Thermal Model of MEMS Thruster

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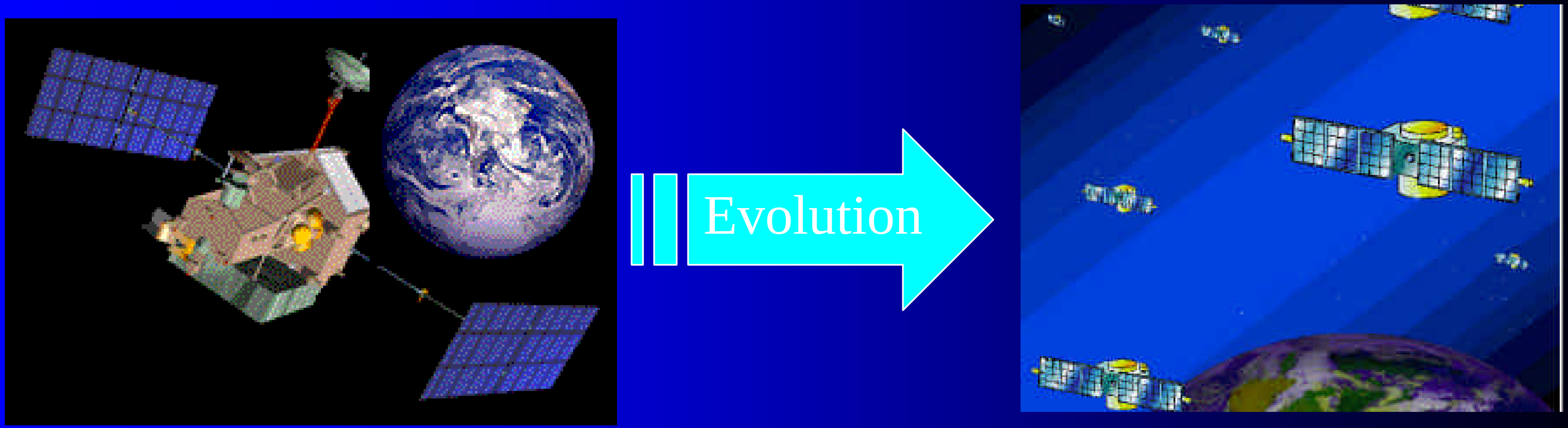
Code 597

Overview

- Introduction
- Statement of Problem
- Approach
- Results
- Conclusion

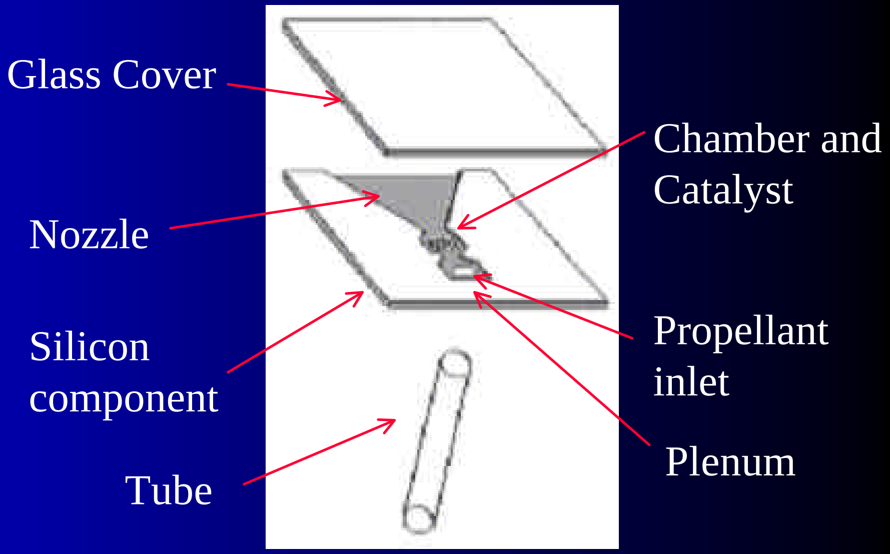
Introduction

- Innovative science missions call for nanosatellites that are smaller, low-cost, and efficient.
- Nanosatellites require micro-components such as instruments, power, and propulsion.
- Current propulsion technology is not available for this application.
- GSFC is developing monopropellant MEMS thruster, applicable to the nanosatellites.



MEMS Thruster

- Monopropellant MEMS (Micro-Electro-Mechanical) thruster goals:
  - Thrust: 10-500 µN
  - Impulse Bit: 1-1000 µN-s
  - Specific Impulse:
    - 130 seconds (Hydrogen Peroxide)
    - 200 seconds (Hydrazine)
- MEMS thruster is fabricated of silicon component and glass cover.
- Nozzle, plenum, chamber and injector are etched in silicon.
- Monopropellants:
  - Hydrogen Peroxide, H_2O_2
  - Hydrazine, N_2H_4
- Catalysts:
  - Silver
  - Platinum on Aluminum oxide



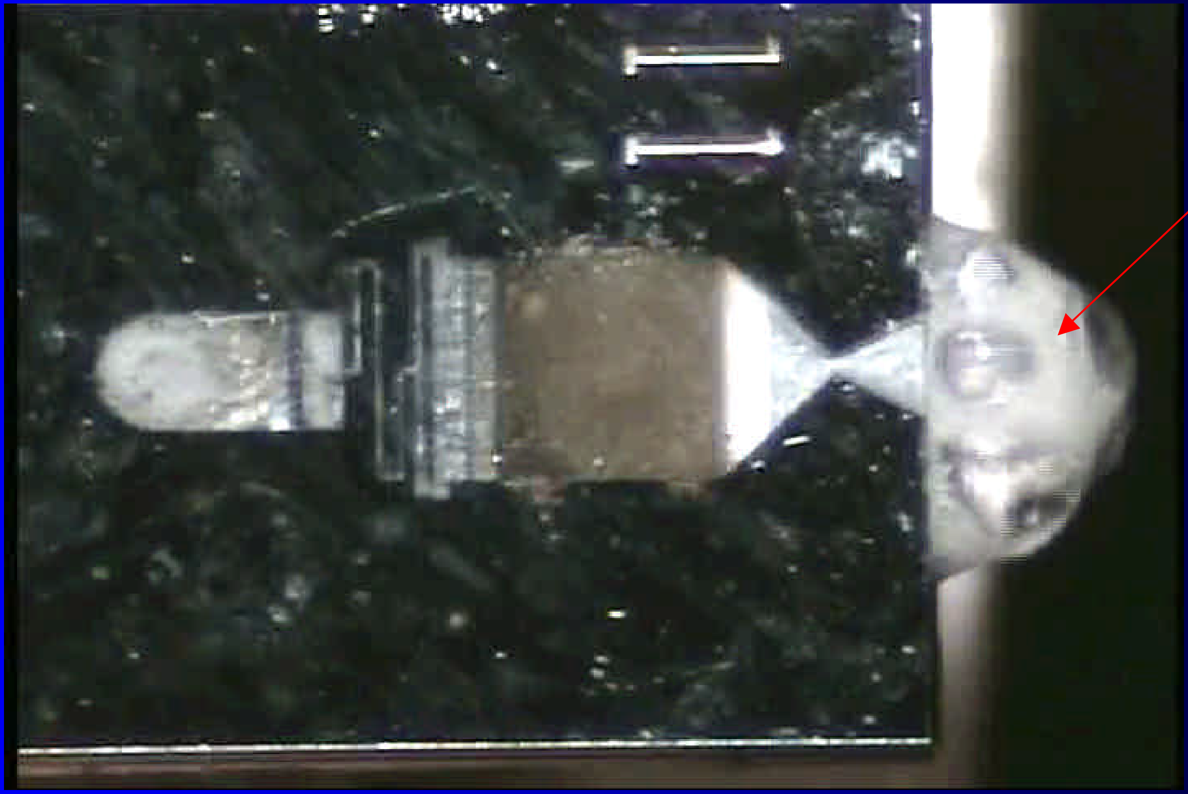
GSFC MEMS Thruster Demo

$H_2O_2\ (l) + n\ H_2O\ (l) \rightarrow (1+n)\ H_2O(g) + 1/2\ O_2\ (g) + \text{Heat.}$

Experiment Conducted by
Code 574 Propulsion Team

Statement of Problem

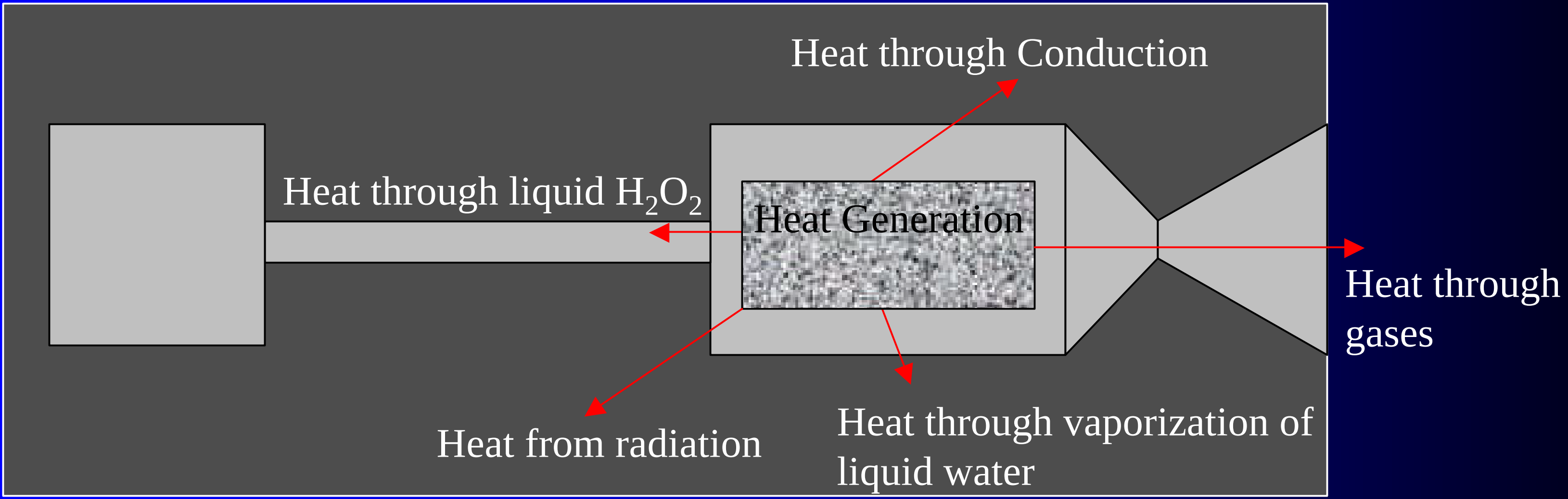
- Problem: Determine why full decomposition of hydrogen peroxide is not occurring in the MEMS Thruster.
  - Suspected Cause: Poor Thermal Design
  - Consequences:
    - Lower exit velocity and specific impulse
    - Low performance



Liquid and Gas exhaust products

Approach to the Problem

- Evaluate applicability of ANSYS software to analyze flow through MEMS passages
- Develop thermal model of the baseline MEMS thruster design
- Determine characteristic design parameters that need to be changed in Baseline MEMS design to increase chamber temperature

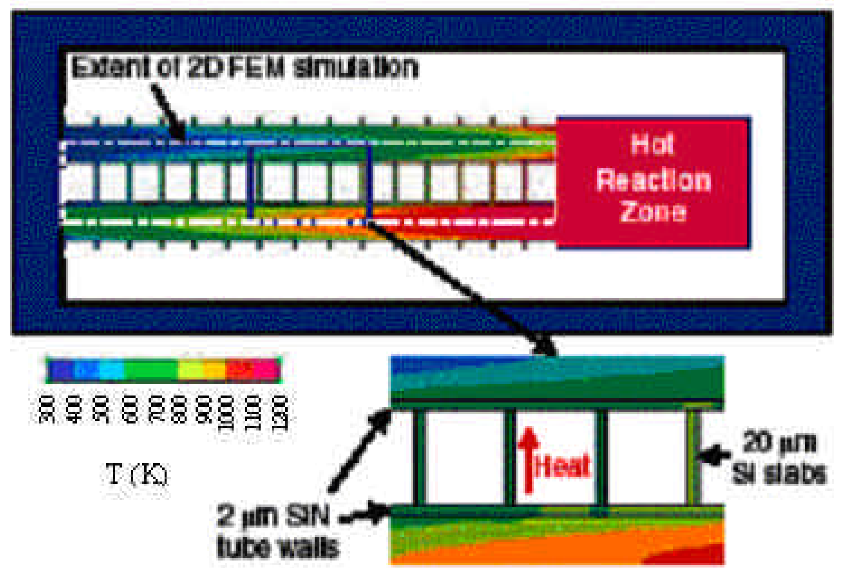


Analysis Tool

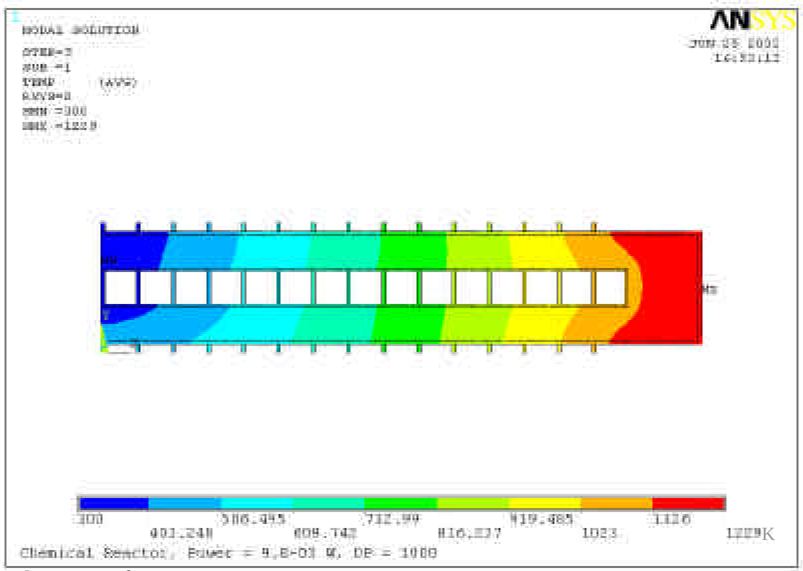
- Use ANSYS fluid module to determine the temperature profile and heat loss.
  - ANSYS Computational Fluid Dynamics module: FLOTRAN
- Limitations of FLOTRAN:
  - Single fluid (liquid or gas phase)
  - Either incompressible or compressible flow
  - Incapable of doing chemical reactions

FLOTRAN Validation

- Duplicate the fuel cell model performed analytically and experimentally by MIT
- The results are in good agreement.
- Difference in temperature due to different boundary conditions.



CFD-ACE Software



Flotran Software

MIT Analysis

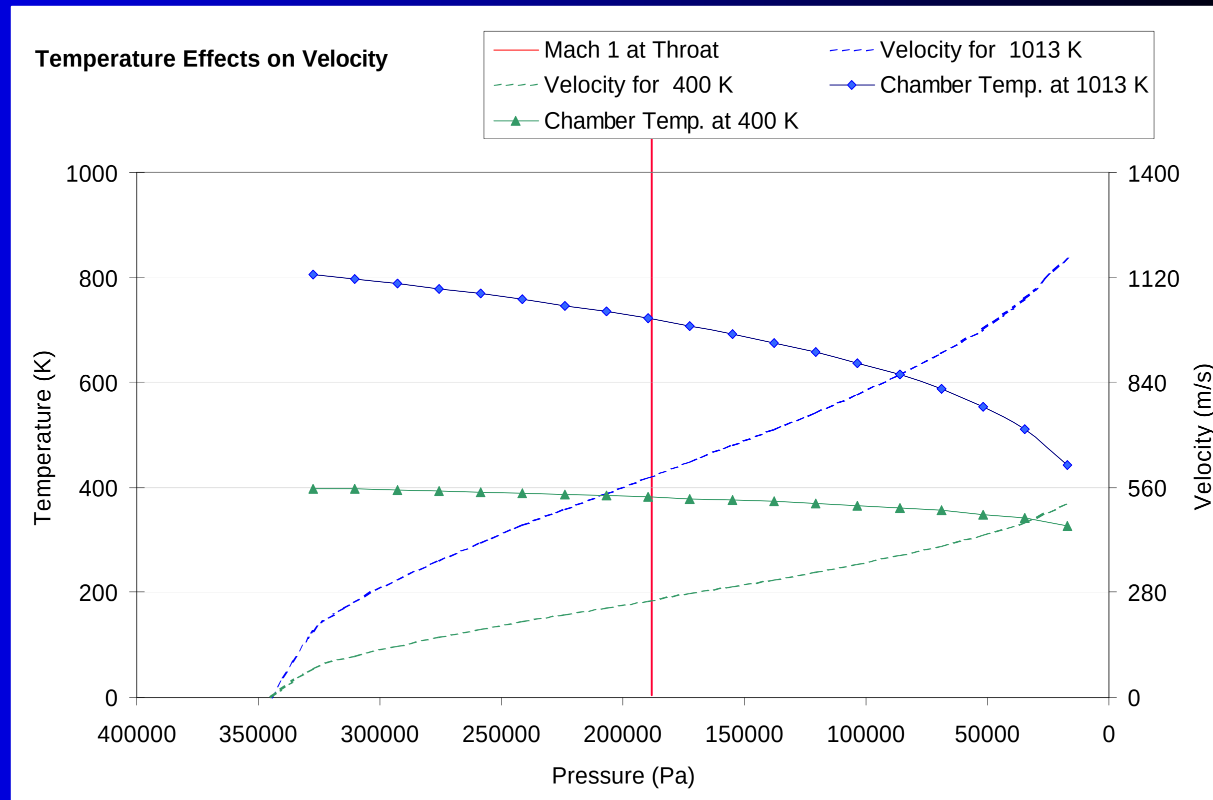
GSFC Analysis

Assumptions and Limitation

- Assumptions of Thruster Model
  - Steady State
  - 100 % complete decomposition
  - Fluid is incompressible liquid hydrogen peroxide
  - Thruster Nozzle Not included
  - Ambient air convection
  - Radiation neglected
    - It will be included in future.
- Limitation of Thruster Model
  - Fluid Solver (FLOTRAN) can't perform chemical reaction, so the temperature may be higher than adiabatic flame temperature

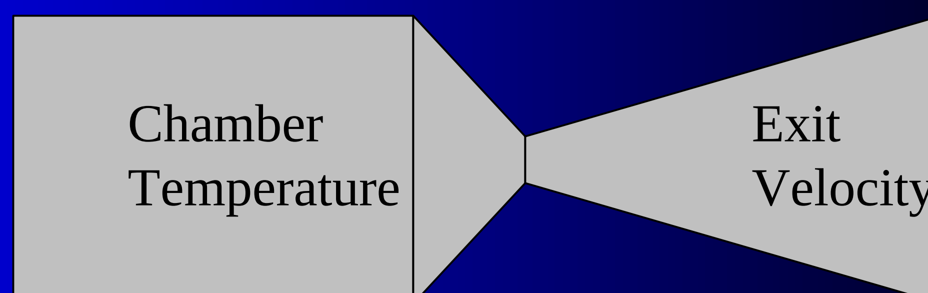
Justification for Deleting Nozzle

- Nozzle have compressible gas. The model is only analyzing incompressible liquid.
- Exit velocity strongly depends on chamber temperature.



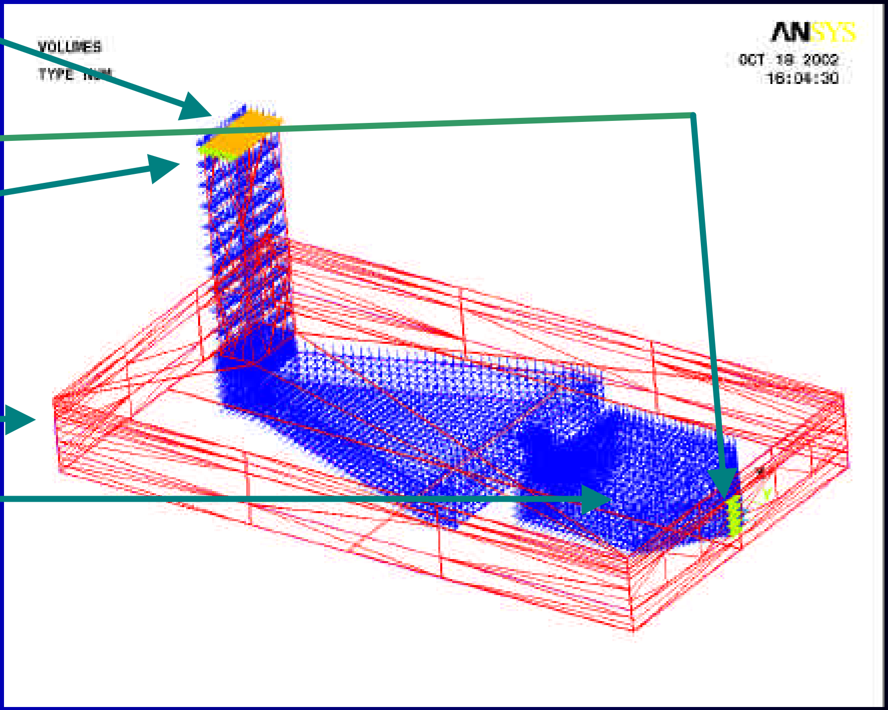
$$v_x = \sqrt{\frac{2\gamma R T_o}{(\gamma - 1)M}\left(1 - \left(\frac{P_x}{P_0}\right)^{\frac{\gamma - 1}{\gamma}}\right)}$$

$$T_x = T_o\left(1 - \frac{(\gamma - 1)v_x^{2}}{2\gamma R T_o}\right)$$



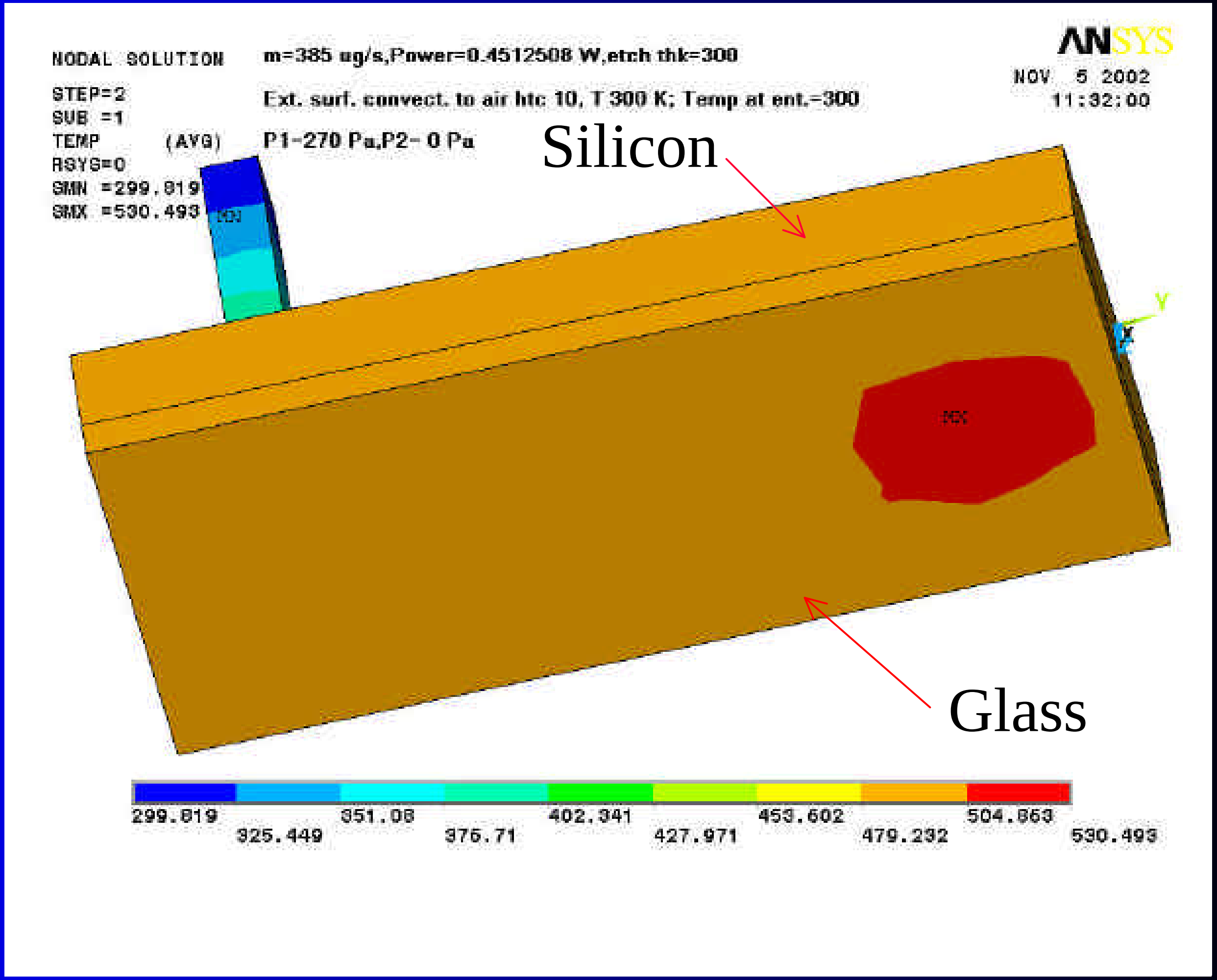
Element and Boundary Conditions

- 3D CFD Fluid Element Type in model - FLUID142
- Inlet Pressure Range: 270 Pa to 350 kPa (0.04 psi to 50 psi)
- Outlet Pressure: 0 Pa
- Temperature Fixed at 300 K at entrance
- Exterior Surface exposed to ambient air convection.
- Uniform heat generation in the chamber



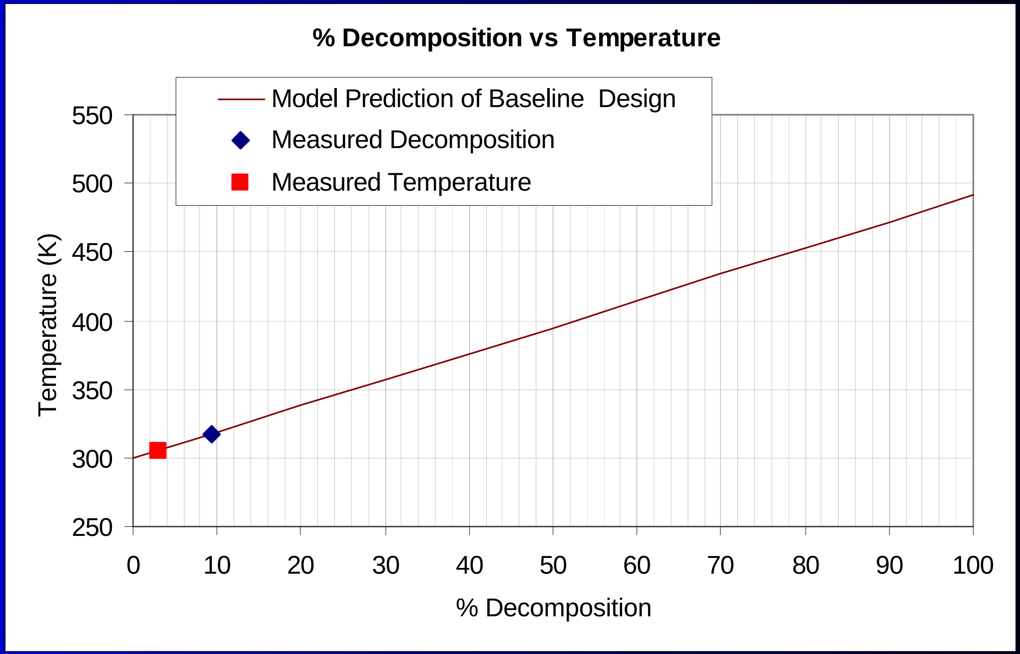
Thermal Model of Baseline Design

- Assumption
  - Mass Flow Rate: 385 µg/s
- Calculation
  - Heat Generation: 0.45 W
- Model Prediction:
  - Maximum Temperature: 530 K



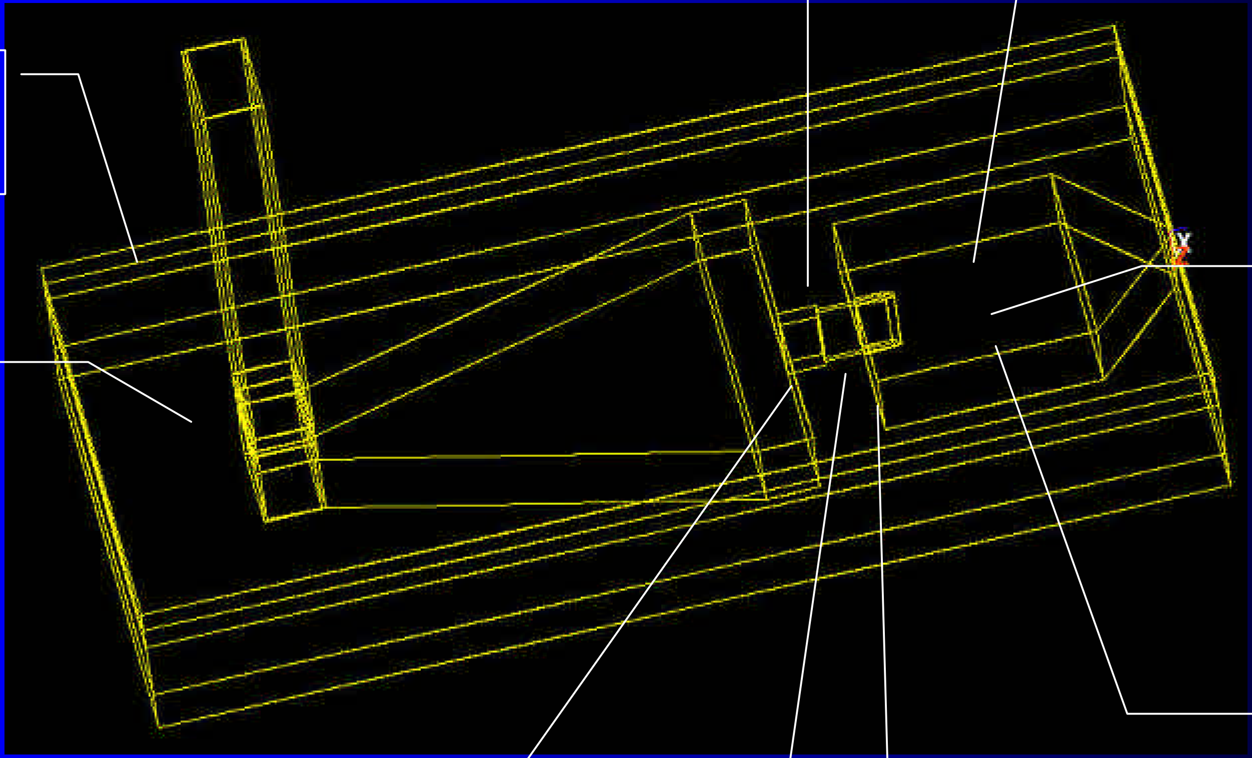
Model Validation of Baseline Design

- Two measurements:
  - Temperature on Thruster
  - Decomposition of exhaust products, liquid $H_2 0_2$ and liquid water, collected on refractometer



- Measured 305 K on glass cover
- Measured 9% decomposition based on exhaust products. It correlate to 315 K.
- Temperatures reasonably close to each other. Possible source of error: Thermocouple is in poor contact with glass cover.

Thruster Redesign Parameters



Cylinder Model

Chamber Sizing Analysis

Thermal Conductivity

Material Volume

Reaction Time

Chamber Length

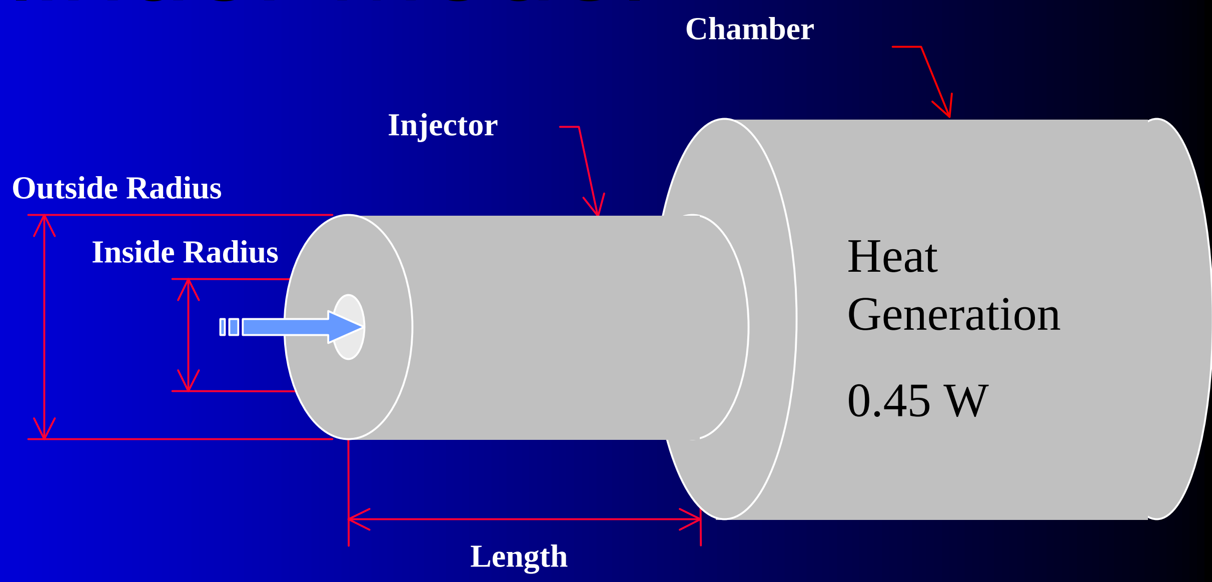
Fluid Velocity

Injector Length

Injector Diameter

Cylinder Model

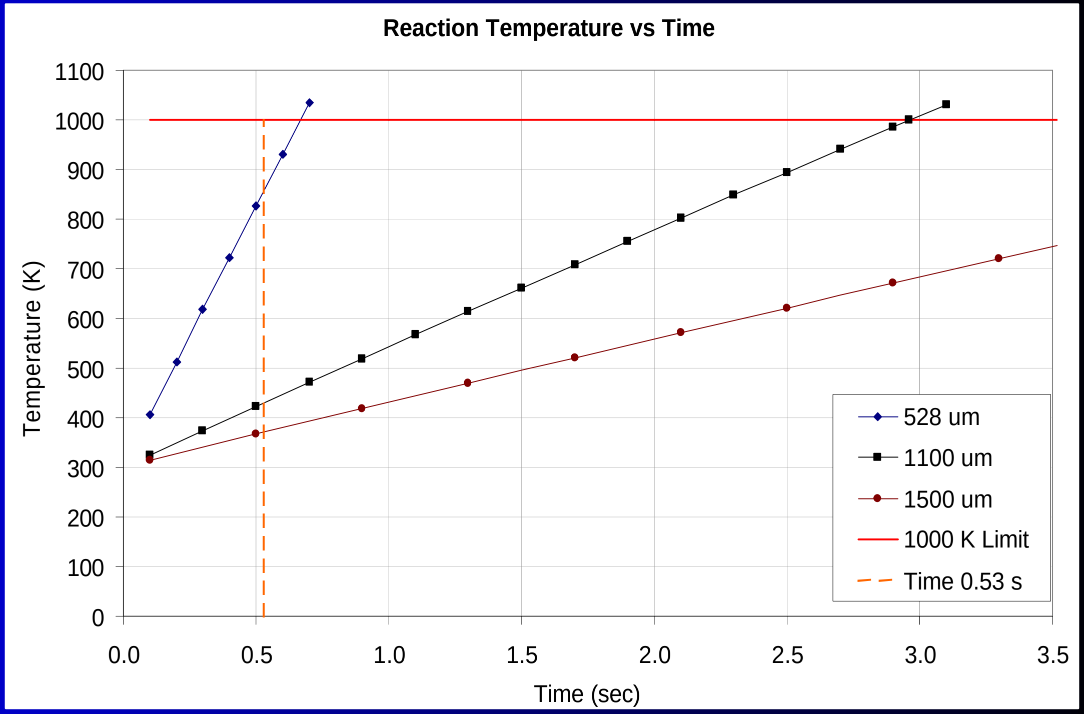
- Goal: Investigate injector size parameters to obtain higher temperature using FLOTRAN
- Thin wall and small diameter provide low thermal loss and create high chamber temperature



Inside Radius	Outside Radius	Fluid length	Thickness	Power Generation	Net Heat to Fluid	Solid Conduction	Temp.	Solid/ Fluid Heat Transfer Ratio
µm	µm	µm	µm	(W)	(W)	(W)	(K)	
5	**15**	**100**	**10**	**0.45**	**0.2739**	**0.1718**	**745**	**0.63**
10	20	100	10	0.45	0.2022	0.2448	617	1.21
10	30	100	20	0.45	0.1225	0.3263	486	2.66
100	200	1000	100	0.45	0.0300	0.4173	340	13.92
100	400	1000	300	0.45	0.0122	0.4375	315	35.93
300	320	1000	20	0.45	0.0365	0.4138	381	11.33
300	400	10000	100	0.45	0.1200	0.3202	428	2.67
300	400	1000	100	0.45	0.0081	0.4421	316	54.25
380	400	1000	20	0.45	0.0288	0.4220	365	14.67

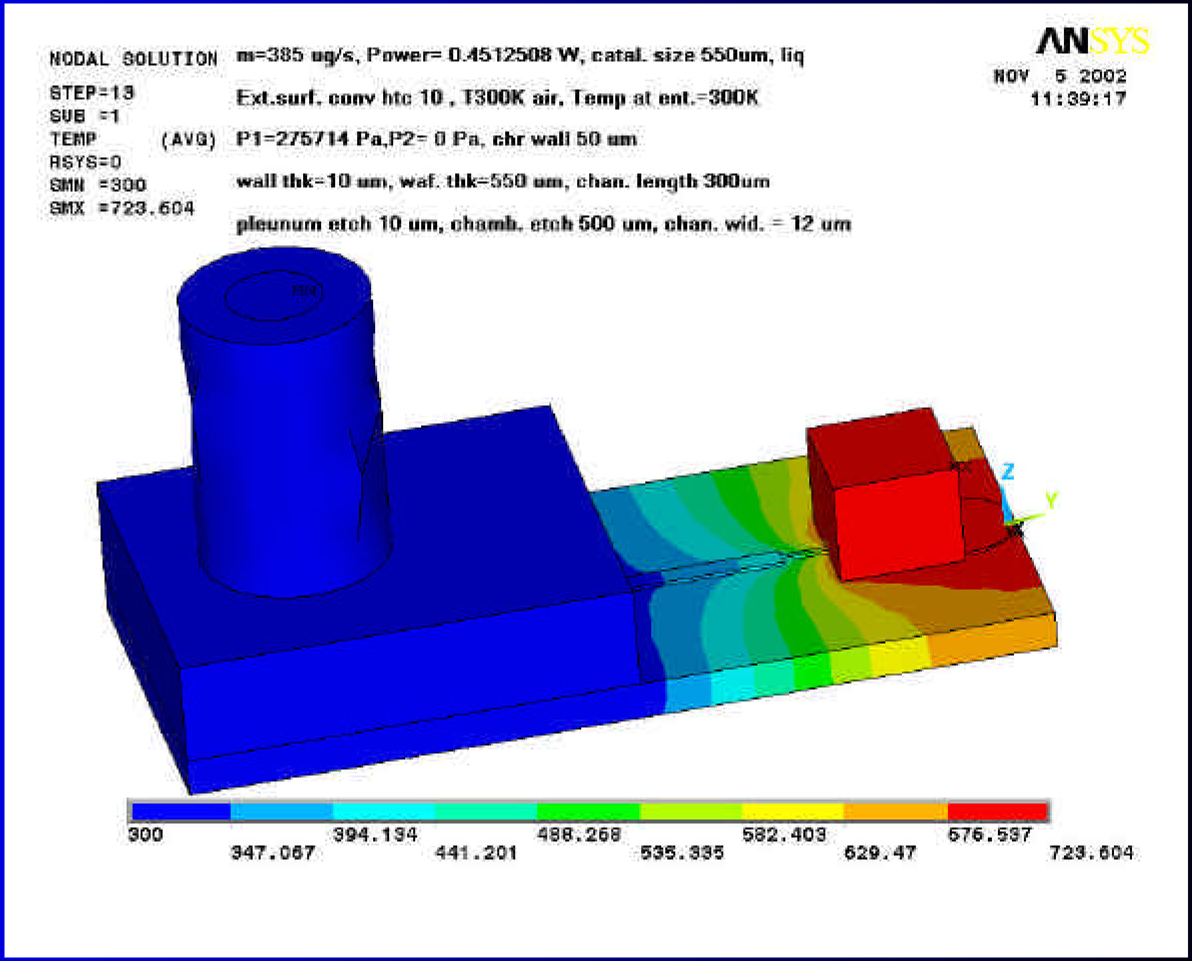
Chamber Sizing Analysis

- Goal: Investigate various lengths of square chamber sizes to obtain high temperature in short time
- Important constraint in catalyst bed design: Residence Time. Various experiments reveal residence time between 0.53 to 0.64 seconds. These numbers corresponds to 528 μm to 562 μm based on mass flow rate of 385 μg/s.
- Square chamber length should be between 528 μm to 1100 μm to provide faster thermal response time and adequate complete reaction.

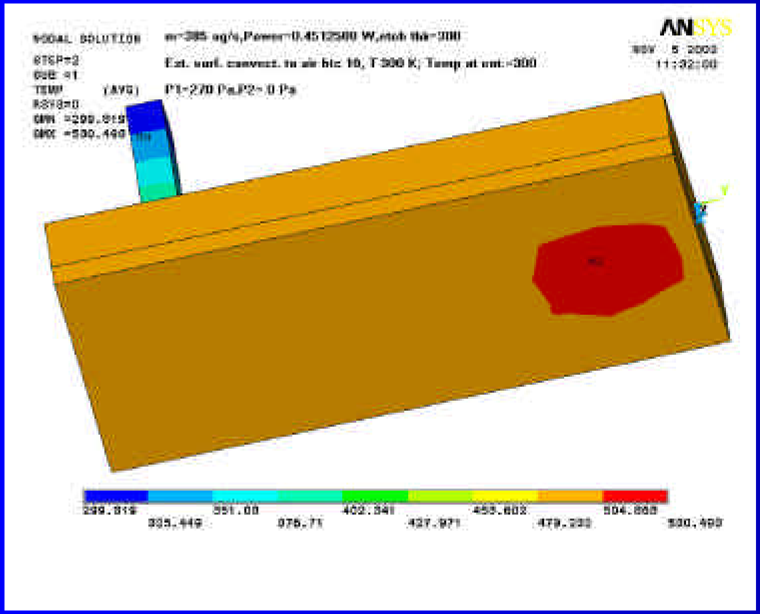


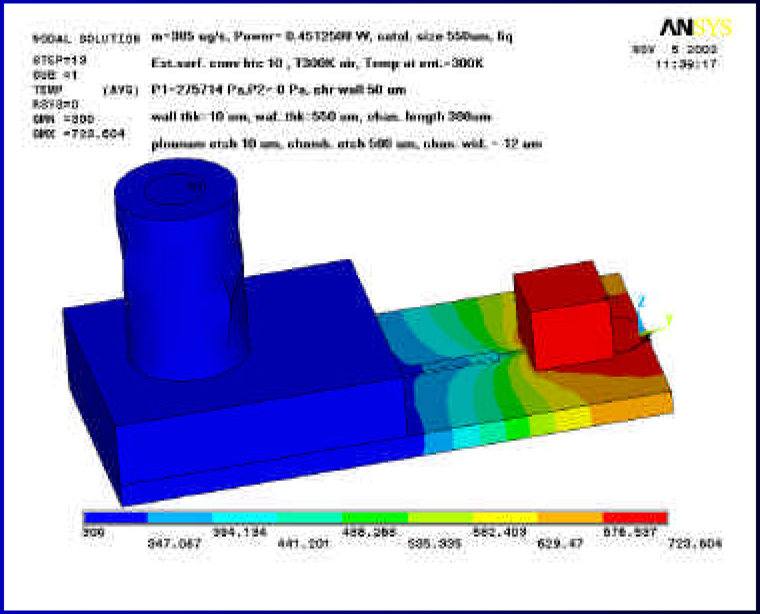
Thermal Model of New Design

- Assumption
  - Mass Flow Rate: 385 µg/s
  - Chamber Length: 550 µm
- Calculation
  - Heat Generation: 0.45 W
- Model Prediction
  - Maximum Temperature: 724 K
- 36.6 % increase in temperature from baseline design



Analytical Comparisons





	Q_{Heat} (W)	Q_{liquid} (W)	Q_{solid} (W)	Q_{gases} (W)	Max. Gas Temp (K)
Baseline Design	0.450	0.098	0.321	0.031	607
New Design	0.450	0.034	0.114	0.302	833
Percent %		-65.3	-64.5	874.1	37.2

$$\Delta T_g = \left(\frac{c_{pl}}{c_{pg}} \right) \Delta T_l$$

Conclusion

- ANSYS is a reliable tool in analyzing MEMS thruster designs.
- ANSYS has limitations in studying reactive flow :
  - limited to single phase flow (liquid or gas)
  - cannot model chemical reactions in the flow
- Baseline design heat losses to liquid and solid were too large to allow full hydrogen peroxide decomposition.
- Established changes in characteristic design parameters in designing an efficient MEMS thruster
  - The new thruster design should realize a significant improvement in performance because of the increase in the reaction chamber temperature and faster thermal response time.
    - 36.6 % increase in temperature
    - Heat addition to gases increased by 874%

Current Work

- Investigate thermal expansion between thin walls and glass
- Perform Stress Analysis on silicon and glass components
- Perform a thermal transient analysis with ANSYS
- Fabricate and test new thruster
- Investigate methods to improve ANSYS modeling capability to include chemical reactions and two-phases flow with University of Vermont

Any Questions?