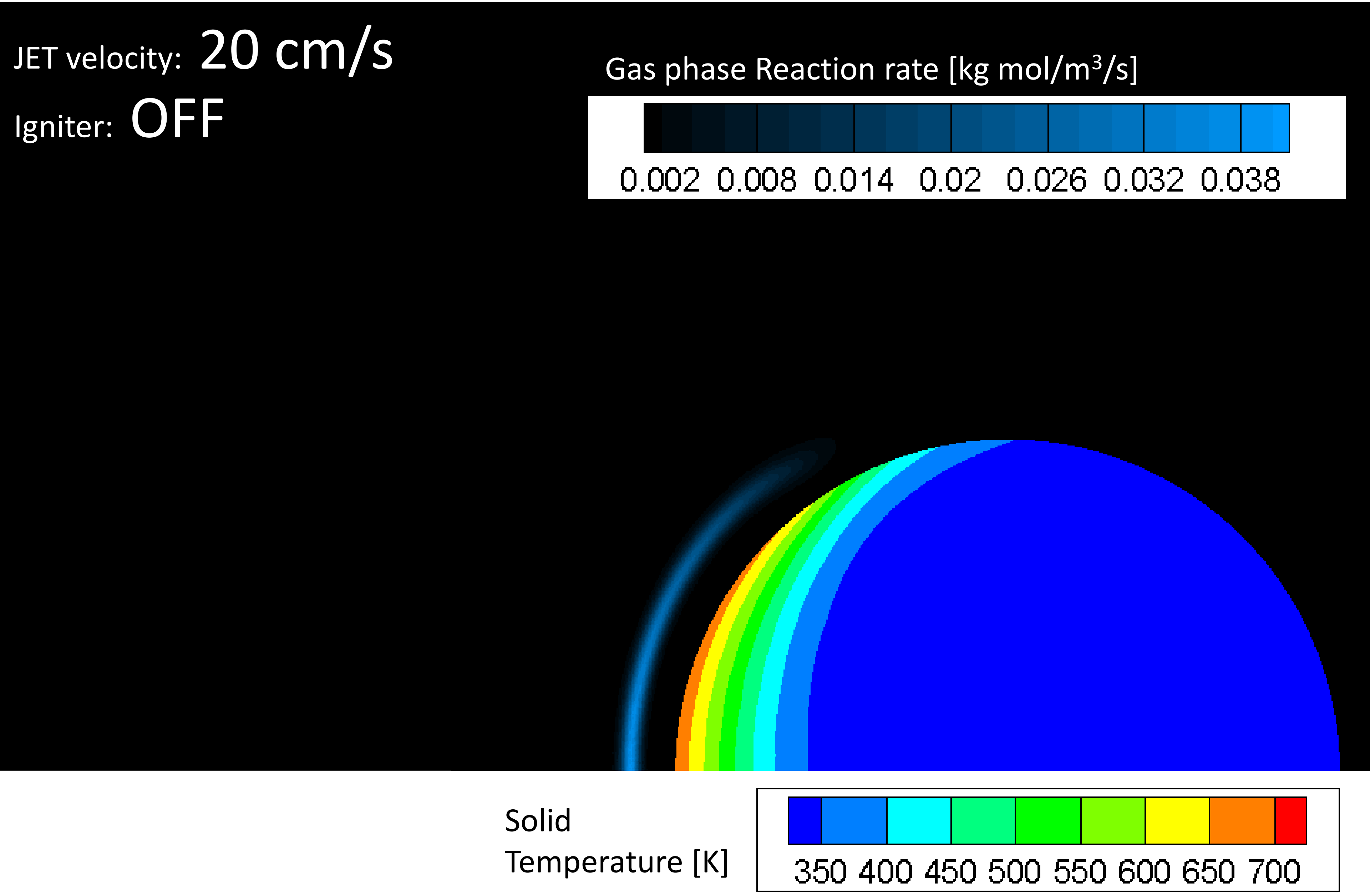
Flame spread (80sec.)



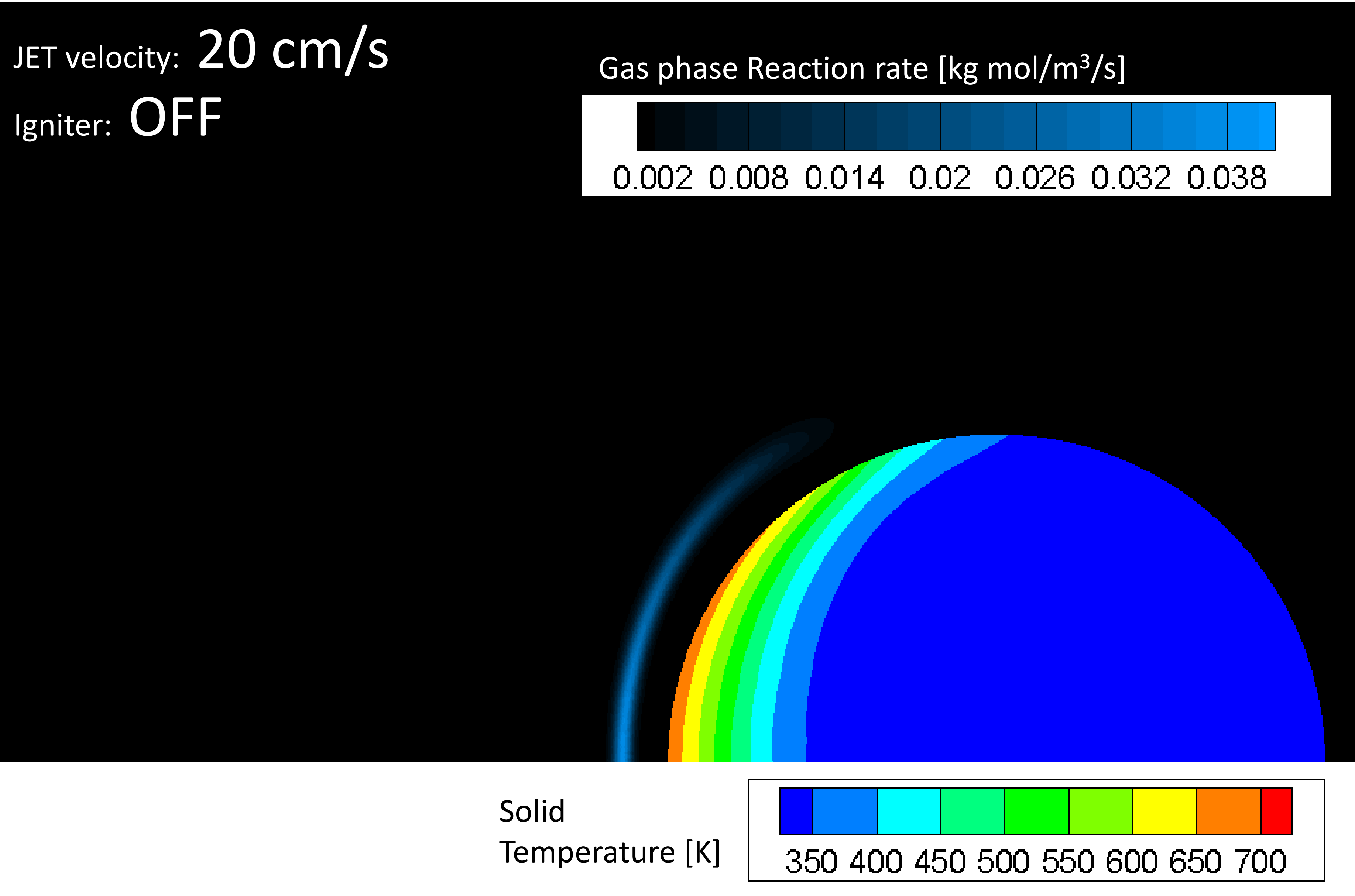
Flame spread (90sec.)



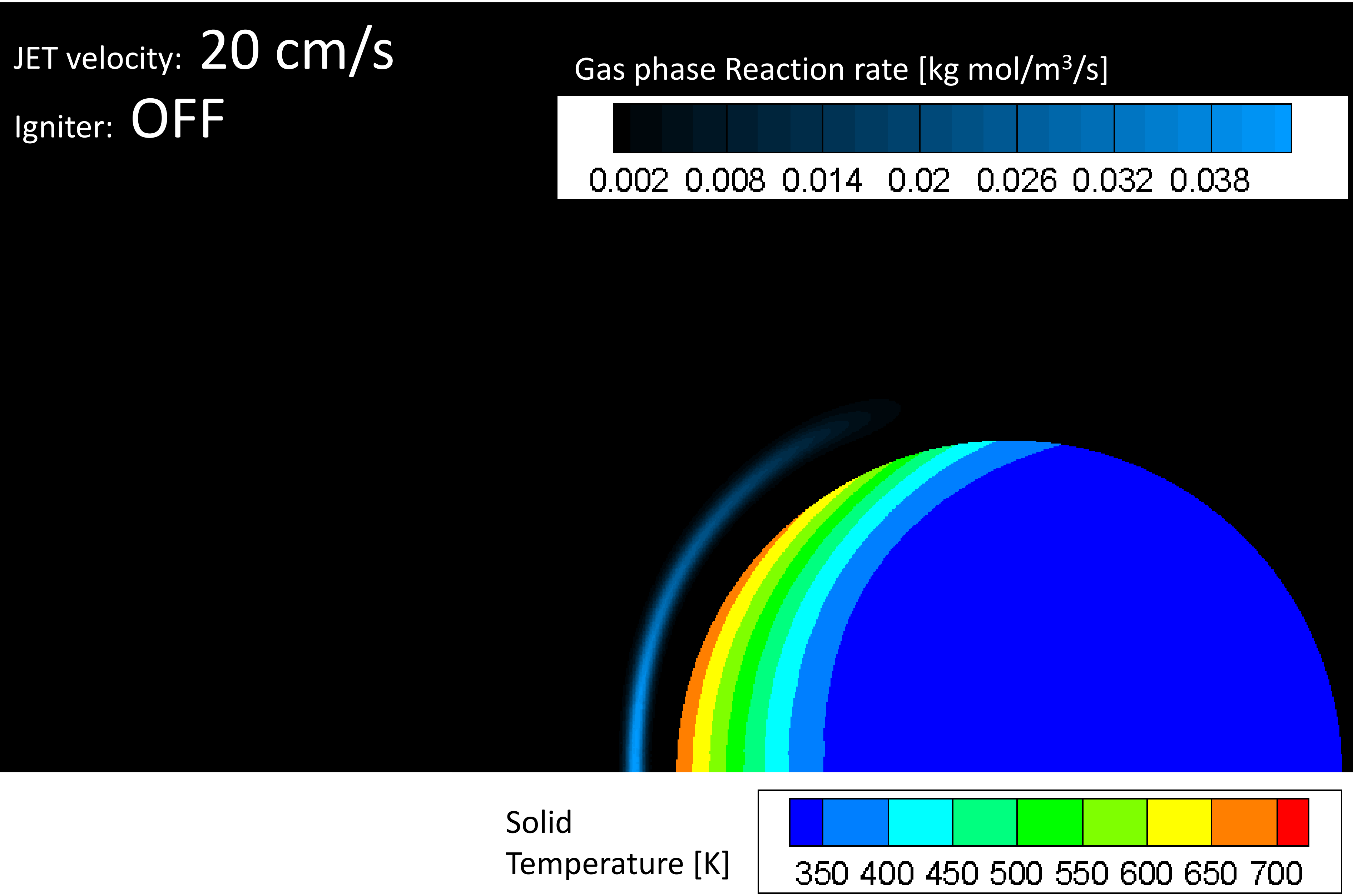
Flame spread (100sec.)



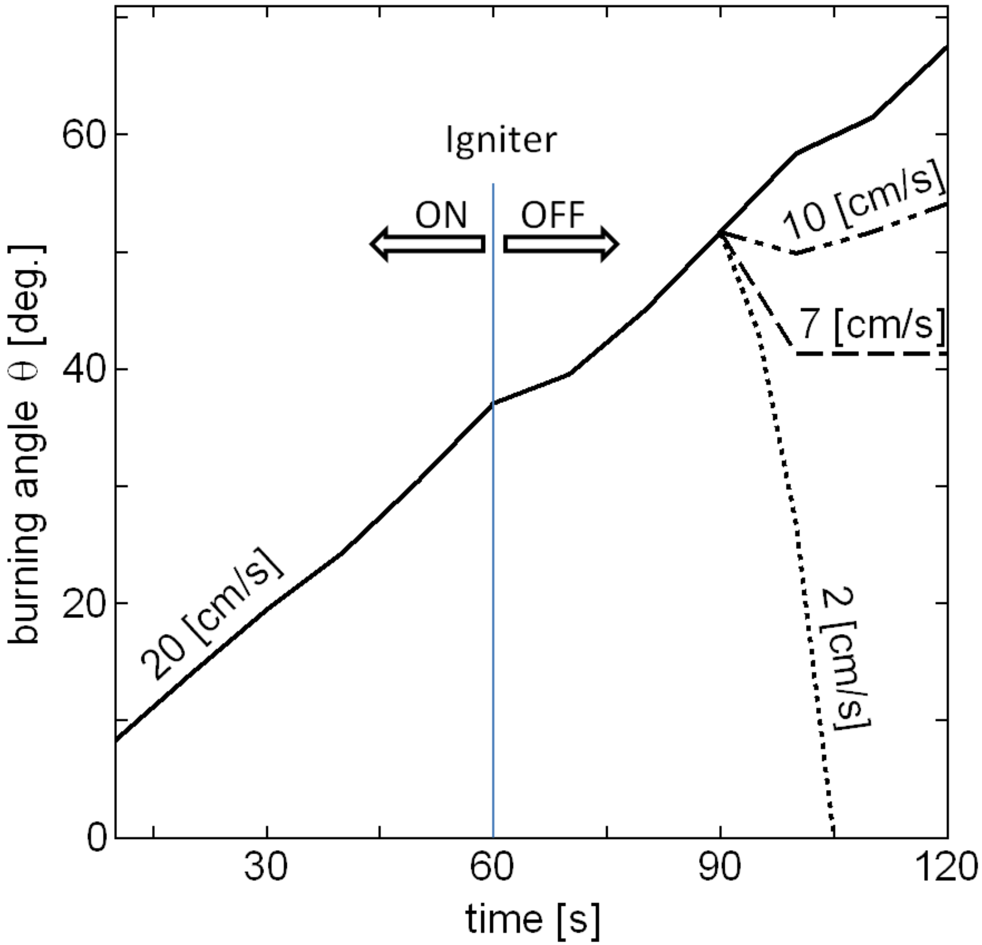
Flame spread (110sec.)

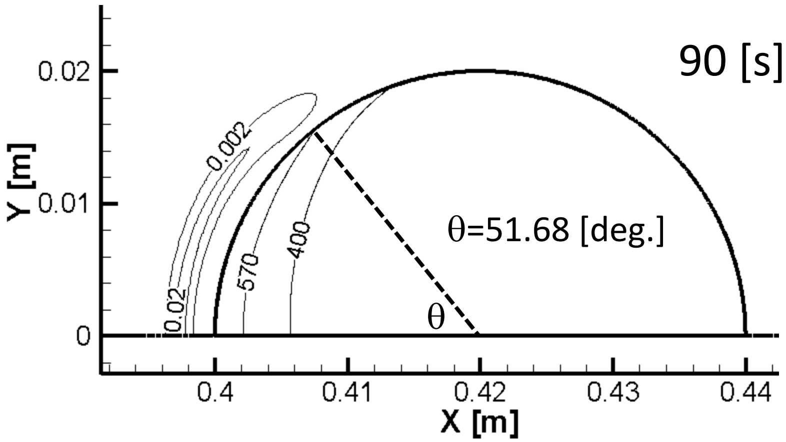


Flame spread (120sec.)



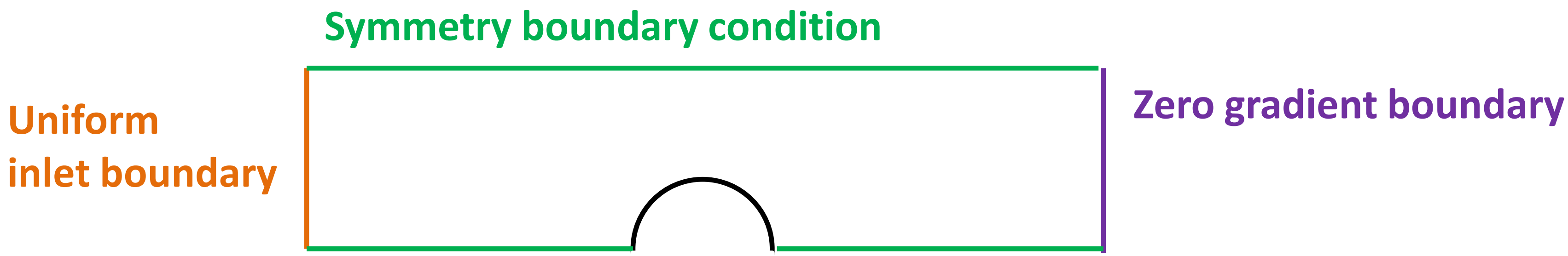
Flame spread graph





Burning angle θ is defined by the solid surface temperature (570K).

Surface energy balance: $\lambda_g(\partial T/\partial n)_g = \lambda_s(\partial T/\partial n)_s + \dot{m}L + \varepsilon\sigma T_S^4$

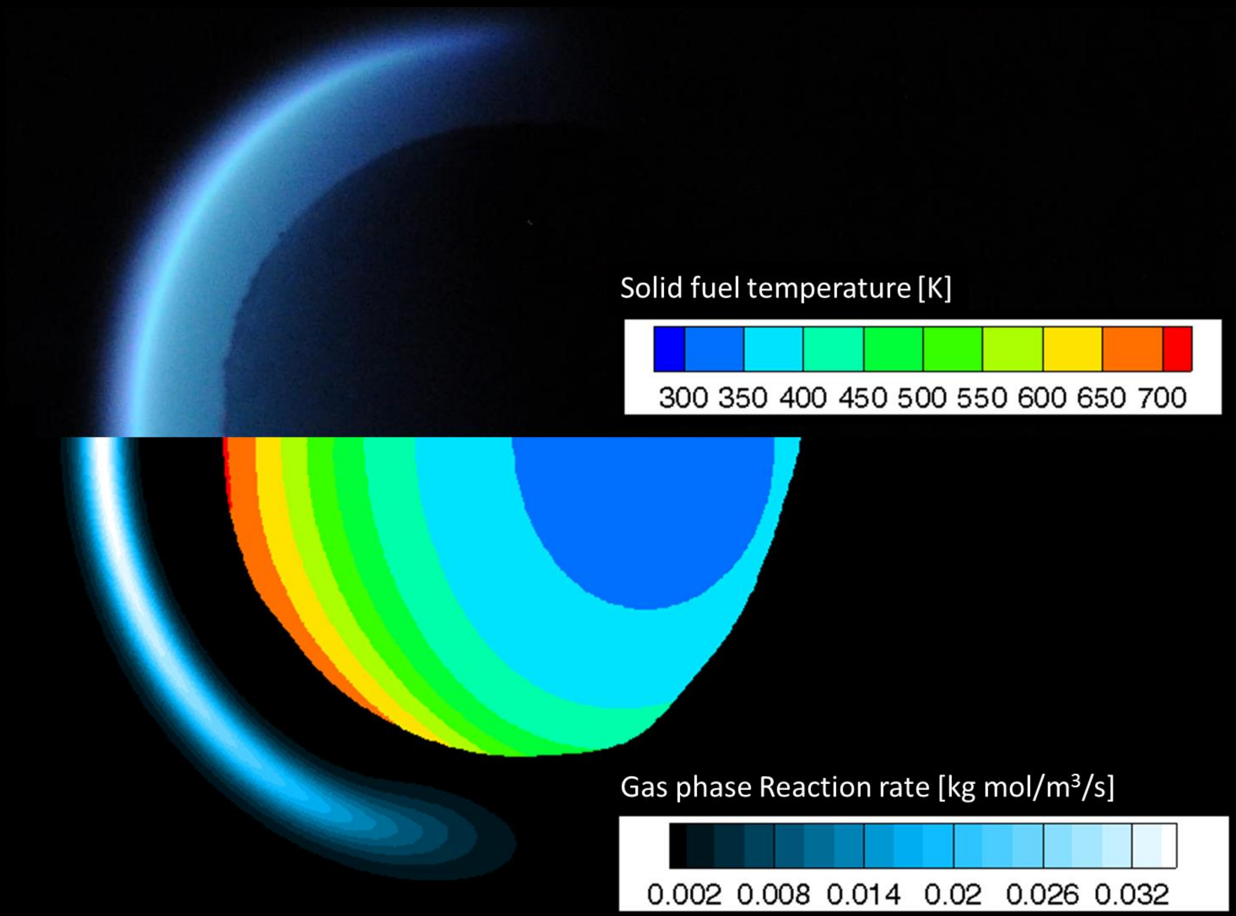


Parameter Φ was introduced to the interfacial energy balance boundary condition to complete the description for the quasi-steady gas-phase system.

$$\Phi = \frac{\lambda_s \left.\dfrac{\partial T}{\partial n}\right|_s}{\lambda_g \left.\dfrac{\partial T}{\partial n}\right|_g} = \frac{\text{heat flux into the solid}}{\text{heat flux from the gas}}$$

Φ is assumed to have an uniform value (independent of angle) and is treated as a parameter for successive quasi-static gas phase flames

large Φ ⇨ More heat loss to the solid from the gas phase.



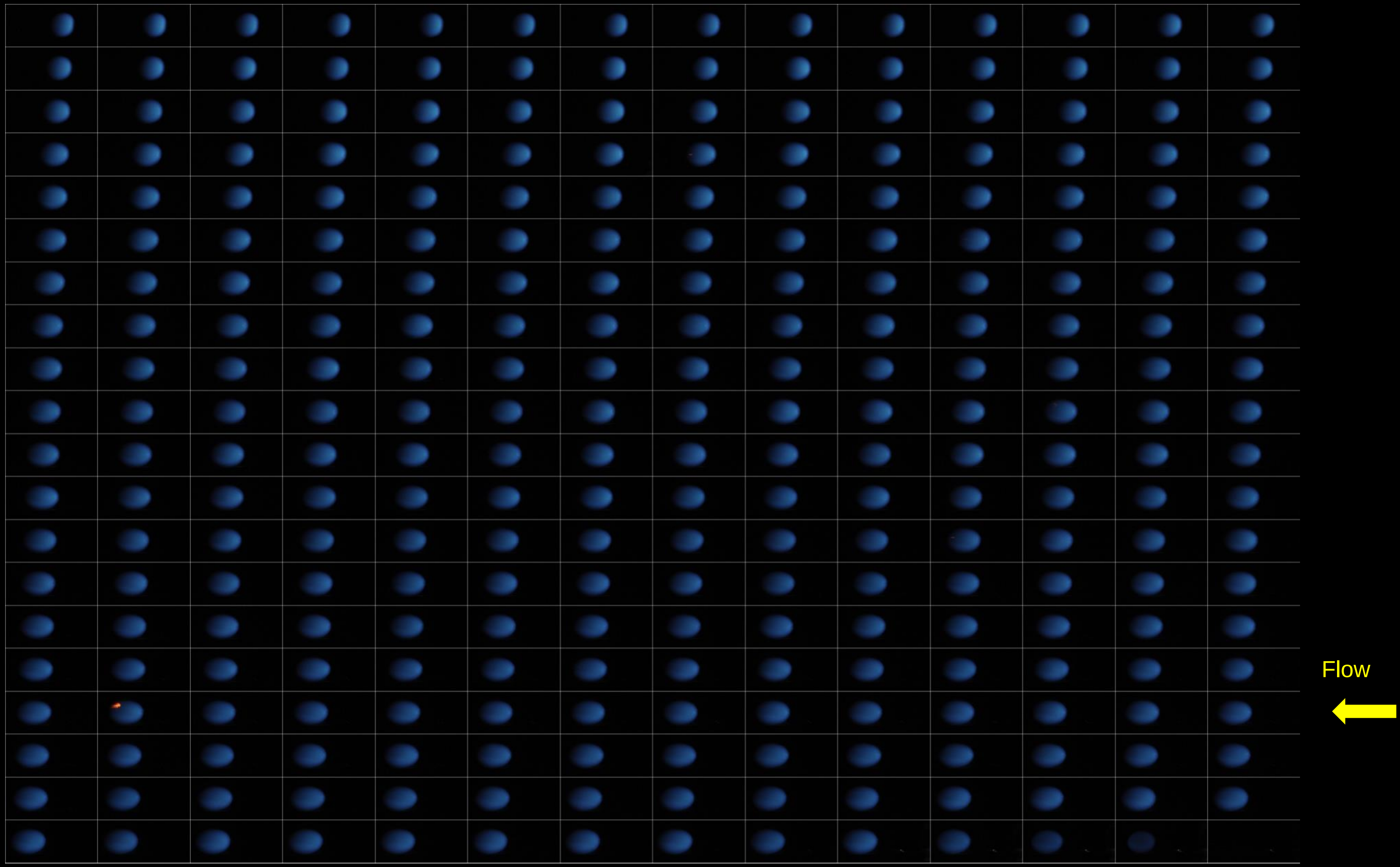
Flame burning an acrylic sphere (top) from is compared to model computation (bottom). The comprehensive model even includes solid phase shape change effects. Adjusted solid phase chemical kinetic parameters will improve the prediction of the flame standoff distance.

Fuel: Acrylic sphere; Atmosphere: 17% O_2/N_2; 1 atm; Flow speed: 12 cm/s (left to right)

Dynamic flow change effects

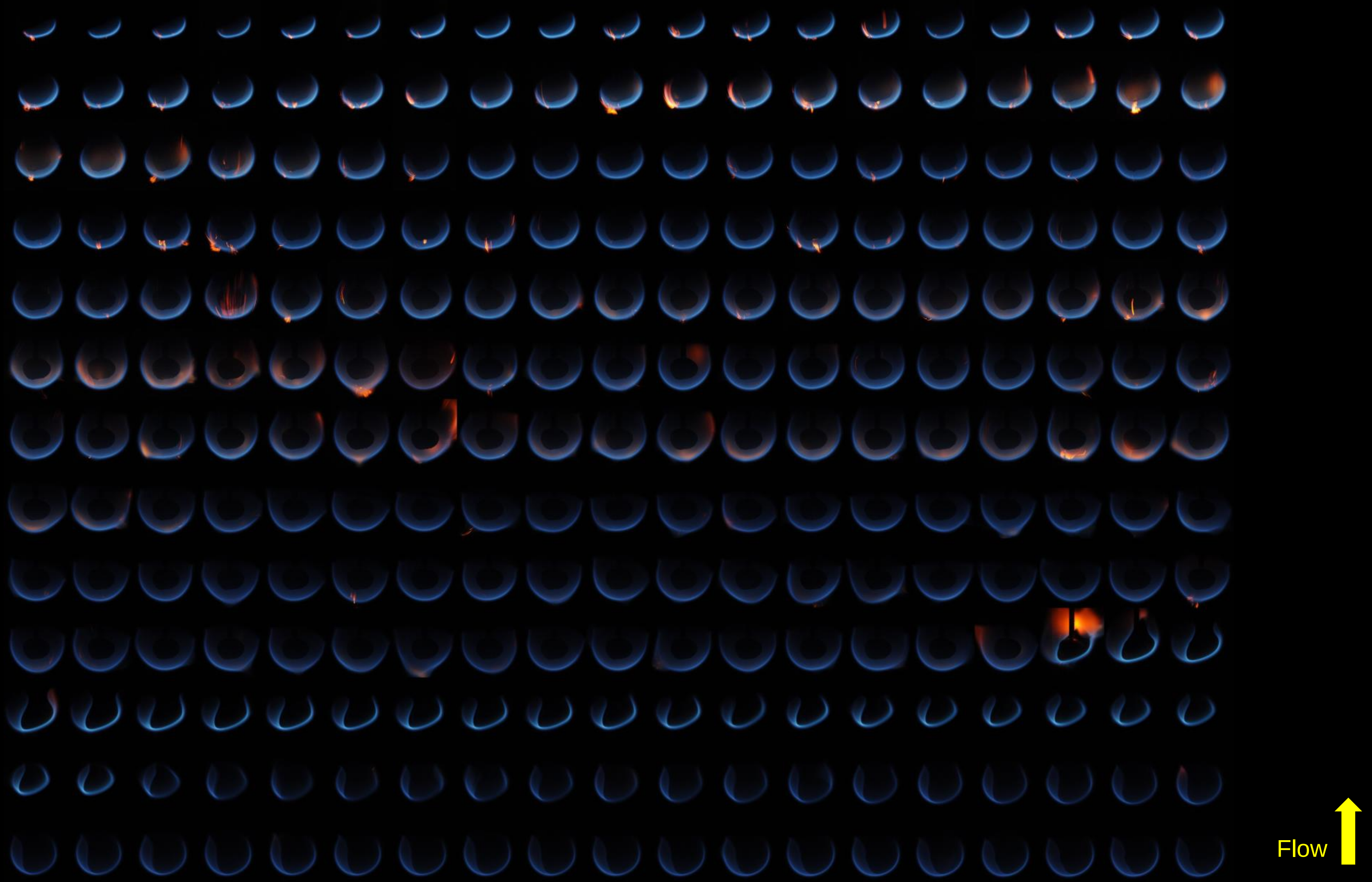
Flow ↑

4. Flat PMMA Samples



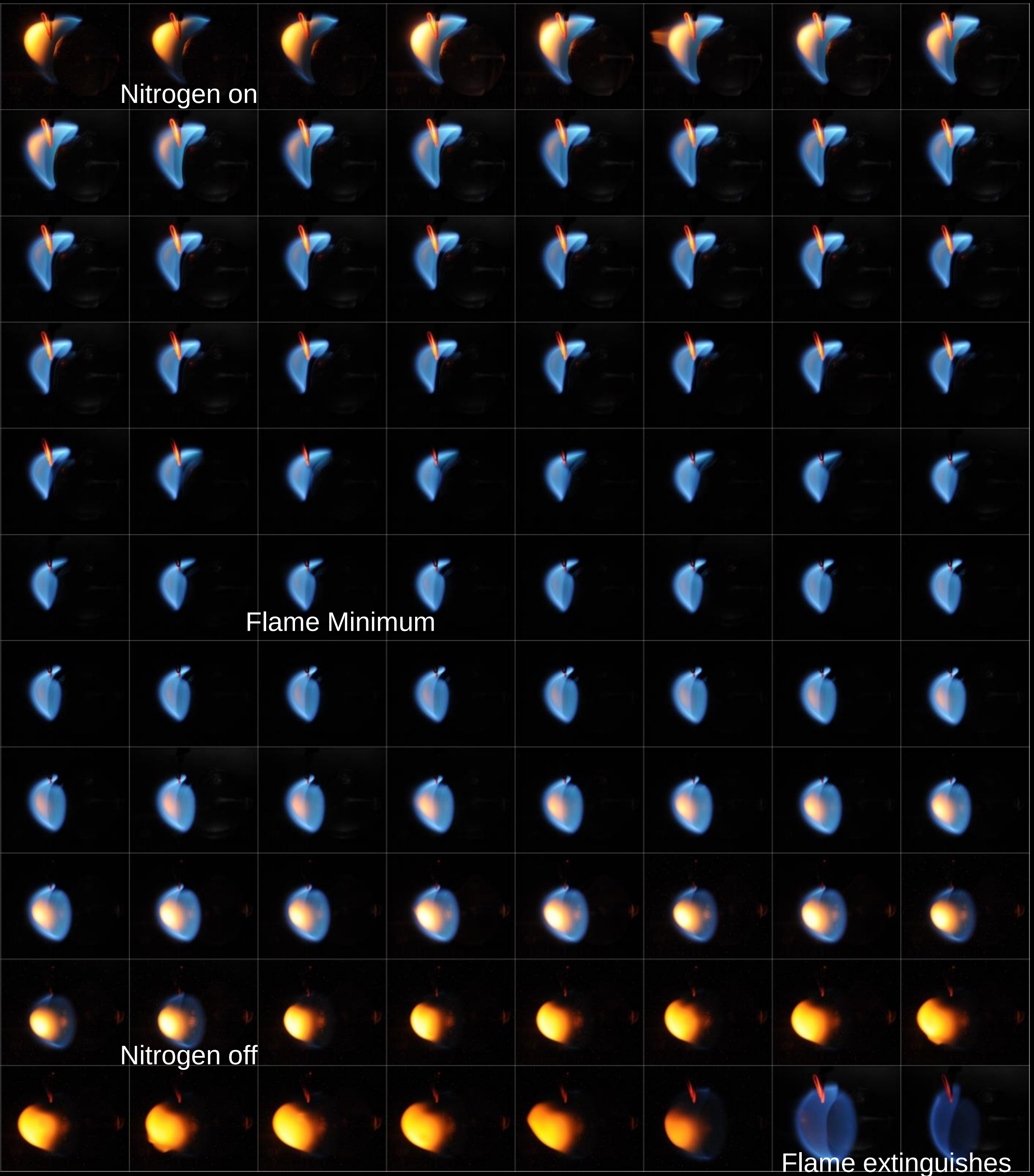
Top view image montage for a 1-cm wide flat acrylic sample burning in air at low flow speed (around 9 cm/s). Images progress from left to right then top to bottom (1.3 seconds between images). The air flow direction is from right to left. The flame is about 1 cm in size and can persist for a very long time at this low air flow speed. The flame goes out only in the last two frames when the air flow is completely shut off.

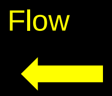
5. Nitrogen Suppression and Wake Flames



Flow of less than 1 cm/s. Near the end of the burn, a jet of nitrogen is imposed but it fails to extinguish the flame. (Solid is very warm.) Finally after a series of flow reductions, the flame goes out when the flow speed is zero.

Fuel: PMMA; 15-mm initial diameter; 17% O_2/N_2; 1 atm; Time between images: 1.3 sec





PMMA sphere burning in wake configuration in air.

Flow is from right to left

Nitrogen flow of 500 cc/min weakens but does not extinguish the flame

Summary

- Microgravity flames were found to be especially sensitive to air flow speed in the range 0 to 5 cm/s.

- The gas phase response is much faster compared to the solid and so as the flow speed is changed, the flame responds with almost no delay.

- At the lowest speeds examined (less than 1 cm/s) all the flames tended to become dim blue and very stable. However, heat loss at these very low convective rates is small so the flames can burn for a long time.

Summary (continued)

- ♦ At moderate flow speeds (between about 1 and 5 cm/s) the flame continually heats the solid fuel resulting in an increasing fuel temperature, higher rate of fuel vaporization, and a stronger, more luminous flame as time progresses.

- ♦ Thicker solids can store a great deal of heat even with only a small flame. One result is that extinction with the nitrogen jet was not possible for the given flow rate.

- ♦ Only the smallest flames burning acrylic slabs appeared to be adversely influenced by solid conductive heat loss, but even these burned for over 5 minutes before self-extinguishing.
  - This has implications for spacecraft fire safety since a tiny flame might be undetected for a long time.
  - While the small flame is not particularly hazardous if it remains small, the danger is that it might flare up if the air convection is suddenly increased or if the flame spreads into another fuel source.

Acknowledgments:

Fumiaki Takahashi, National Center for Space Exploration Research

Bob Hawersaat, NASA Glenn Research Center

Jay Owens, National Center for Space Exploration Research

Tibor Lorik, ZIN Technologies

Chuck Bunnell, ZIN Technologies

Dennis Siedlak, Georgia Institute of Technology

Carol Reynolds, NASA Marshall Space Flight Center

Don Pettit, NASA Johnson Space Center

Joe Acaba, NASA Johnson Space Center

Suni Williams, NASA Johnson Space Center

Chris Cassidy, NASA Johnson Space Center

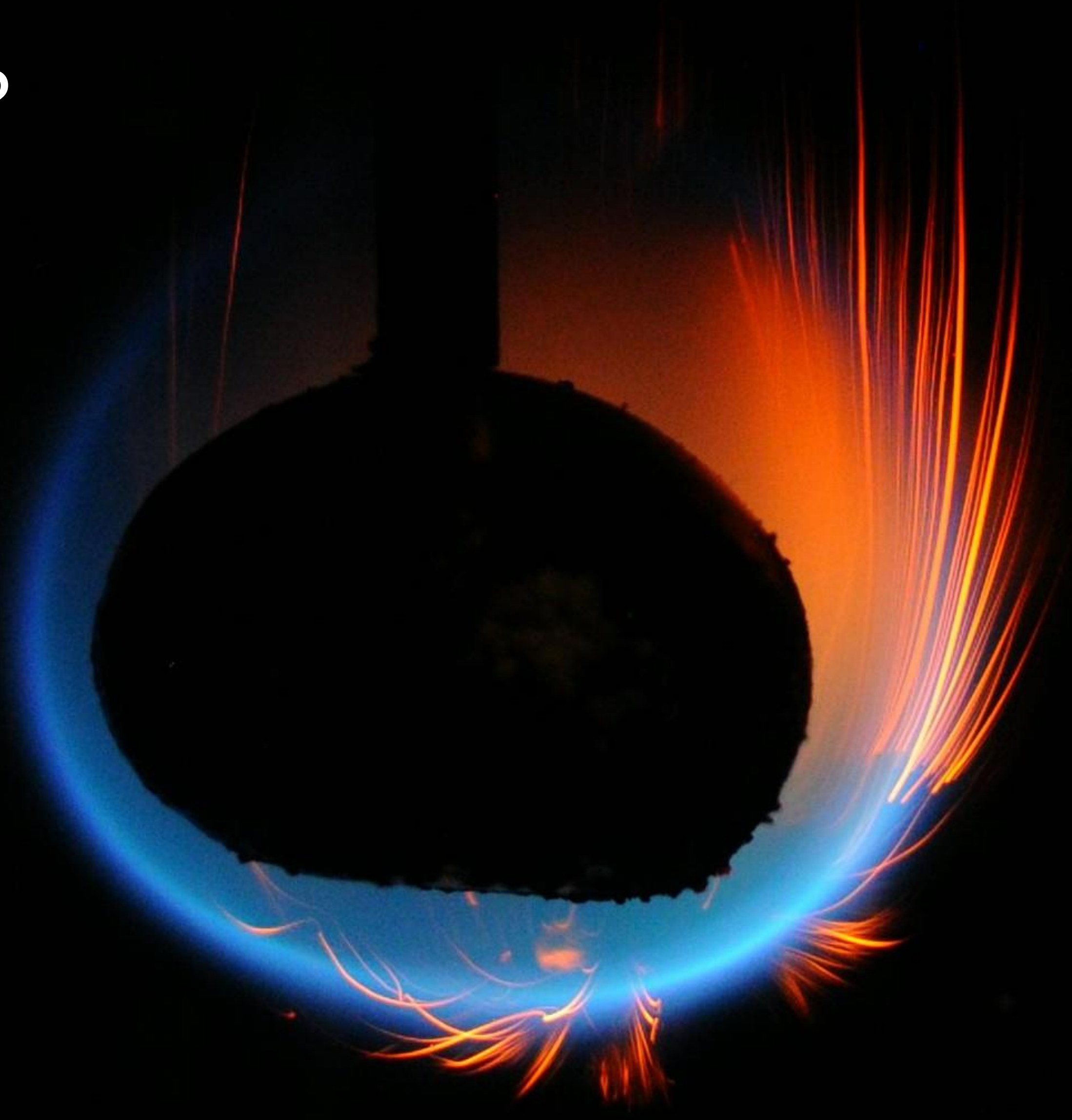
Burning and Suppression of Solids

BASS

NASA GRC • NCSER • CWRU • ZIN

Astronauts Don Pettit, Joe Acaba, Suni Williams, and Chris Cassidy return to Earth, Kazakhstan, 2012-2013

Questions?



PMMA sphere burning in 17% O_2 with occasional vapor jetting