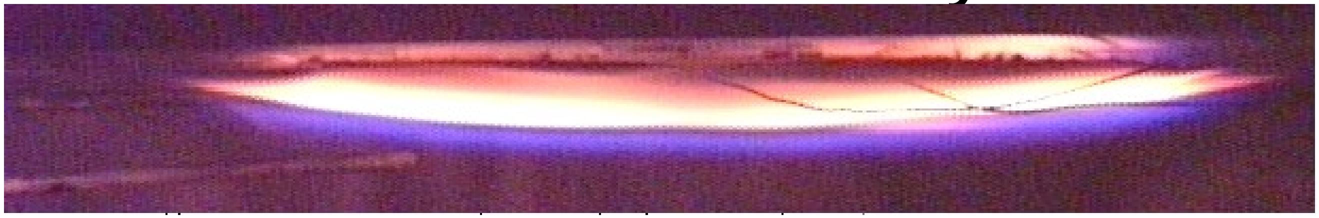
# An Inverted Cone Calorimeter with Forced Flow as a NASA Flammability Test Method



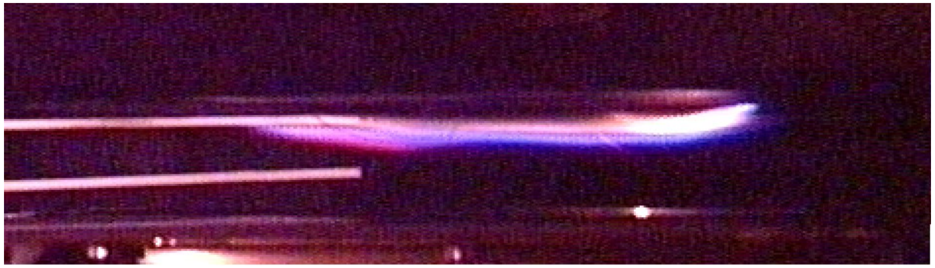
S. L. Olson & S. Gokoglu
NASA Glenn Research Center at Lewis Field

# Acknowledgements

•NASA Exploration Technology Development Program's Fire Prevention, Detection, Suppression program (FPDS).

NASA-Glenn

- Fletcher Miller
- David Urban
- Gary Ruff



NASA – WSTF

- Harold Beeson
- David Hirsch
- Jayme Baas
- Jon Haas
- Nate Greene

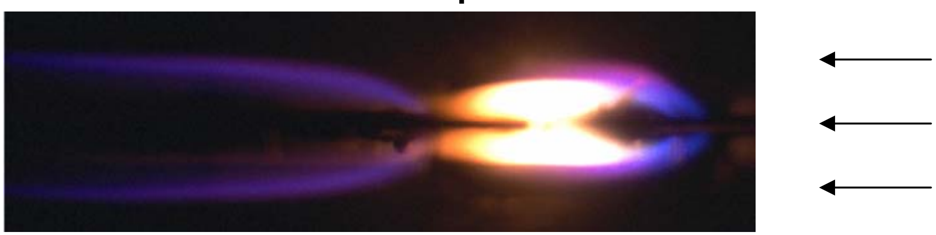
CWRU

- James T'ien

# Shortcomings of NASA's Current Tests

- NASA Test 1 is not always conservative. There are materials will support downward but not upward spread:
  - Certain charring foam materials.
  - Some materials containing fire retardants.

- Concurrent flame spread may not be the preferred direction in space.



- NASA Test 2 is not conservative for ignition delay or certain toxic products.

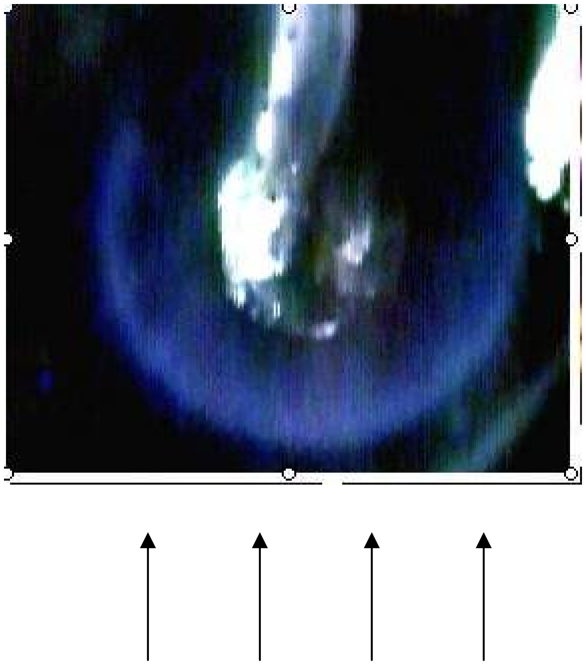
- Neither test considers gravitational or low-speed forced flow influences, now known to be important.

**NASA Test 1, "Upward Flame Propagation" test.**

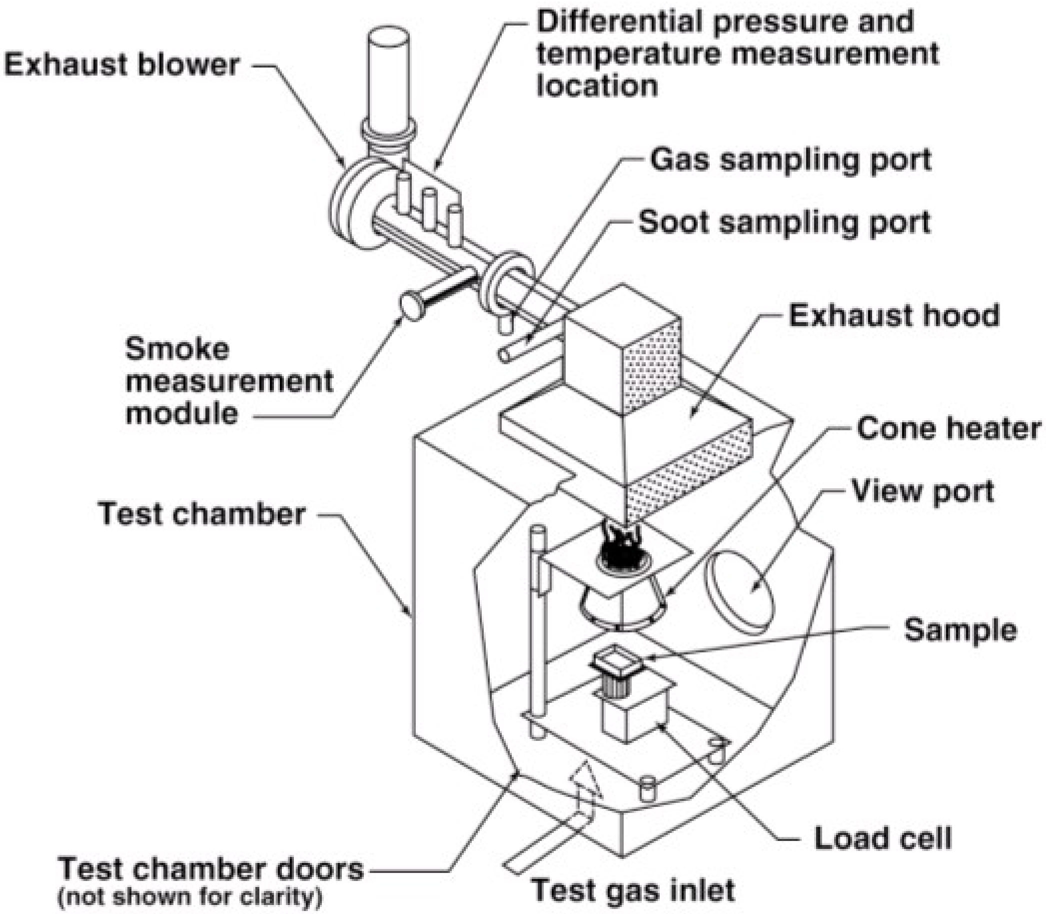
# Material Flammability Test Conundrum

- Most microgravity data is for thin solids.
- Most actual material applications involve thick solids.
- Long-duration microgravity periods, along with the proper facility, are needed to obtain data for thick solids.
- For the foreseeable future, there is no space-based facility to conduct solid fuel flammability tests.

**Pencil-size plastic rod**
**In Mir experiment**

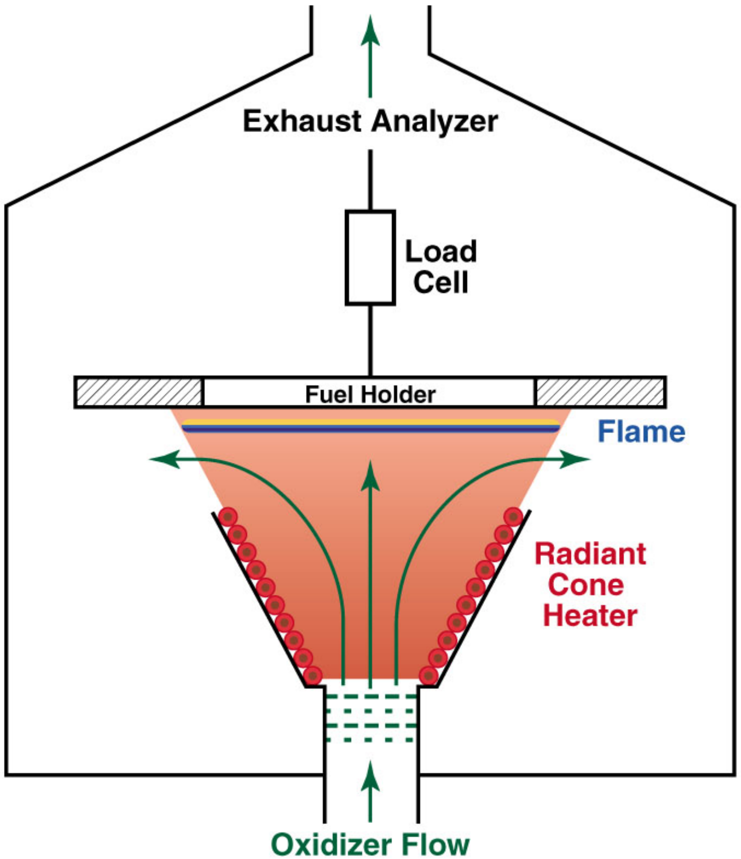


# ASTM and ISO Standard Cone Calorimeter – basis of NASA Test 2



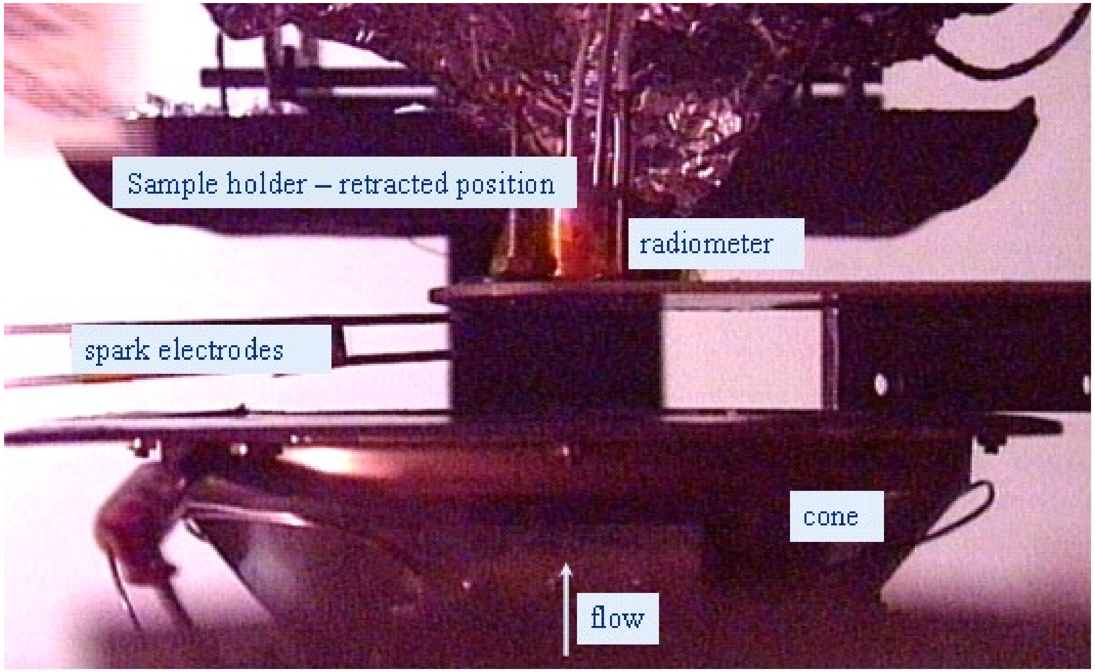

**WSTF Controlled Atmosphere Cone**

# Equivalent Low Stretch Apparatus (ELSA)

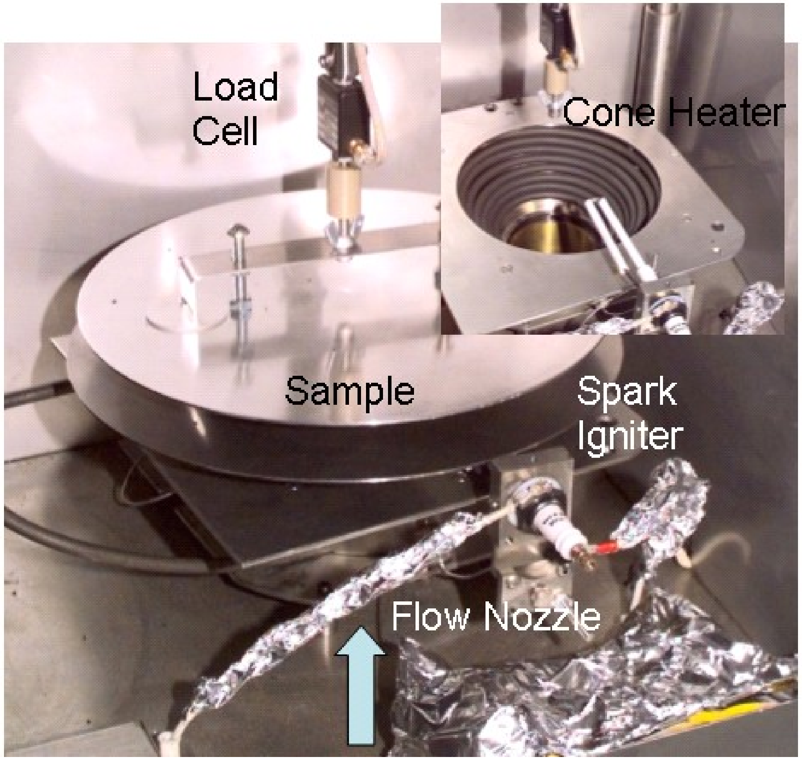



- Uses a familiar geometry
- Reduces but does not eliminate buoyancy
- Measurable quantities
  - Piloted Ignition Delay
  - Auto-ignition
  - Mass burning rate
  - Combustion products

# ELSA Prototypes



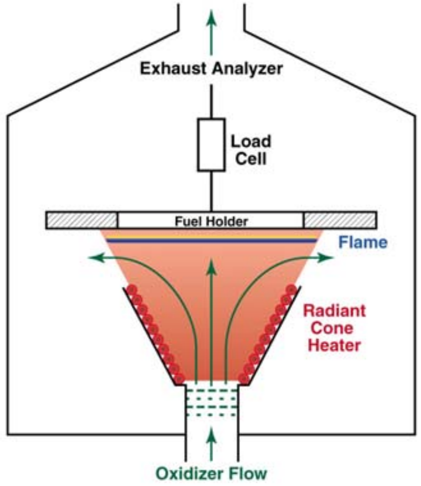

**WSTF's version uses a circular sample in a flat disk holder.**

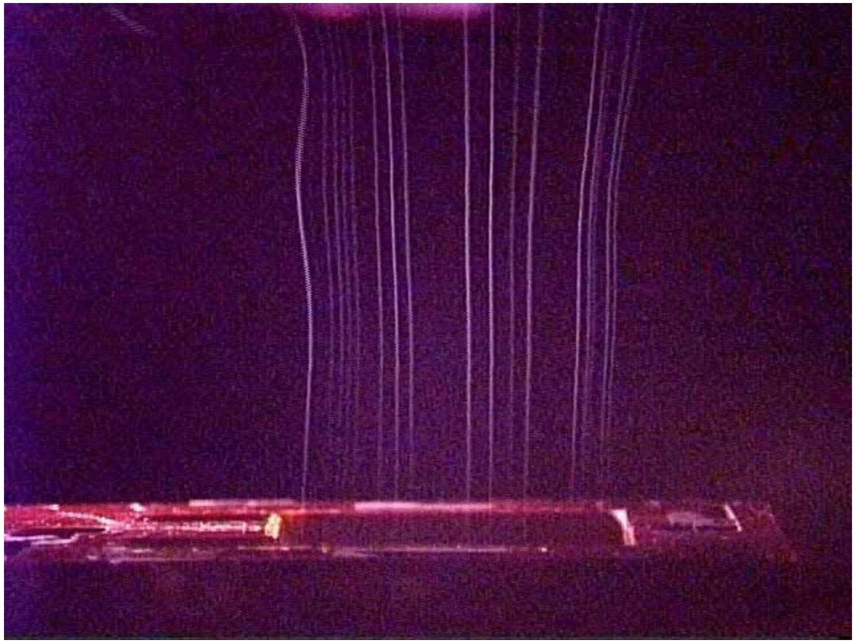


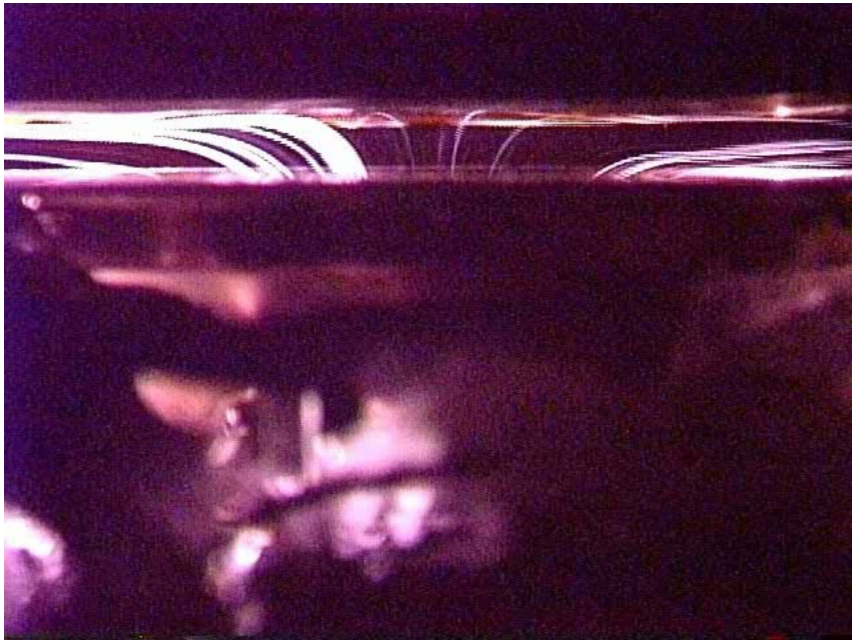

**Glenn's version uses a square sample in a curved edge holder, and does not have the load cell or exhaust analysis system.**

# Cellulose Ignition – ½ speed

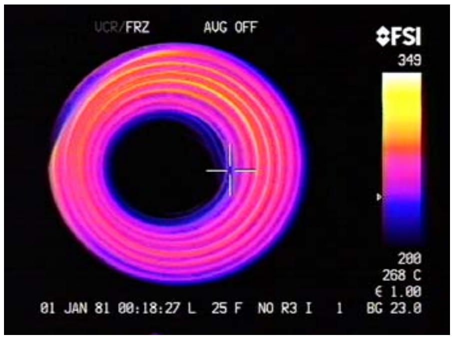
# Smoke flow visualization (isothermal cone)

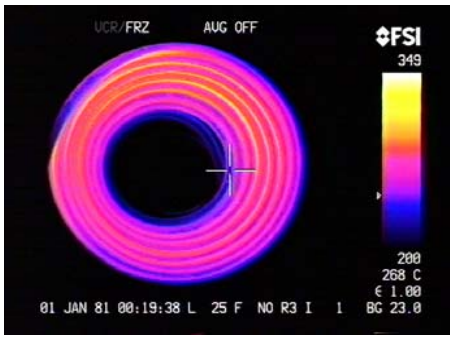


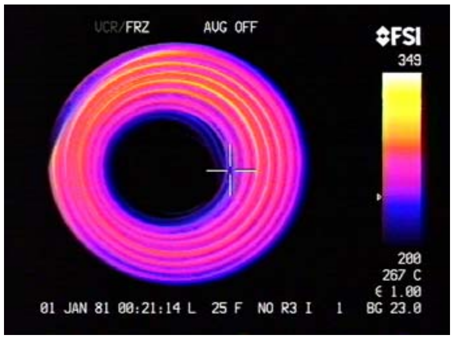



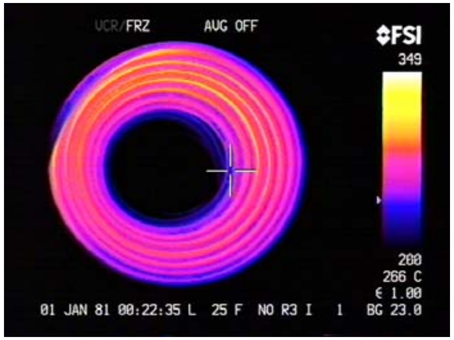


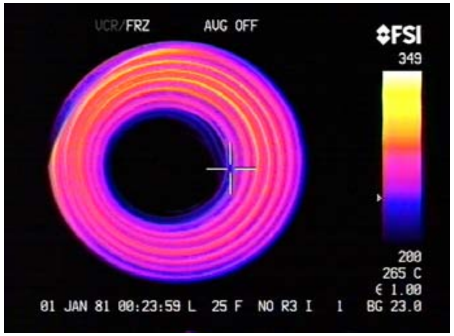
# IR images of Cone with Nozzle (0,5,10,15,20,25,30 s-1)

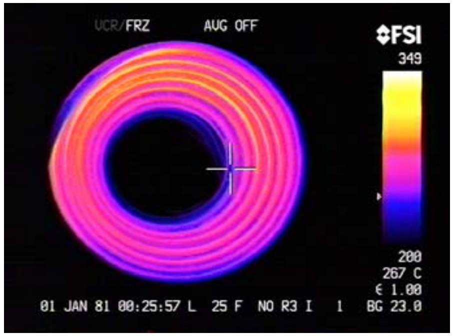


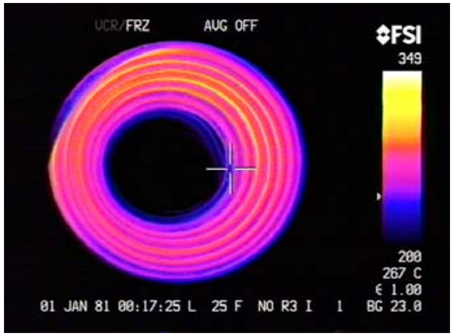




**No effect of flow on cone**

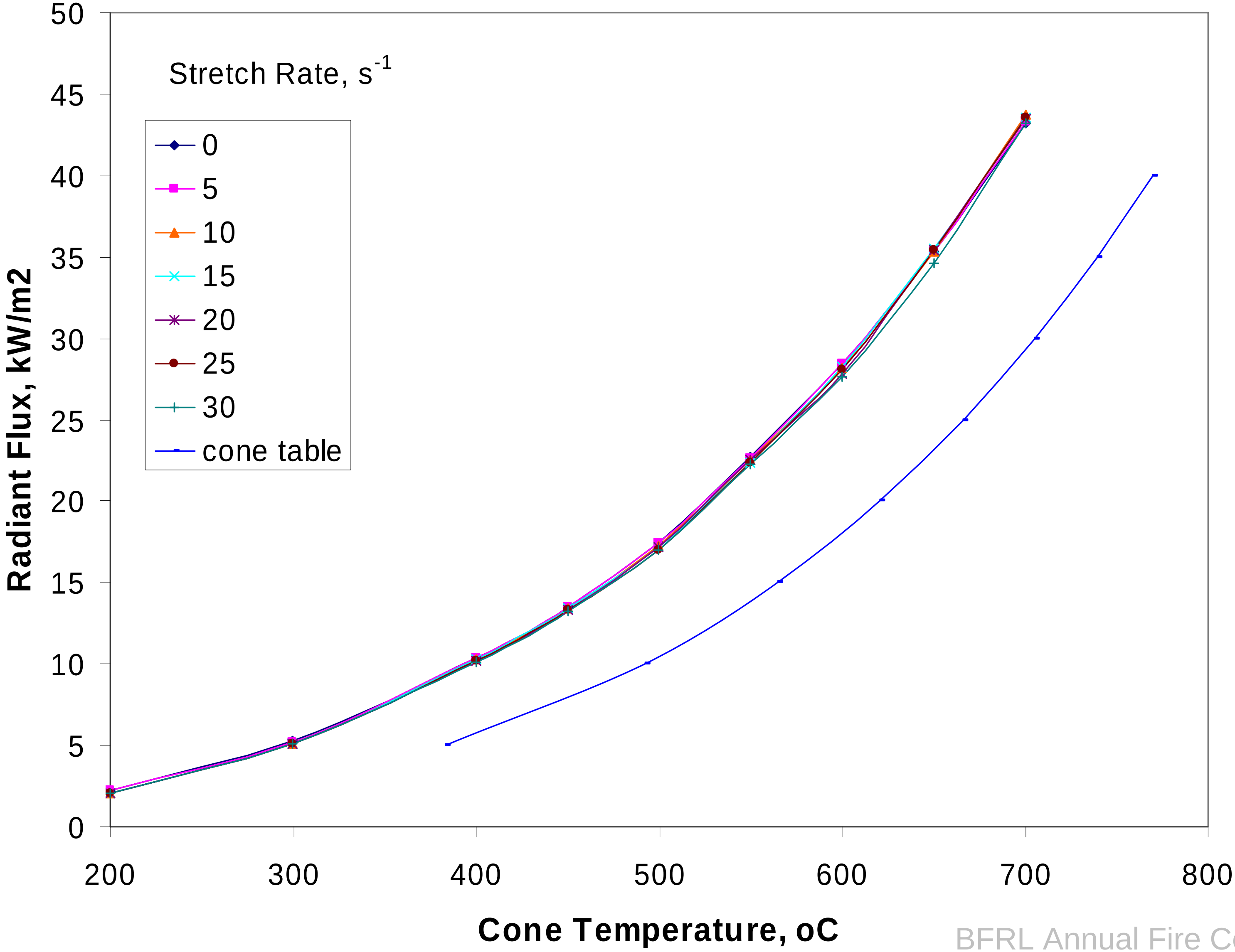


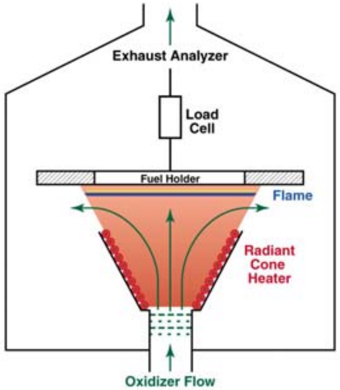
Glenn Research Center

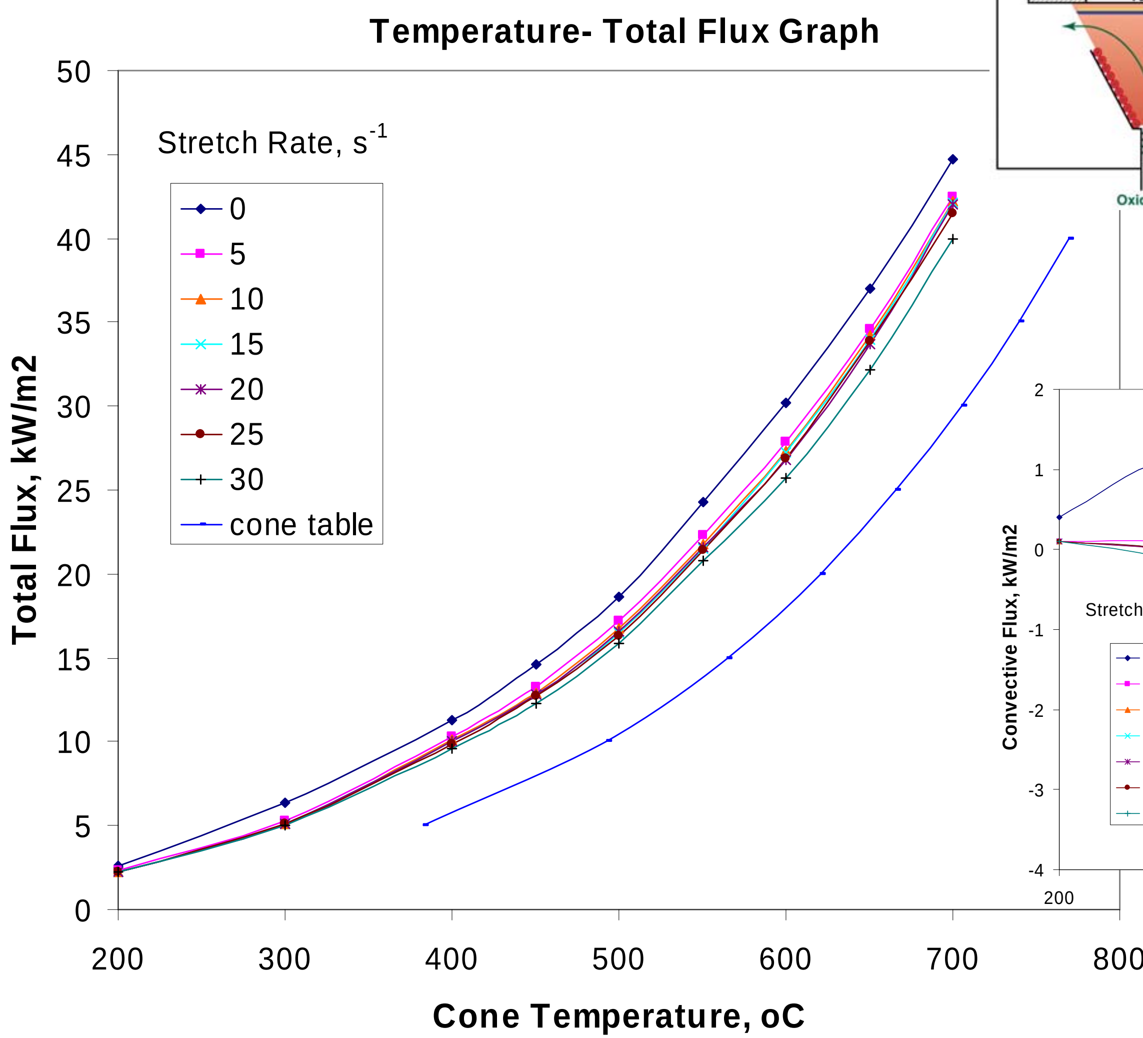
White Sands Test Facility

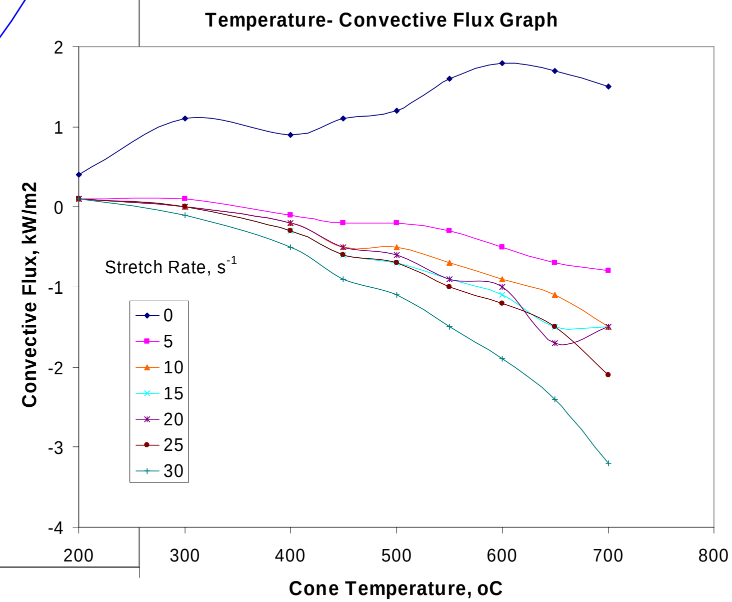
Las Cruces, New Mexico

# Temperature- Radiant Flux Graph

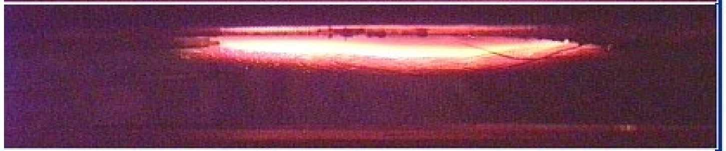
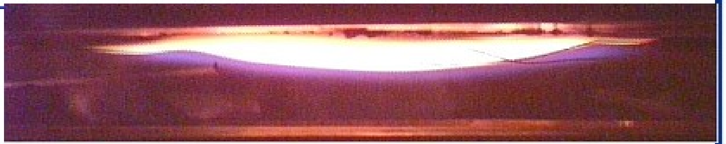
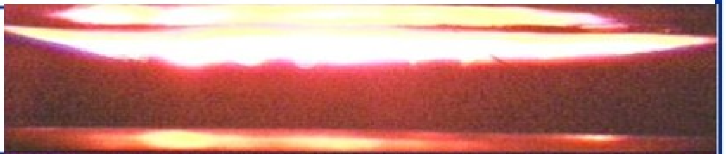
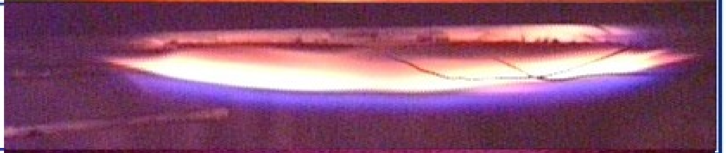



Exhaust Analyzer
Load Cell
Fuel Holder
Flame
Radiant Cone Heater
Oxidizer Flow


Temperature- Total Flux Graph
Total Flux, kW/m2
Cone Temperature, oC
Stretch Rate, s-1
0
5
10
15
20
25
30
cone table
50
45
40
35
30
25
20
15
10
5
0
200
300
400
500
600
700
800


Temperature- Convective Flux Graph
Convective Flux, kW/m2
Cone Temperature, oC
Stretch Rate, s-1
0
5
10
15
20
25
30
2
1
0
-1
-2
-3
-4
200
300
400
500
600
700
800

# Fuels Tested with ELSA

| Material | Thick-ness | Notes | Picture |
|---|---|---|---|
| Combitherm | 0.2 mm | waxy smell, melts, bubbles, and drips as it burns. (4 $s^{-1}$) Ignition in 7 seconds, completely consumed in 28s |  |
| Kevlar felt | 2 - 3 mm | minor odor, particle-laden flame. No deformation, flexible char. Ignition 63 s, self-extinguish after 25s, (4 $s^{-1}$) |  |
| Nomex felt | 12 mm | No ignition at 6.4 $s^{-1}$ for 2 minutes, Flashing of flame after flow off (4 $s^{-1}$) for minutes, but flame never sustained. Smoldering sample had to be extinguished with $H_2O$. |  |
| Pyrell foam | 5 mm | Ignited within 1-2s, burned completely within 20s, no dripping. Strong odor. 6.4 $s^{-1}$ |  |
| PMMA | 24 mm (clear, cast) | Ignited 34 s, no dripping. Sizzles as it burns. Can measure regression rate for this thick material. Does not char. |  |
| Cellulose | ~ 0.1 mm | Ignited 14 s. Moisture sensitive so more scatter in ignition delays. Burns away leaving thin fragile black char fragments. |  |
| Kydex 100 | 1.4 mm | Ignited 43 seconds. Swells and chars as it burns. Bright luminous flame. Smells acrid, and products are corrosive and toxic. Self-extinguishes in air if heat flux is removed. |  |

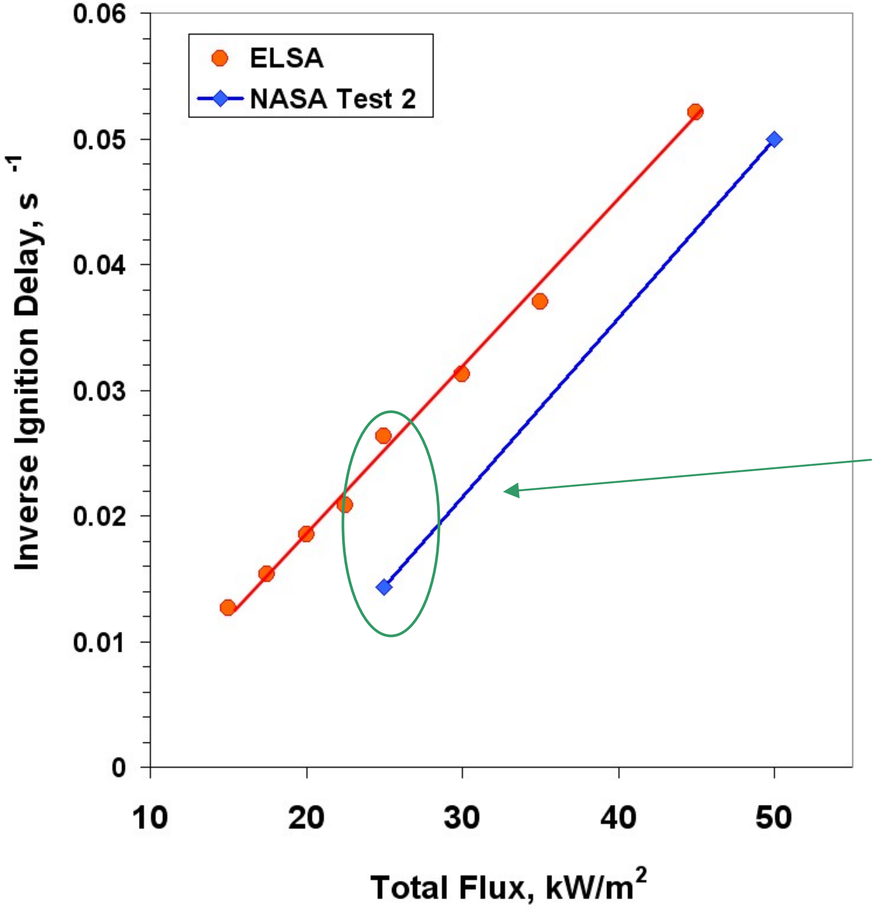
# KYDEX testing

- Kydex 100 (PMMA + PVC)
  - Passes most flammability tests (incl. NASA Test 1 for STS, ISS)
  - Applications in aircraft, mass transit vehicle interiors
  - Used in Test 1 as a calibration material

| | PVC | PMMA | Test 1 extinction limit |
|---|---|---|---|
| LOI | 45-50% | 17% | 29% (14.7 psia) |

**Ignition Delay** -Test 2 (STD-6001) 70 s (25, 30% $O_2$)
(25 $kW/m^2$)

# ELSA Kydex Ignition Delay in AIR




Ignition delay for a thin fuel

$$\frac{1}{t_{ign}} = \frac{\pi}{4} \frac{\dot{q}''_{net}}{\rho \tau C_p \Delta T_{ign}}$$

**Ignition Delay** at 25 kW/m2

-Test 2 (STD-6001) 70 s *(25, 30%O2)*

- ELSA 44 s *(21%)*

Can evaluate material's effective thermal response parameter (TRP) from data.

# FLUENT Model

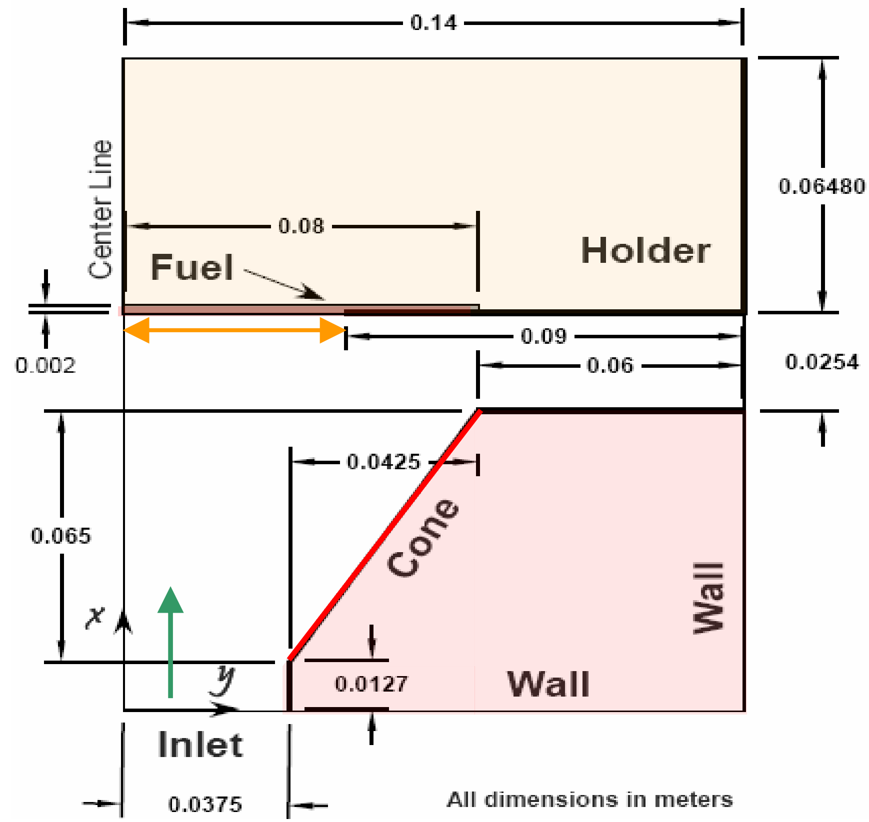
Objectives:

1) Determine the lower stretch limit and overall flow patterns.

2) Use as a design optimization tool to improve the device.

Axisymmetric geometry

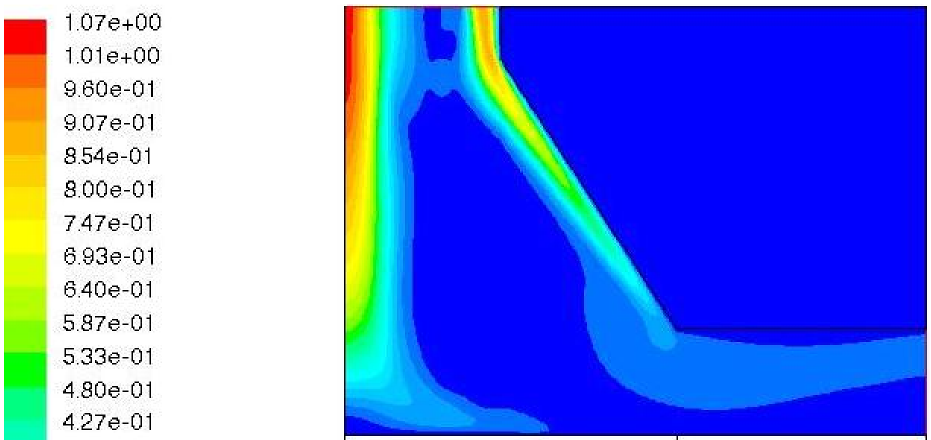
- Cone 950K (~ 25 kW/m2)
- Inert fuel 600K
- Adiabatic holder and wall
- No combustion or fuel vapor (yet)



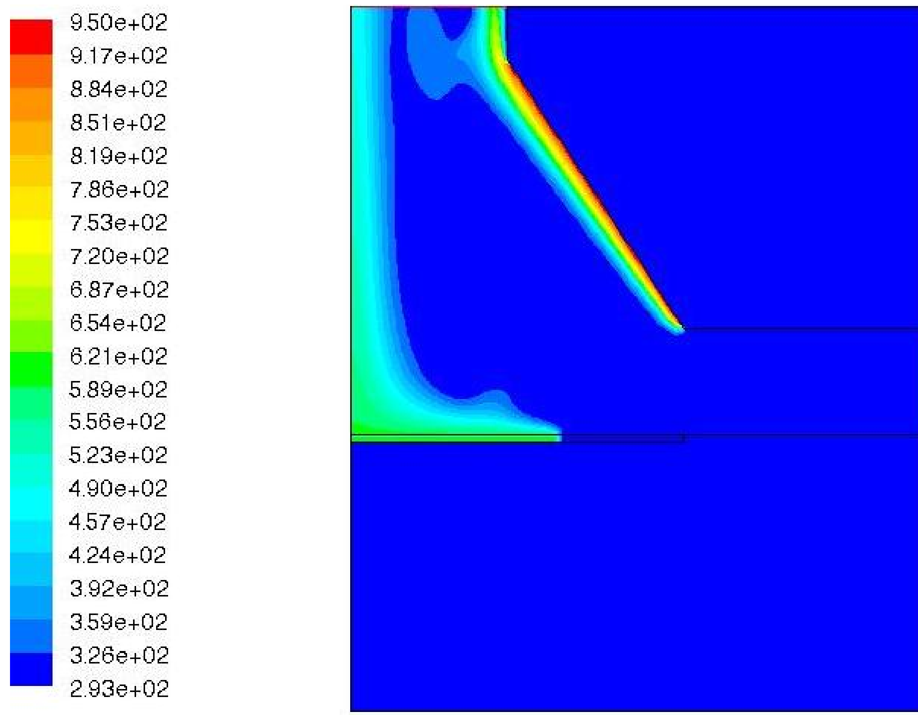

Stretch = $U_J/D$

# Inverted (std cone) open top

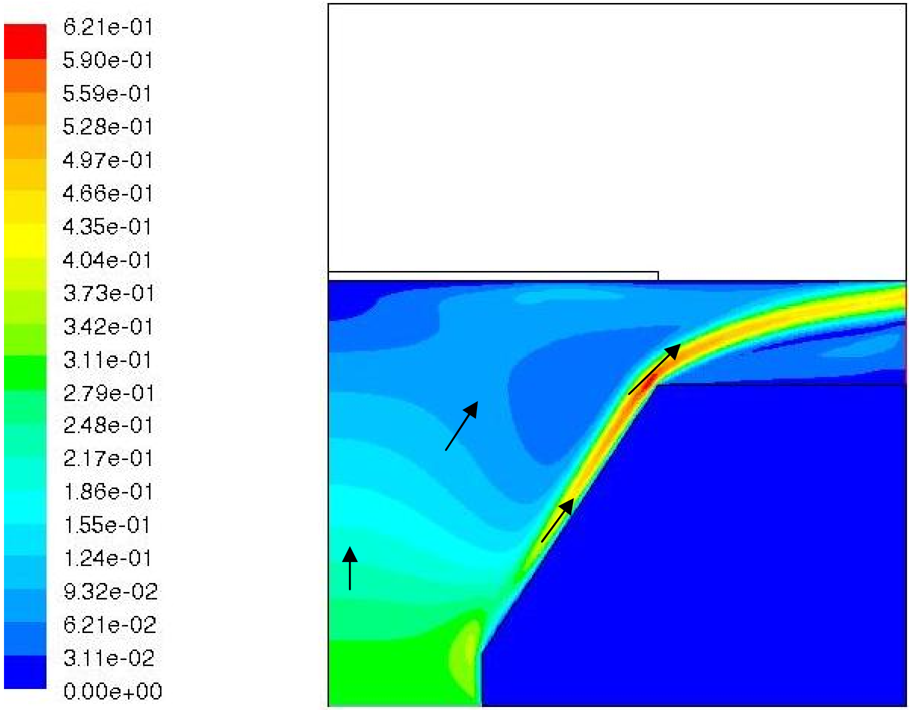
## Velocity magnitude (m/s)



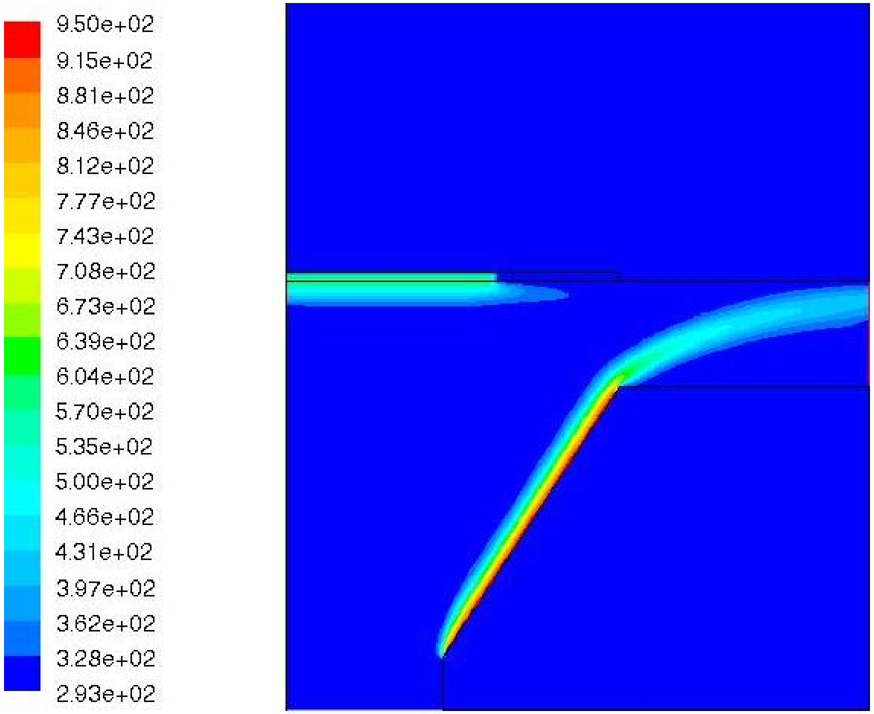

## temperature (K)



# $a_f = 4\ s^{-1}$

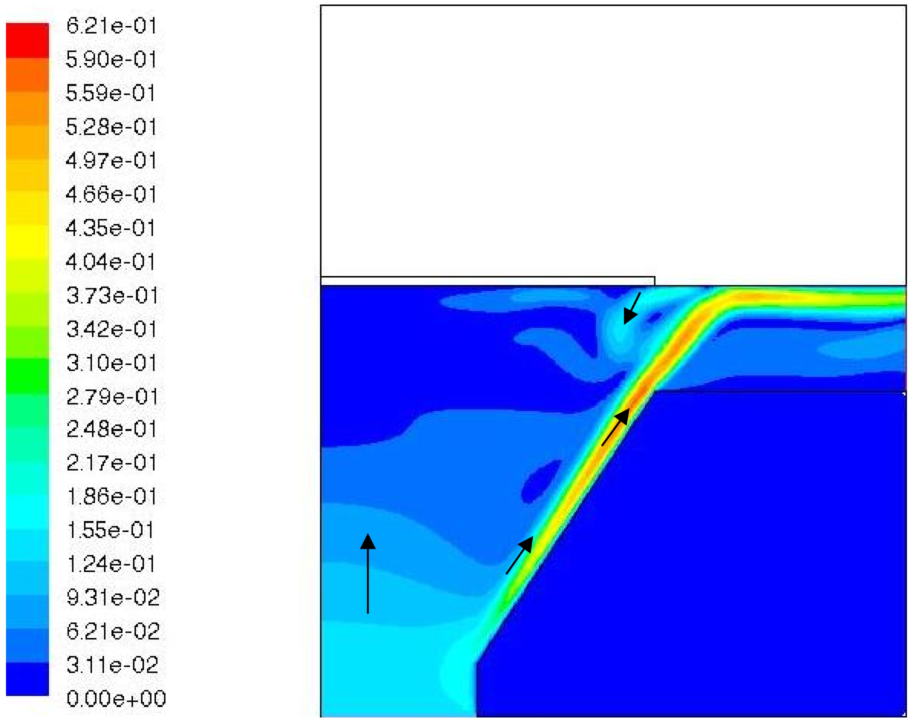



**Velocity magnitude (m/s)**

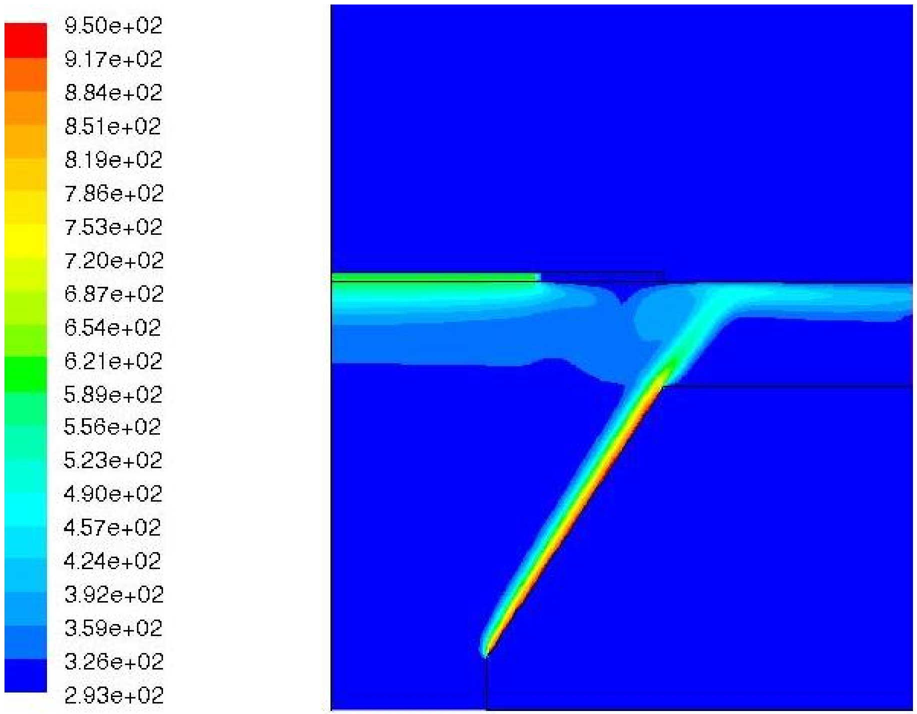



**temperature (K)**

# $a_f = 2\ s^{-1}$

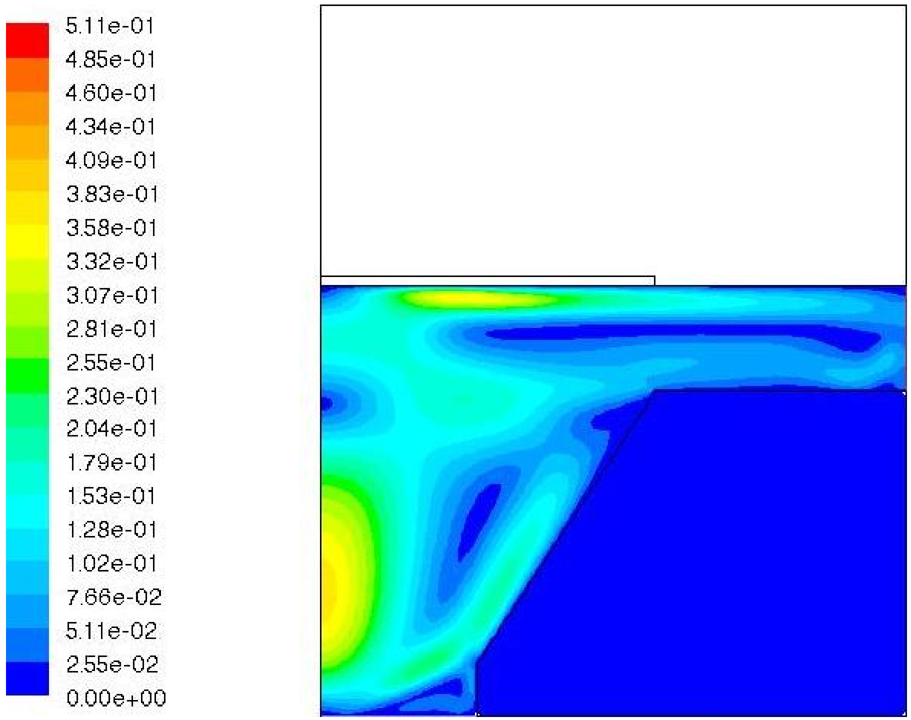



Velocity magnitude (m/s)

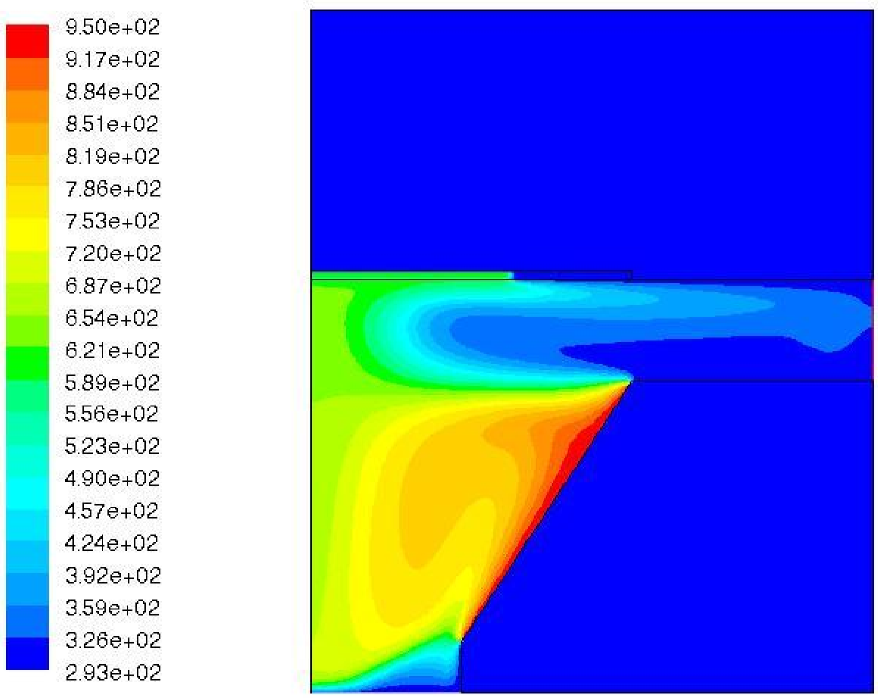



temperature (K)

# $a_f = 0\ s^{-1}$ closed bottom

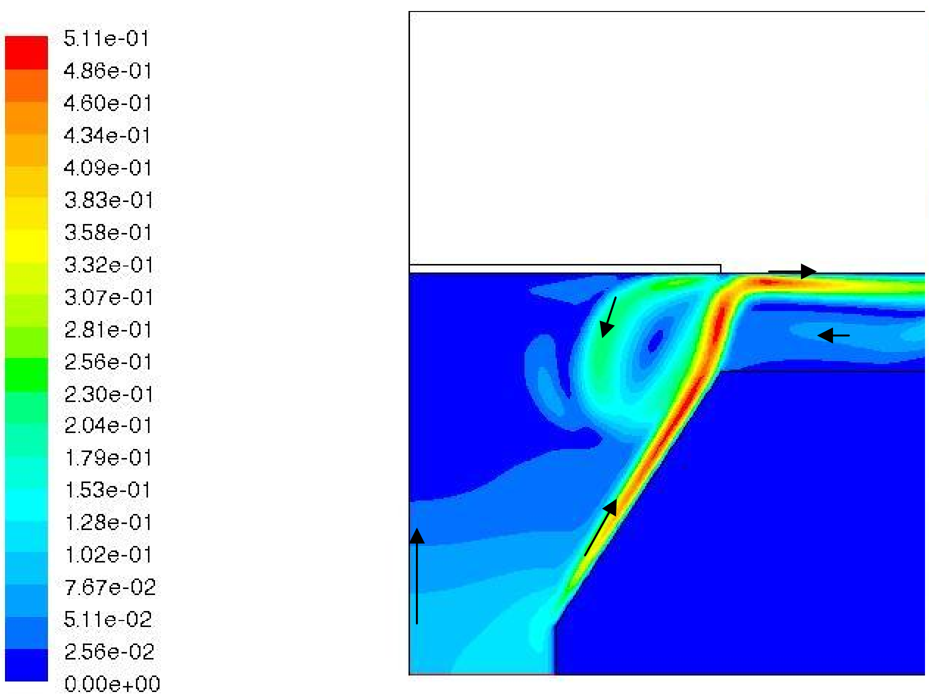


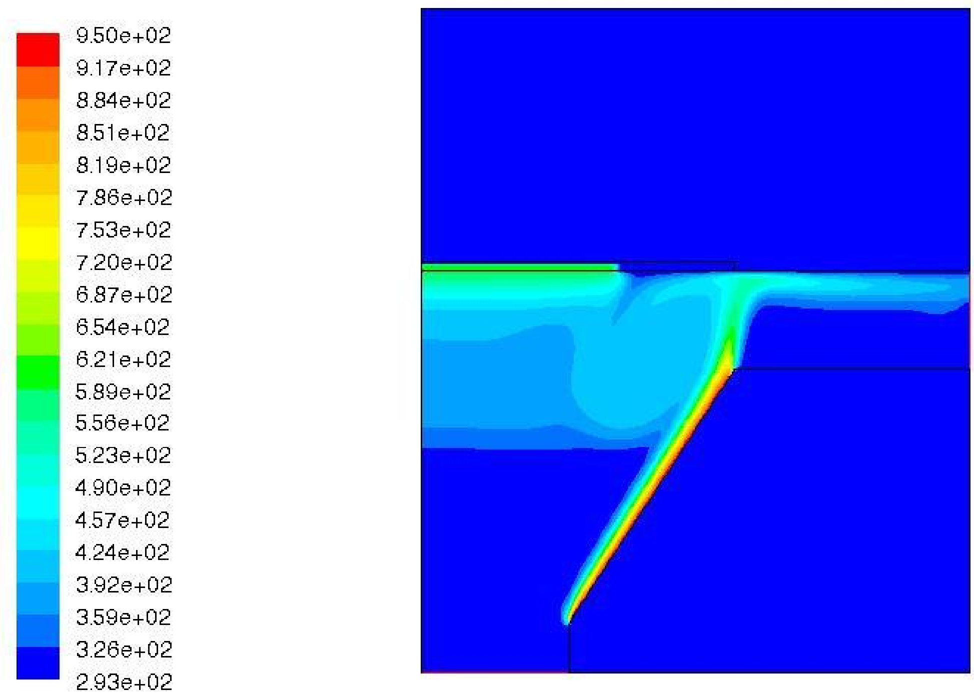

**Velocity magnitude (m/s)**




**temperature (K)**

# open bottom




**Velocity magnitude (m/s)** **temperature (K)**

# Summary

ELSA is one of three test methods NASA is evaluating for use with exploration atmospheres (high $O_2$, low pressure) [FIST, Narrow Channel].

Buoyant flow due to gravity is minimized by igniting and burning the material in a ceiling fire configuration.

Axisymmetric Geometry: stagnation flow and uniform flux from cone.

Various fuels have been tested. Dripping and swelling are ameliorated with screens.

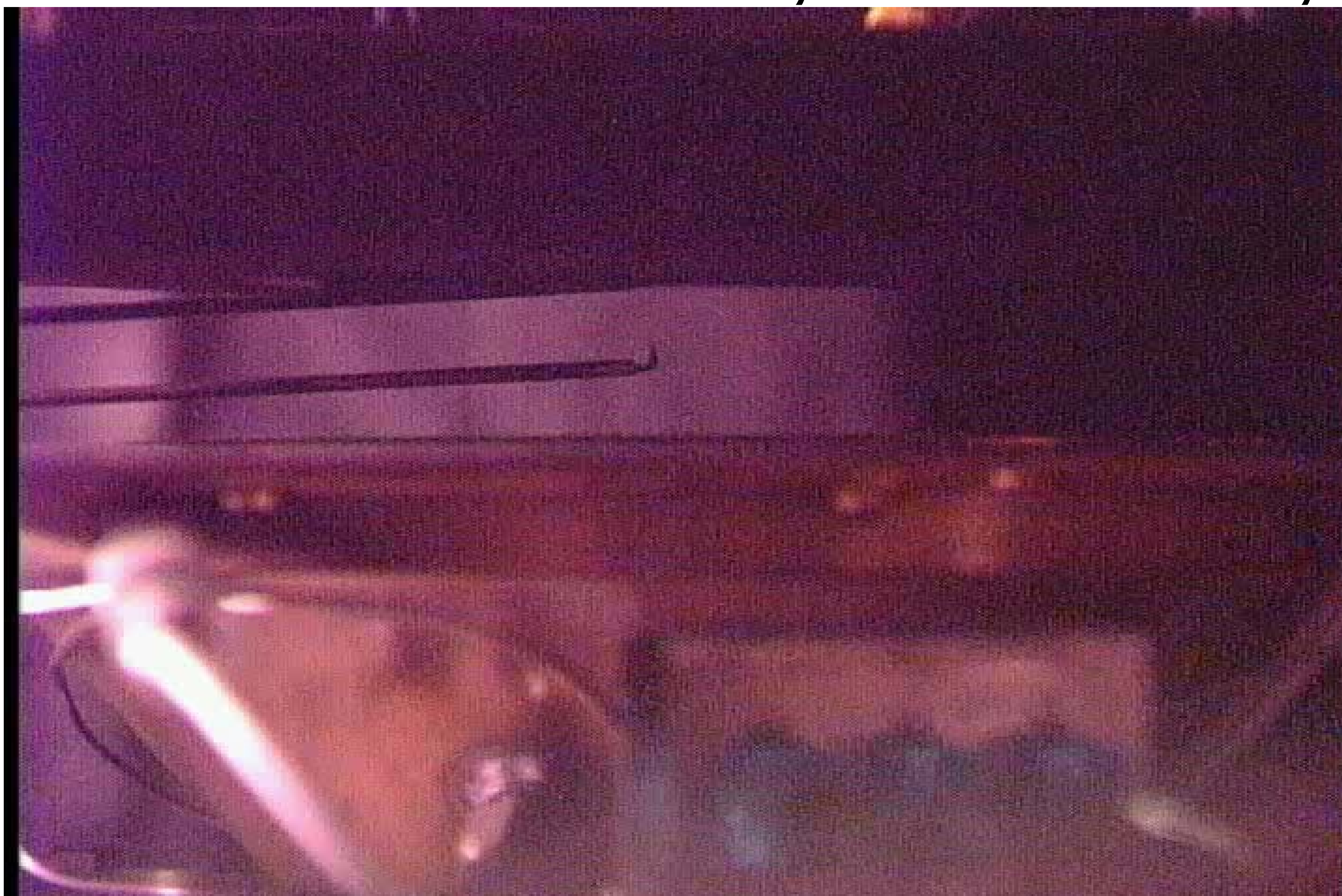
ELSA compared to NASA Test 2:

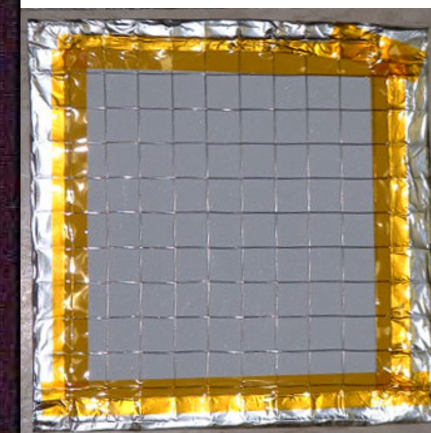
- shorter ignition delay
- slower burning rates
- reduced heat release rates
- increased CO rates

Recent FLUENT modeling show that the inverted cone is the preferred geometry for minimizing buoyant flow effects. The model is serving as a guide to optimize the device.

# Backups

# Kydex Ignition Test
# forced 0 $s^{-1}$, 25 kW/m2, air





# Thermally Thin Theory (Quintiere, F&M 2006)

$$\frac{1}{t_{ign}} = \frac{\pi}{4} \frac{\dot{q}''_{net}}{\rho \tau C_p \Delta T_{ign}}$$

<u>Kydex Properties</u>

$\rho$ = 1.35 g/cc = 1.35x$10^6$ g/$m^3$

$\tau$ = 0.14 cm = 0.0014 m

Cp = 1.21 J/g °C = 0.00121 kJ/g °C

$\Delta T_{ign}$ ~ 300-400 °C

Slope based on properties

400°C

0.00086 kJ/$m^2$

300°C

0.0011 kJ/$m^2$

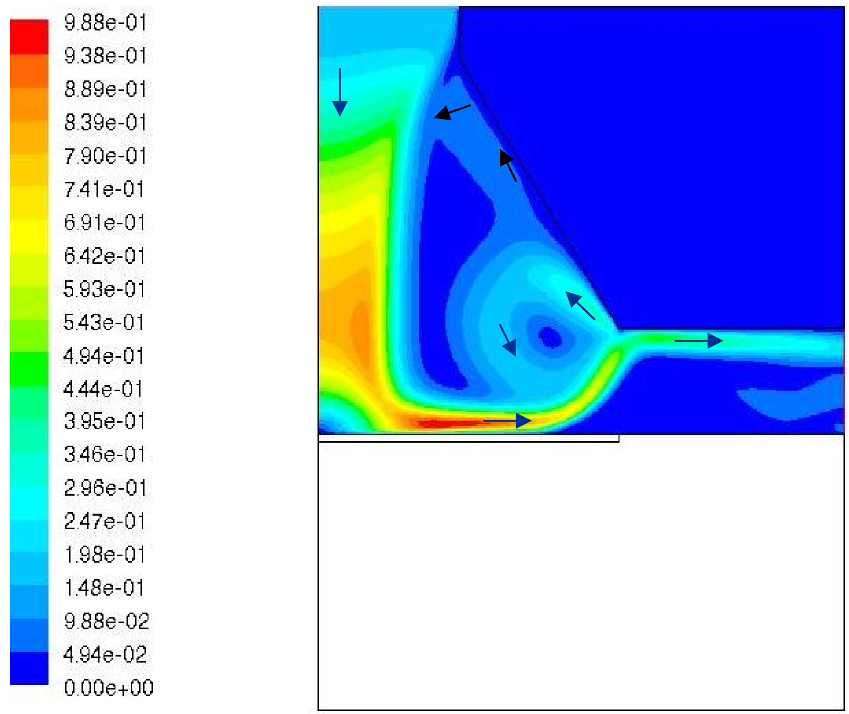
Slope from data

0.0013 kJ/$m^2$

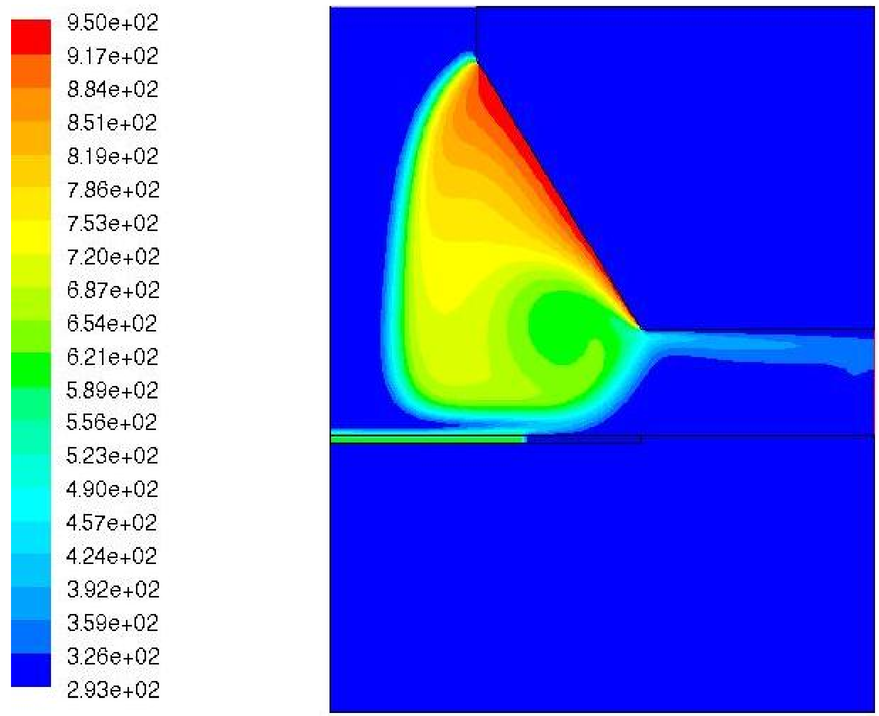
Ratio actual/theo ~ 1.5 (400°C)

~ 1.1 (300°C)

# Inverted (std cone) $a_f = 2\ s^{-1}$




**Velocity magnitude (m/s)**




**temperature (K)**

# For more details…….


- Armstrong, J.B., Olson, S.L., and T'ien, J.S.; "Transient Model and Experimental Validation of Low Stretch Solid-Fuel Flame Extinction and Stabilization in Response to a Step Change in Gravity", ***Combustion and Flame***, V.147, pp 262-277, 2006
- Olson, S.L., Beeson, H.D., Haas, J.P., and Baas, J.S.; “An Earth-Based Equivalent Low Stretch Apparatus for Material Flammability Assessment in Microgravity and Extraterrestrial Environments”, ***Proceedings of the Combustion Institute*****,** Vol. 30/2 pp 2335-2343, Jan. 2005.
- Olson, S.L., and T’ien, J.S.; “Buoyant Low Stretch Diffusion Flames Beneath Cylindrical PMMA Samples”, ***Combustion and Flame***, V.121, pp. 439-452, 2000.