REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* July 2014	**2. REPORT TYPE** Briefing Charts	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Matthew R. Gilpin, David B. Scharfe, Marcus P. Young, Rebecca N. Webb

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q0CA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive
Edwards AFB, CA 93524

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2014-224

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Briefing Charts presented at 12th Annual International Energy Conversion Engineering Conference, Cleveland Ohio, 28-30 July 2014.
PA#14391

14. ABSTRACT
A bi-modal solar thermal system capable of providing propulsive and electric power to a spacecraft has been identified as a promising architecture for microsatellites requiring a substantial ΔV. The use of a high performance thermal energy storage medium is the enabling technology for such a configuration and previous solar thermal studies have suggested the use of high temperature phase change materials (PCMs) such as silicon and boron. To date, developmental constraints and a lack of knowledge have prevented the inclusion of these materials in solar thermal designs and analysis has remained at the conceptual stage. It is the focus of this ongoing research effort to experimentally investigate using both silicon and boron as high temperature PCMs and enable a bi-modal system design which can dramatically increase the operating envelope for microsatellites. This paper discusses the current progress of a continued experimental investigation into a molten silicon based thermal energy storage system. Using a newly operational solar furnace facility, silicon samples have been melted and results indicate that volumetric expansion during freezing will be the primary difficulty in using silicon as a PCM. Further experimental studies using different materials and test section fill factors have identified potentially reliable experimental conditions at the expense of energy storage density. In addition to conducting experiments, a concurrent computational effort is underway to produce representative models of the experimental system. The current models generally follow experimental results; however, difficulties still remain in determining high temperature material properties and material interactions. This paper also discusses the future direction of this research effort including modeling improvements, analysis of convective coupling with phase change energy storage and potential facility improvements.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Marcus Young
Unclassified	**Unclassified**	**Unclassified**	SAR	64	**19b. TELEPHONE NO** *(include area code)* 661-275-6264

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion

Matthew R. Gilpin, USC

David B. Scharfe, ERC, Inc.

Marcus P. Young, ARFL/RQRS

Rebecca N. Webb, UCCS

USC Viterbi School of Engineering

Introduction

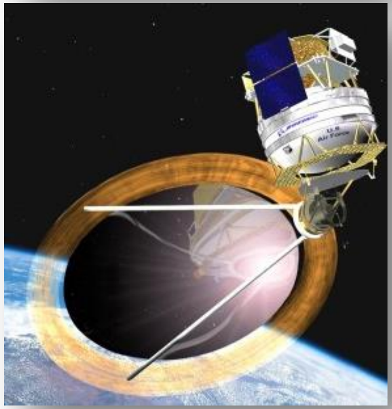
- Solar thermal propulsion (STP) has over 50 years of developmental history and offers a compromise between thrust and efficiency

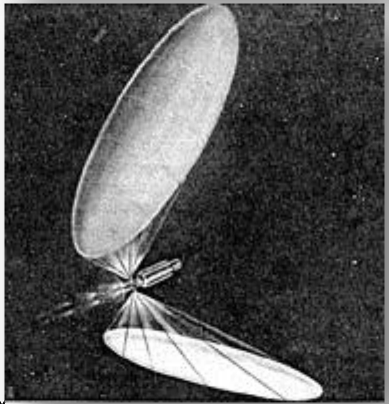
Monoprop. Rocket	**Solar Thermal**	**Electric**
~230s Isp	*300-700s Isp*	*>1000s Isp*

- No solar thermal spacecraft have been flown to date
  - Novel (i.e. "awkward") architecture
  - Scale of proposed systems
  - Adverse impact as a "demo" mission

- A bi-modal solar thermal microsatellite has the potential to greatly increase the operating envelope of the platform

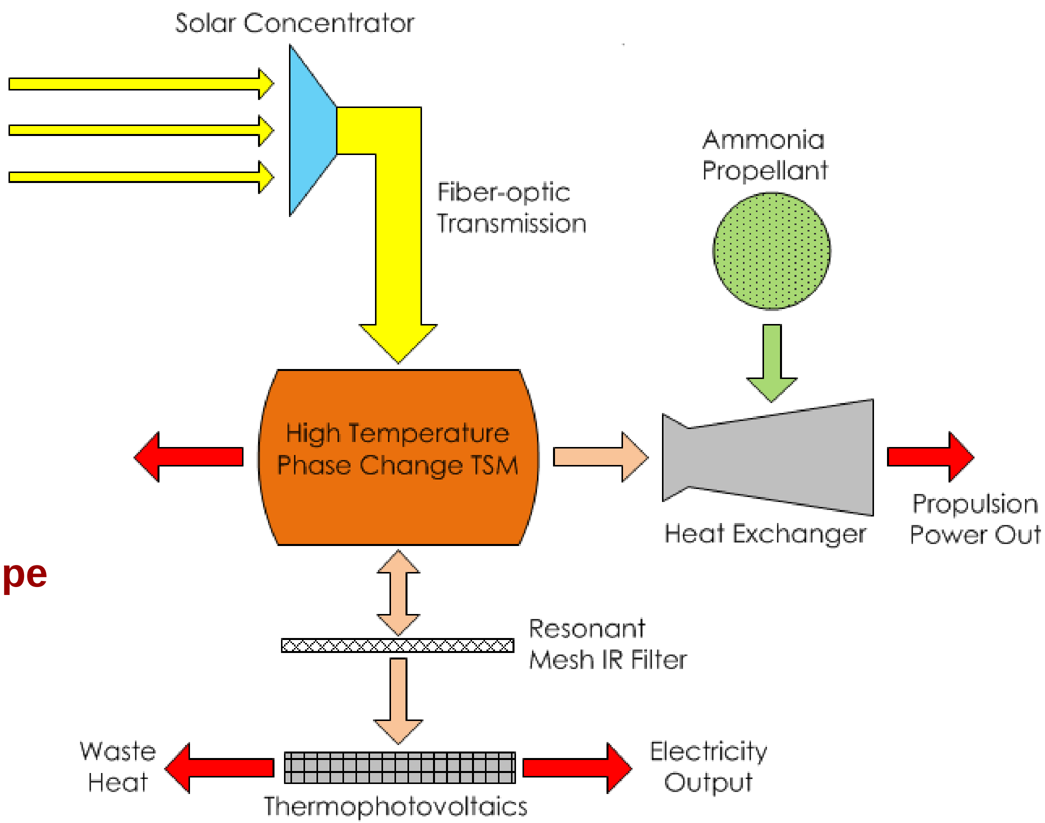
- The development of high temperature latent heat thermal energy storage is currently an enabling technology





Bi-Modal Solar Thermal Propulsion

- A review by the AFRPL Advanced Concepts Group identified STP as a promising candidate for high performance microsatellite missions (*Scharfe 2009*)
- A ***bi-modal microsatellite*** configuration is proposed and further study is recommended
- Microsatellite scaling distinguishes STP
- Large ΔV (> 1 km/s) possible



Expand the Microsatellite Operating Envelope

- Expand possible "piggy-back" launch options
- GEO Insertion: ~ *1760 m/s*
- Near Escape Missions: ~ *770 – 1770 m/s*

Possible with EP, however, STP offers a much shorter burn time and higher maneuverability

Technological Requirements

☐ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☐ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☐ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☐ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

☐ Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

Technological Requirements

Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

Advanced Insulation

- Low Mass
- High Temperature

High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

- Thin PMA (JAXA) "flight ready" concentrators achieve 200 g/m^2 and C. ratios > 10,000:1
- Inflatables (AFRPL, SRS) can achieve < 1 kg/ m^2 and have been reported as being "optical quality"
- Large rigid structures (NASA SD, ISUS) are listed at approx. 3 kg/ m^2 including mounting, tracking, and deployment
- Microsatellite scale system only requires < 2 m^2

Sahara 2004

SRS Technologies

Technological Requirements

Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

Advanced Insulation

- Low Mass
- High Temperature

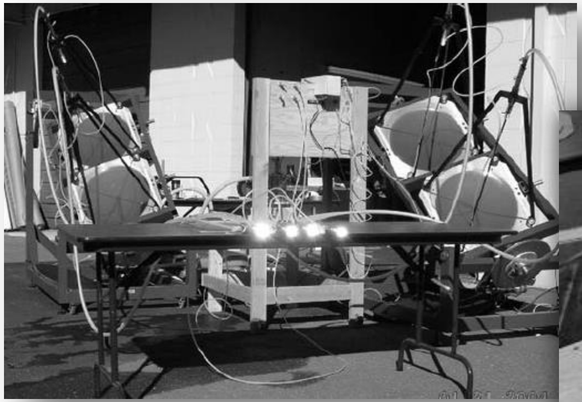
High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

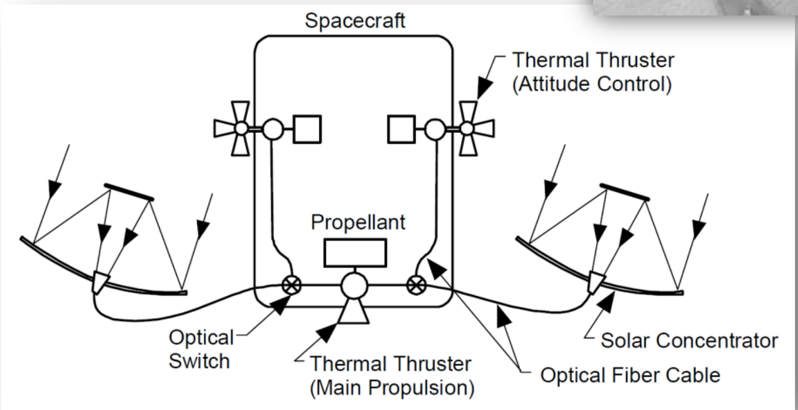
Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

- Current lab systems operate at 35% η_{total}
- Estimated 70% η_{total} for a space qualified system from better materials selection
- Pointing accuracy of approx. 0.1° required



Nakamura 2004



Technological Requirements

☑ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☑ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☑ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☐ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

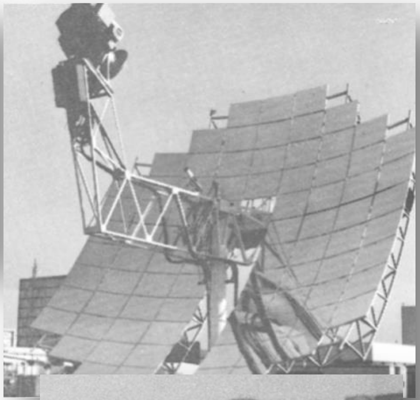
☐ Compatible / Effective RAC

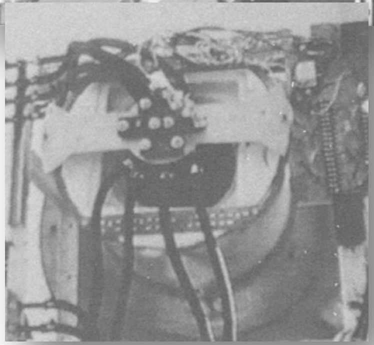
- Long term compatibility
- Effective energy coupling

- Thermophotovoltaics are the strongest candidate
- Operation targets properly matched to solar thermal temperatures.
- Closed Brayton and thermionics scale poorly for microsats
- 15 W/kg in current systems, including radiator

Edtek

McDonnell Douglas





USC Viterbi School of Engineering

Technological Requirements

Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

Advanced Insulation

- Low Mass
- High Temperature

High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

Material	k_{th} @ 1000 C *(W/mK)*	k_{th} @ 1500 C *(W/mK)*	k_{th} @ 2000 C *(W/mK)*	Density *(g/cm3)*
Silicon Carbide	45	30	*25*	3.2
Boron Nitride	17-33	22.5	*18*	1.8
Alumina	6.5	6.6	--	3.8
Zirconia	2	2.5	*3*	5.5
ONRL CBCF	0.17	0.2	0.26	0.2
Calcarb CBCF	0.2	0.35	0.65	0.18
Aerogel Filled Graphite Foams	0.25	0.4	0.75	0.07
Mo - $Zr0_2$ Multifoil	0.001	0.05	0.1	1.4

- Must operate between **1500 – 2600** K
- **Carbon Bonded Carbon Fiber**
  - Can draw from NASA RTG development
  - Carbon foams with filler to limit radiation loss currently offered by ULTRAMET
- **Low Emissivity Vacuum Gap**
  - Typically the first stage in a TPV system
  - Mo/ZrO_2 multifoil blankets also produced for RTGs
- **Ceramic Doped Aerogels**
  - Underdevelopment with JPL, RZSM, and RQRS

Technological Requirements

☑ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☑ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☑ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☑ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material → ?

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

☐ Compatible / Effective RAC → ?

- Long term compatibility
- Effective energy coupling

Existing Sensible Heat Thermal Energy Storage

To date, all STP systems have used sensible heat thermal energy storage

Material	T_{melt} [K]	Cp @ 2500 K [kj/kgK]	ΔT Required for 1 MJ/kg
Grahpite	3923	2.15	475
Boron Carbide	2700	2.68	380
Silicon Carbide	2818	1.01	740
Boron Nitride	3273	1.98	510

- Simplified engineering suitable for time constrained development – Low TRL level of other options
- "…moderate yet acceptable performance" - *Kennedy 2002*

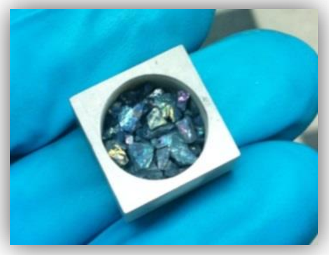
ISUS Data Analysis

- Seven minute "steady" burn corresponds to an "effective" energy storage density of **0.5 *MJ/kg***
- When the RAC achieves 1 *MJ/kg*, ***exit temp*** has dropped by ***> 25%*** and ***Isp*** has dropped by ***15%***
- ISUS spec for thermionic hot shoe temperature was 1900 – 2200 K. If allowed for a radiently coupled TPV system, this would correspond to a ***> 50% decrease*** in power output

Potential High-Temp Phase Change Materials

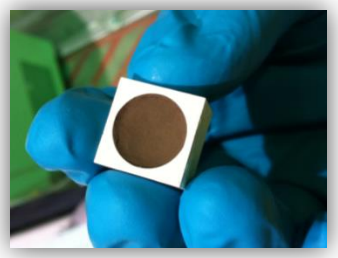
Material	T_{melt} [K]	ΔH_{fus} [MJ/kg]	k_{th} @ T_{melt} [W/mK]
MgF2	1536	0.94	3.8
Beryllium	1560	1.31	*69*
Silicon	1687	1.79	20
Nickel	1728	0.3	*83*
Scandium	1814	0.31	*16*
Chromium	2180	0.4	48
Vanandium	2183	0.45	51
Boron	2350	4.6	*10*
Ruthenium	2607	0.38	*80*
Niobium	2750	0.29	*82*
Molybdenum	2896	.38	*84*

Silicon



- Moderate Performance
- 330s I_{sp}

Boron



- High Performance
- 390s I_{sp}

System Comparison

Bi-Modal System Performance Parameters

100 *kg* Microsatellite - 100 *W* continuous power draw

Silicon System		
Thermal Collection	5.3	*kg*
Thermal Storage	3.3	*kg*
Power	6.7	*kg*
Propellant	36.7	*kg*
Tankage / Thruster	6.1	*kg*
Prop. / Power Total	**58.2**	***kg***
Payload Mass	**41.8**	***kg***

$M_{\text{Propulsion \& Power}} \sim 58\%$

1500 m/s ΔV

Thermal Collection
- Primary concentrator
- Support structure
- Fiber optics

Thermal Storage
- PCM
- Insulation

Power
- TPV cells
- Radiator Panels

Propellant
- Liquid Ammonia

Tankage / Thruster
- Titanium Tank
- Piping
- Nozzle and Heat Exchanger
- Reinforcements

System Comparison

Bi-Modal System Performance Parameters
100 *kg* Microsatellite - 100 *W* continuous power draw

Silicon System		
Thermal Collection	5.3	*kg*
Thermal Storage	3.3	*kg*
Power	6.7	*kg*
Propellant	36.7	*kg*
Tankage / Thruster	6.1	*kg*
Prop. / Power Total	**58.2**	***kg***
Payload Mass	**41.8**	***kg***

$M_{\text{Propulsion \& Power}}$ ~ 58%

1500 m/s ΔV

Boron System		
Thermal Collection	5.4	*kg*
Thermal Storage	1.9	*kg*
Power	6.7	*kg*
Propellant	38.0	*kg*
Tankage / Thruster	6.3	*kg*
Prop. / Power Total	**58.2**	***kg***
Payload Mass	**41.8**	***kg***

$M_{\text{Propulsion \& Power}}$ ~ 58%

1850 m/s ΔV

Thermal Collection
- Primary concentrator
- Support structure
- Fiber optics

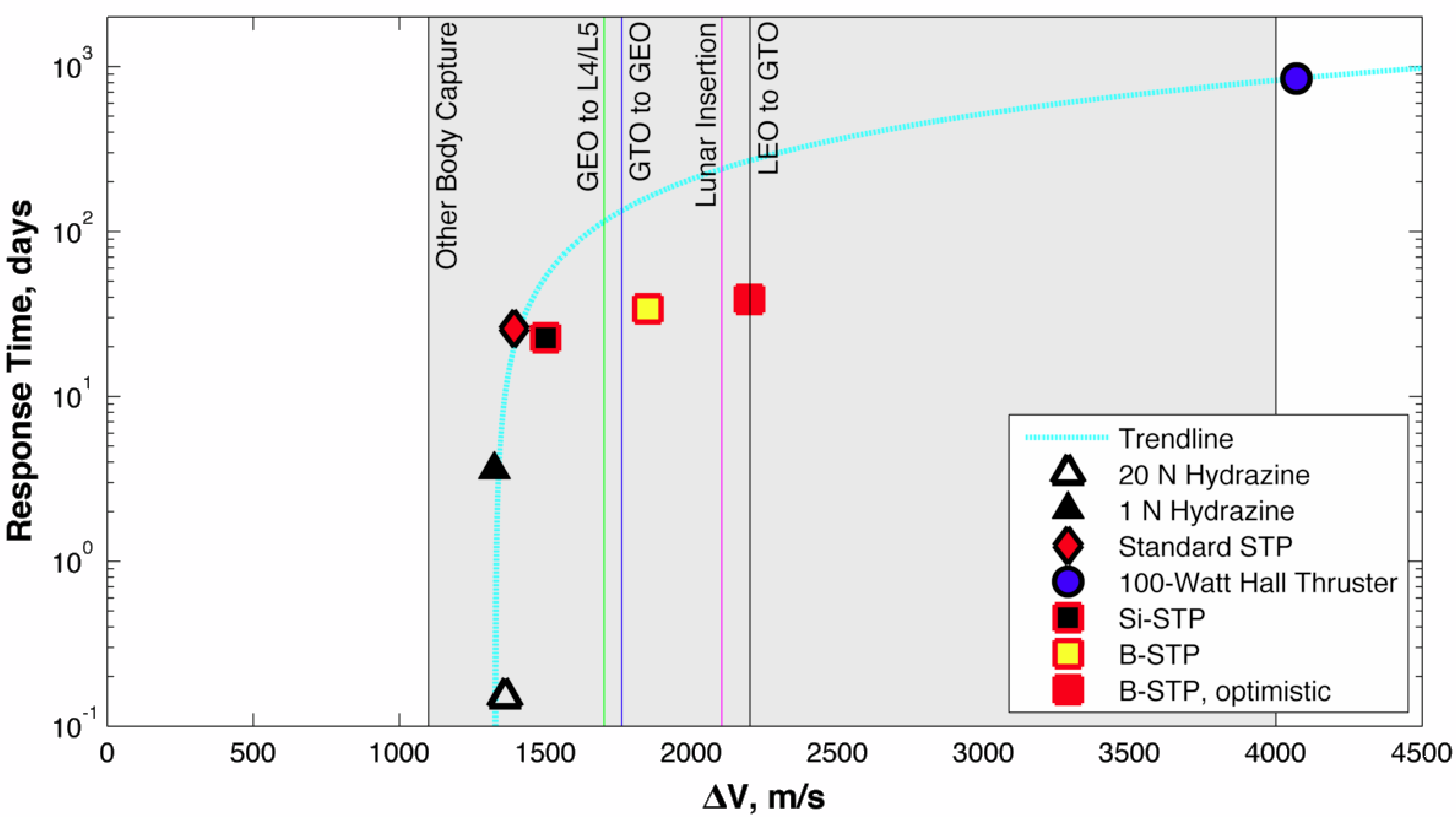
Thermal Storage
- PCM
- Insulation

Power
- TPV cells
- Radiator Panels

Propellant
- Liquid Ammonia

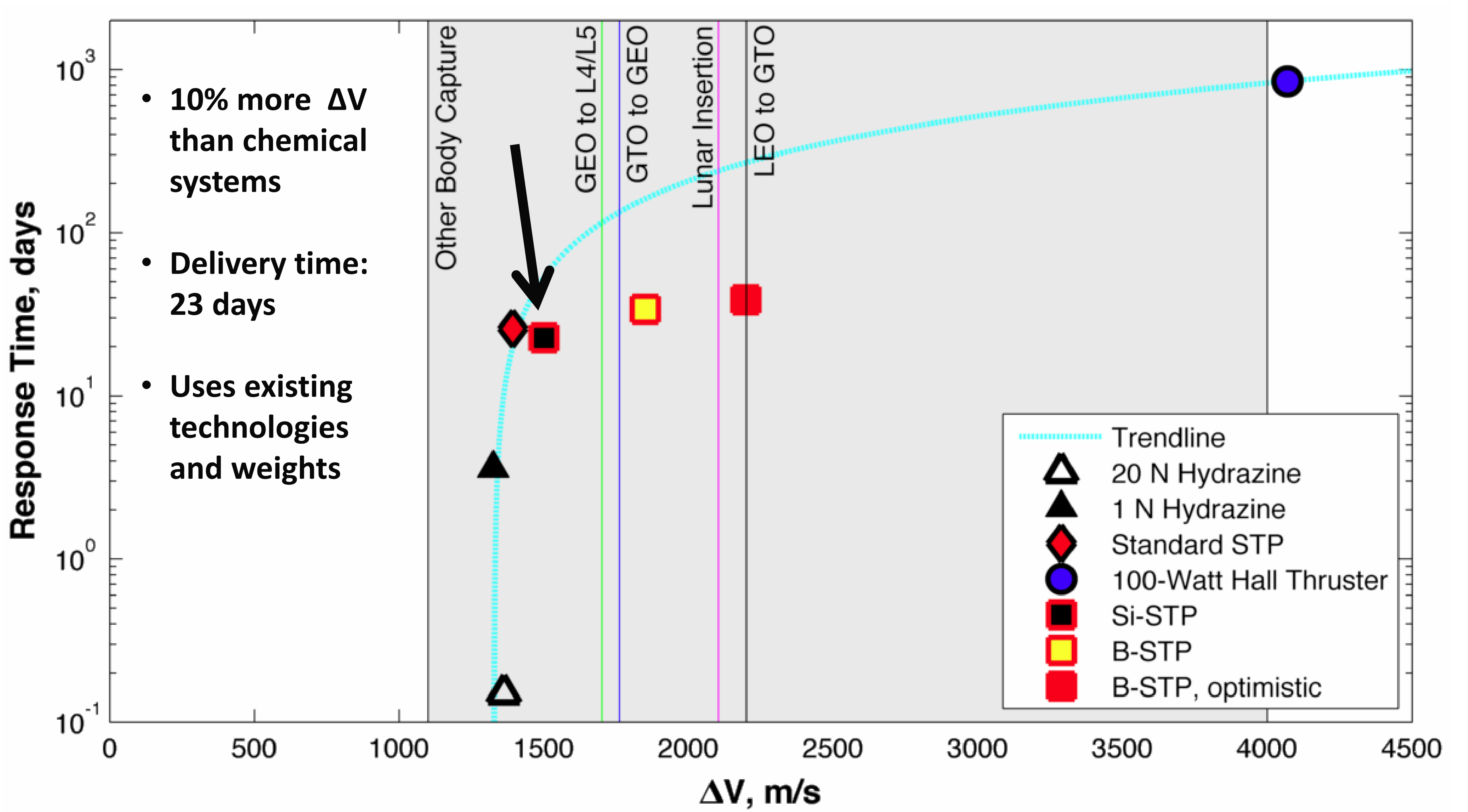
Tankage / Thruster
- Titanium Tank
- Piping
- Nozzle and Heat Exchanger
- Reinforcements

System Comparison



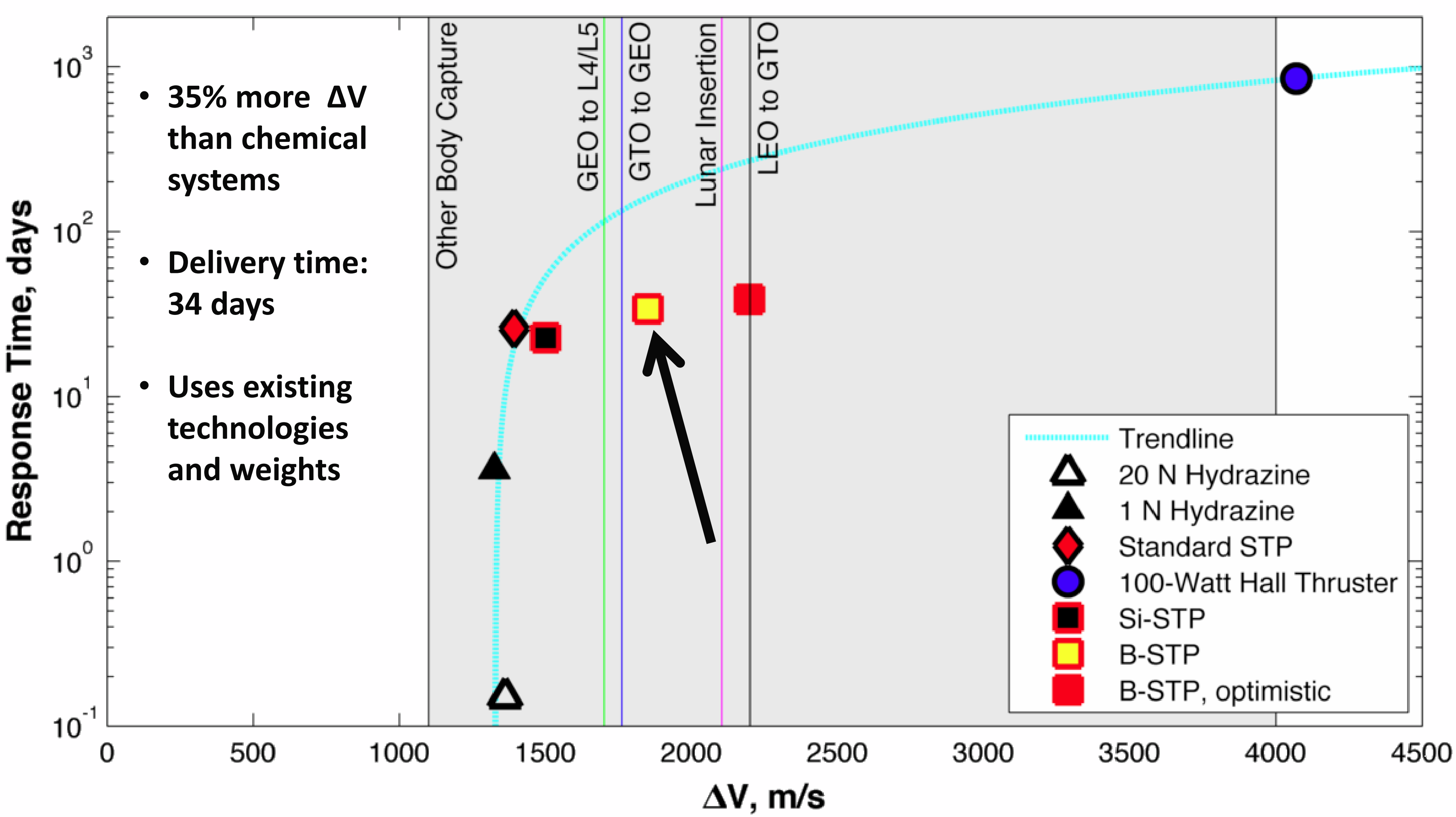
System Comparison

- **10% more ΔV than chemical systems**
- **Delivery time: 23 days**
- **Uses existing technologies and weights**

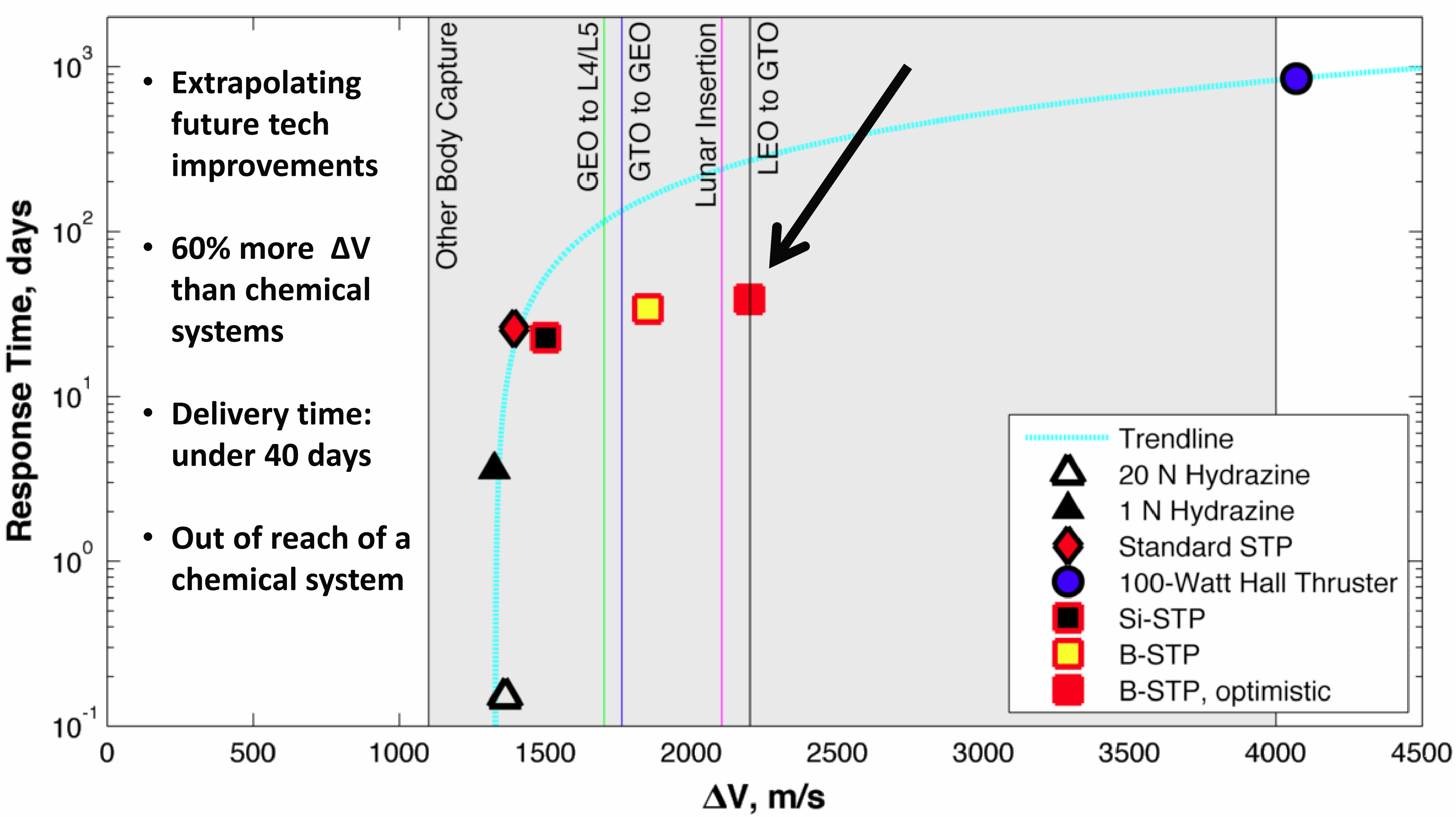


System Comparison

- **35% more ΔV than chemical systems**
- **Delivery time: 34 days**
- **Uses existing technologies and weights**



System Comparison



Experimental Investigation

Demonstrate a Proof of Concept Latent Heat Thermal Energy System Using Molten Silicon

- **No experiments to-date directly targeting energy storage applications**
- **Mentioned as a potential buffer / storage material for TPVs**
  - Woodall 1982 - IBM patent
  - Chubb et al. 1996 - white paper, "ideal storage material"
- **Brief mentions in the solar thermal literature**
  - Laug et al. 1995 – Initial bi-modal study
  - Kennedy 2002 – TRL level not sufficient
  - Abbot 2001 – Trade study

1) Facility Development

2) Materials Selection

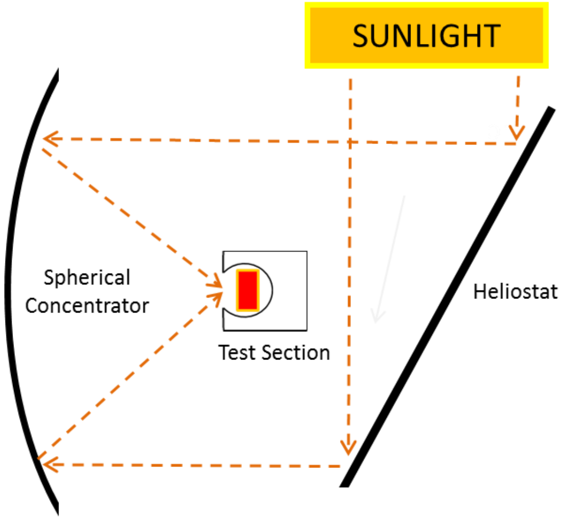
3) Modeling Capability and Analysis

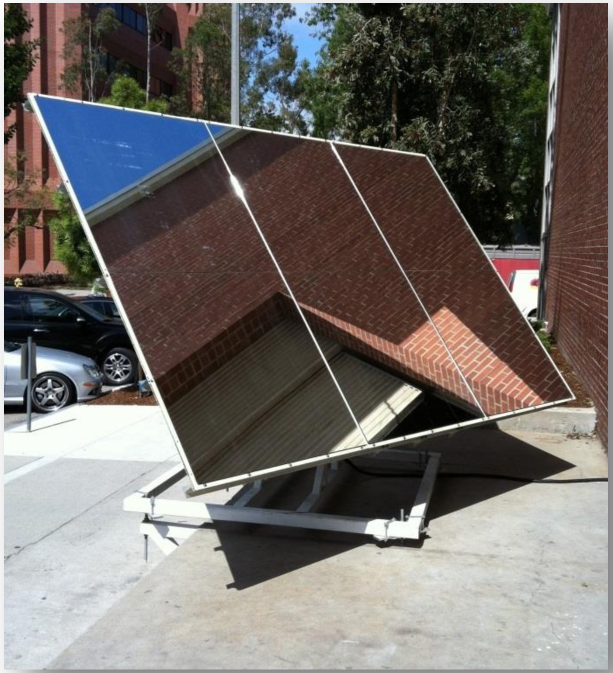
4) Experimental Demonstration

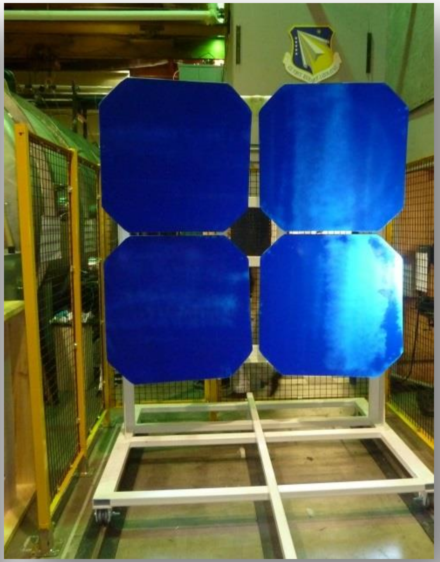
USC Solar Furnace

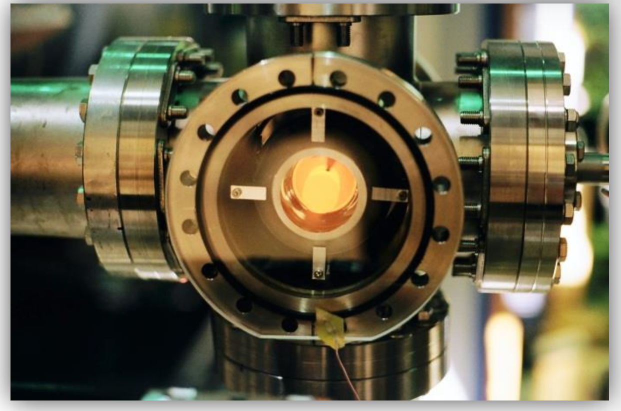
USC Viterbi School of Engineering

- First-surface spherical concentrator
  - r_c = 124”
  - SiO_2 coating optimized to the solar spectrum
  - Manufactured by DOTI Optics
- 3600 in^2 usable concentrator area
- 12 ft x 8 ft computer controlled heliostat
- COTS and surplus components
- Delivers 800-1100 W in a 1” spot



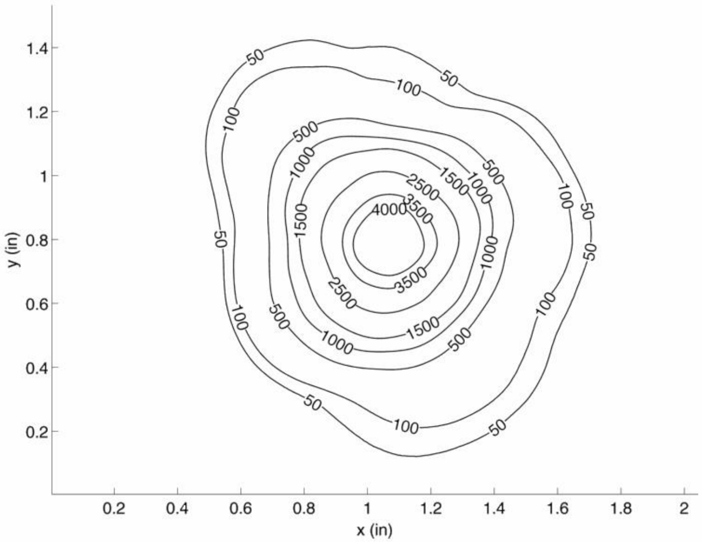


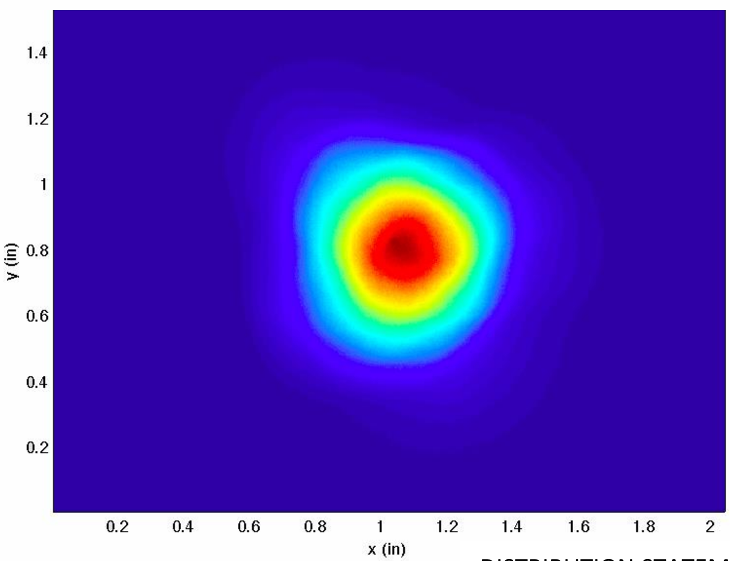




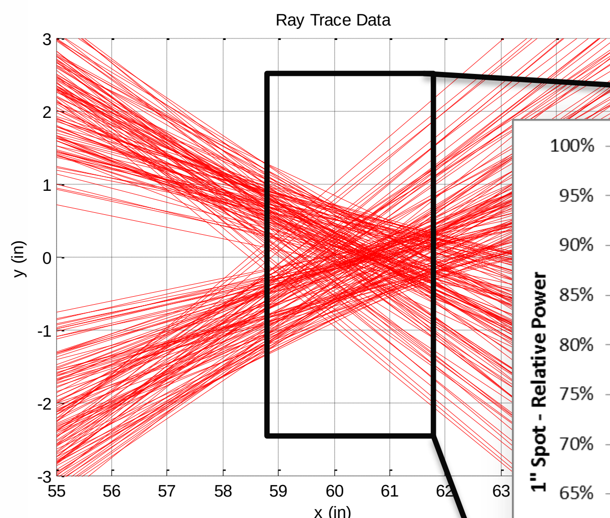
USC Solar Furnace

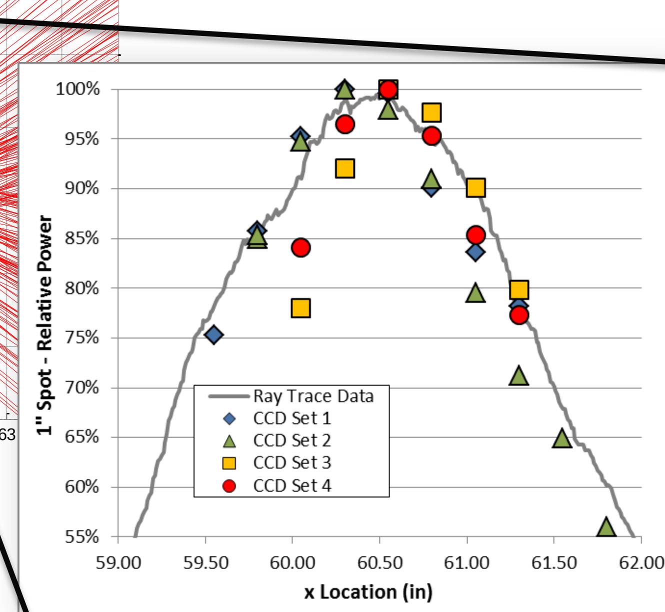
Solar Flux At Best Location





- Peak concentration ratios 4000:1
- Tailored for maximum power delivery in a 1” diameter spot
- Optimized experimental placement using CCD solar flux mapping to compensate for spherical aberrations

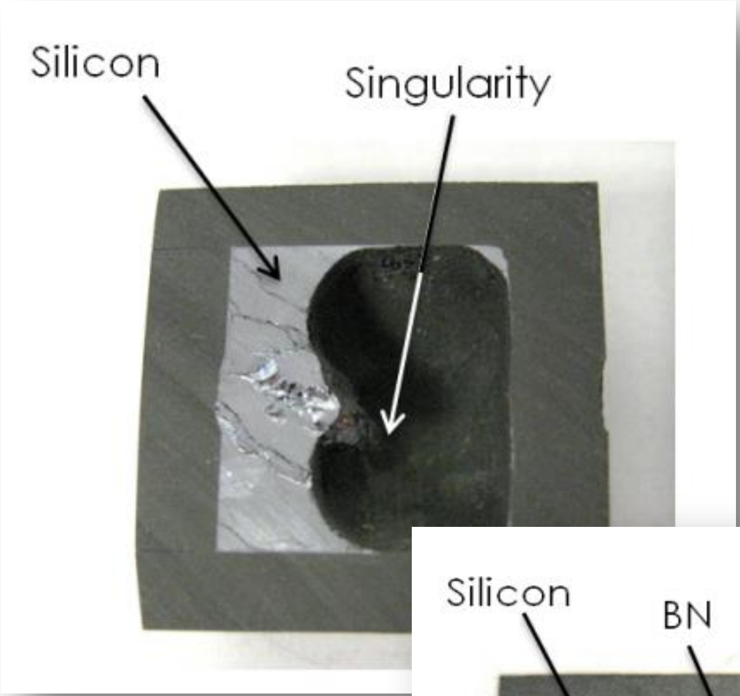


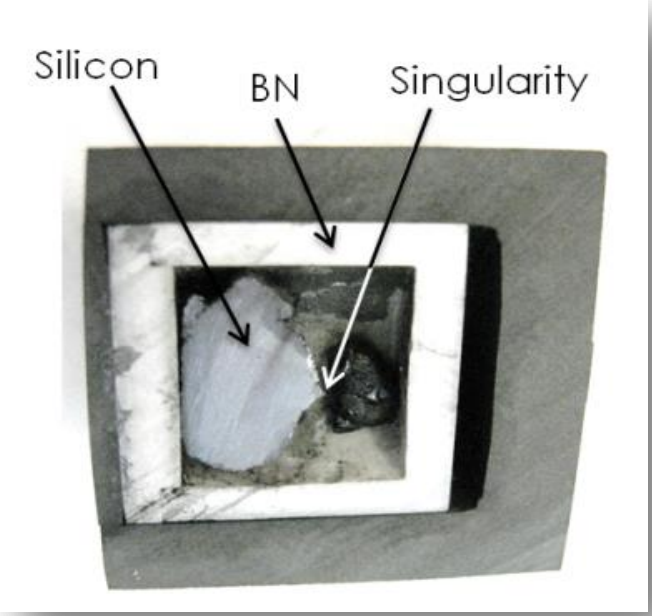


Geometric "Focus" :	62"
Minimum Ø :	59.8"
Best Performance :	60.5"

Materials Studies

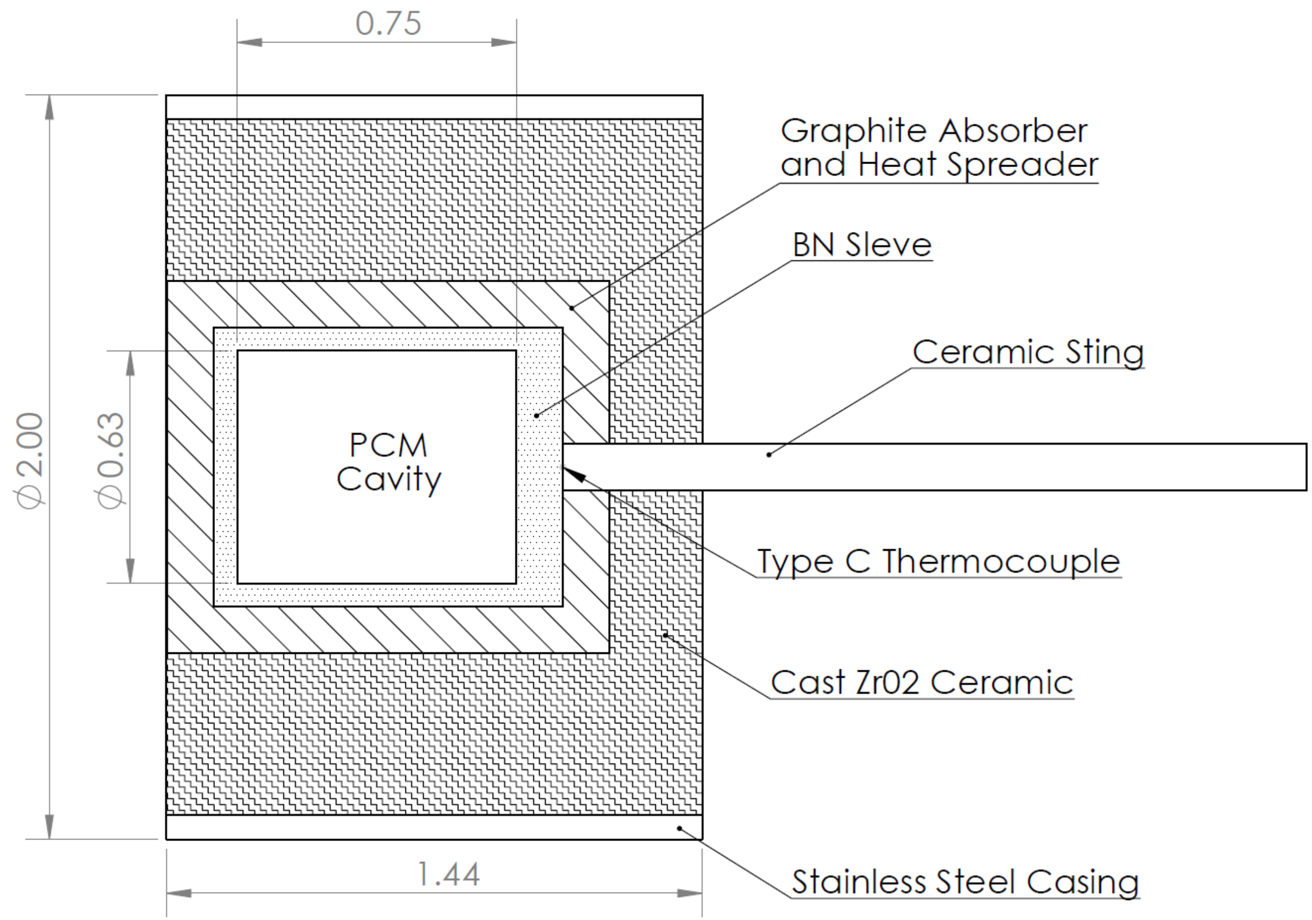
- Possible to draw from semi-conductor industry knowledge
- **Boron nitride** has a self limiting reaction with molten silicon (*also compatible with liquid boron*)
  - Formation of Si_3N_4 limited at 2% boron saturation in the silicon bulk
  - Low level boron contamination expected to have little effect on silicon recrystallization
- Graphite can be used with carbon contamination on the order of 20 ppm
  - Density must be > 1.75 g/cc
  - Grain size must be < 50 µm



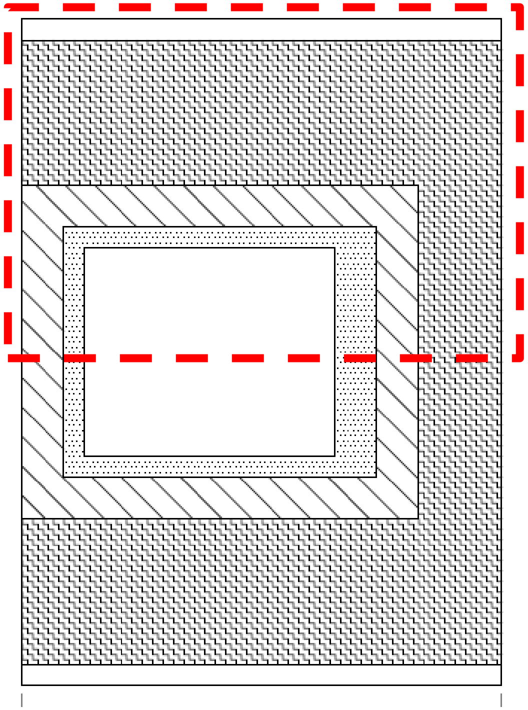


Testing Geometry

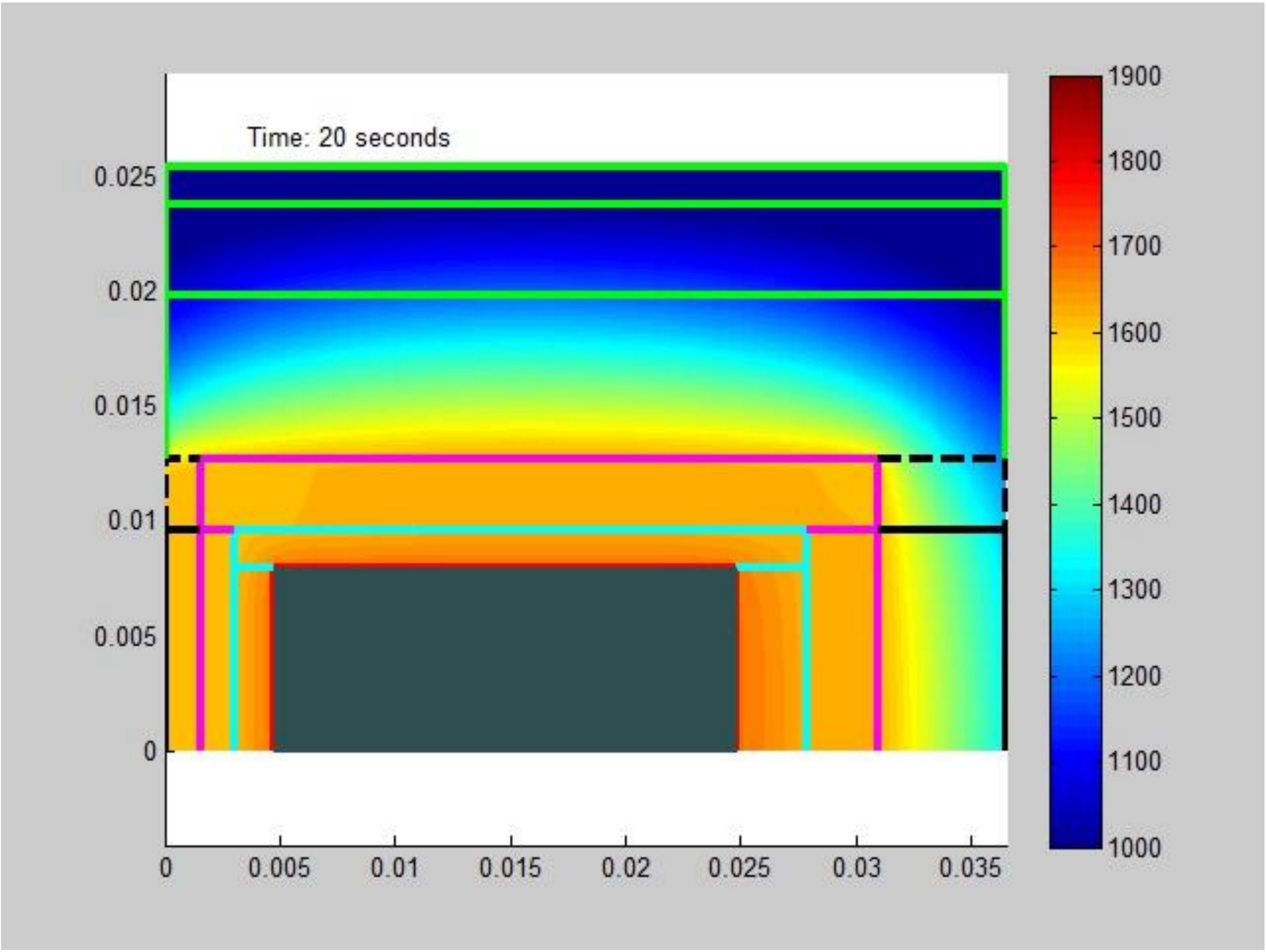
- Cylindrical geometry for ease of manufacture and simplified modeling
- Can be manufactured in house from COTS components
- Sized for 9 g of silicon, however, this is not limited by solar furnace power
- Does not make use of radiation shielding
- Integrated Type C and Type K thermocouples



Predictive Modeling

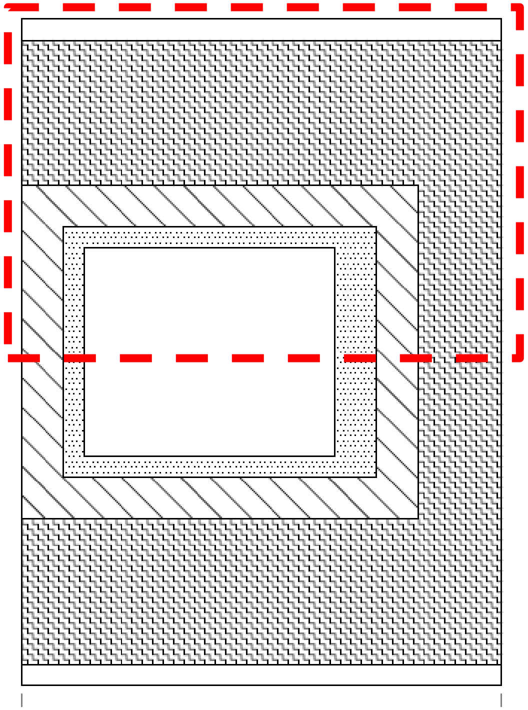


Movie File to Be Added Here

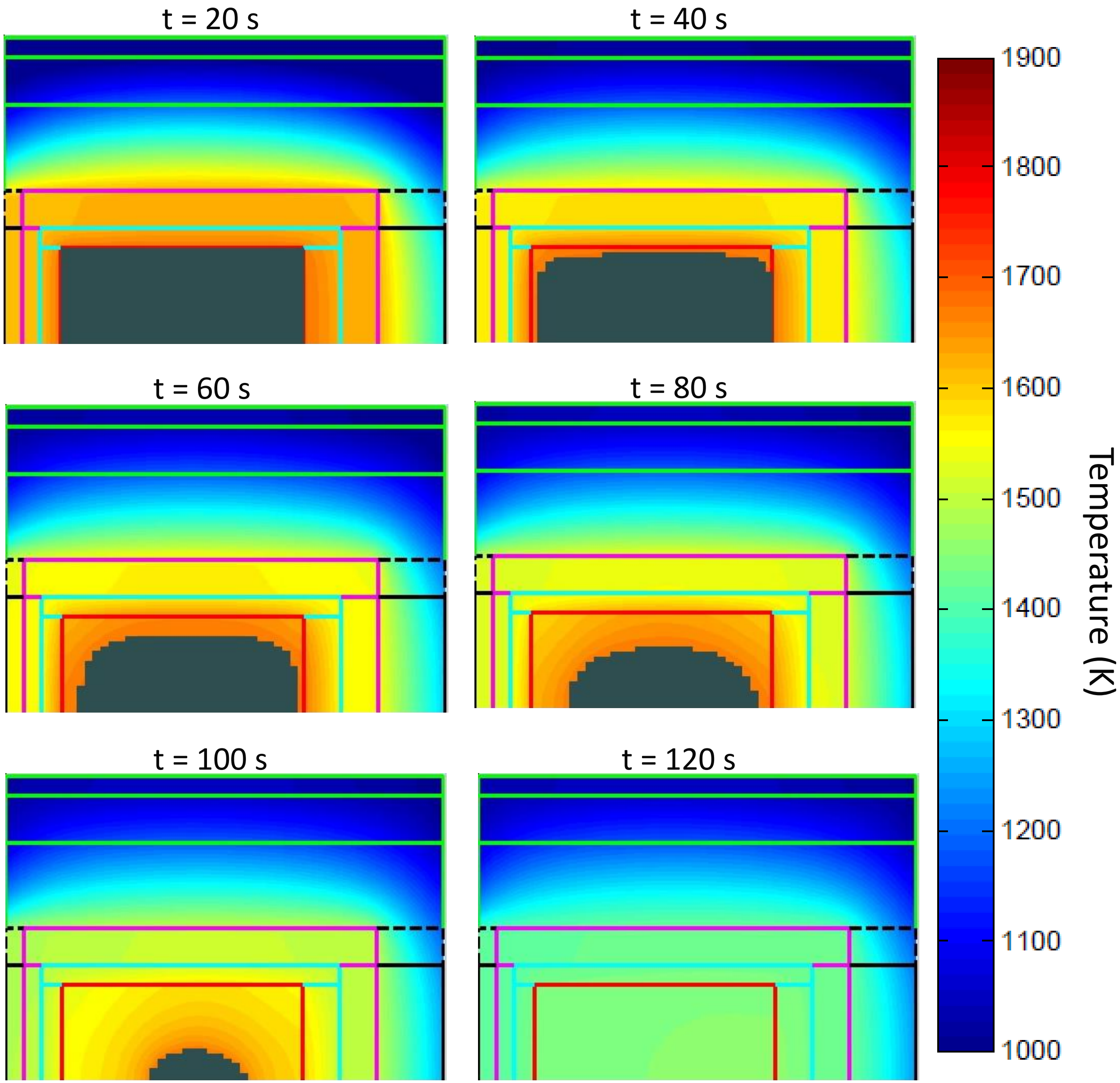


- 2D Axisymmetric about θ
- Radiation and convection boundary conditions
- Neglects PCM density change and void formation
- Latent heat handled by the "enthalpy method"

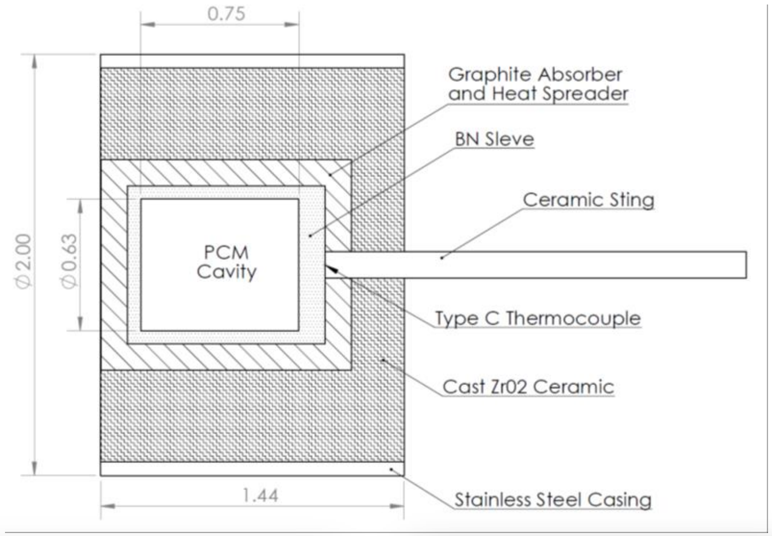
Predictive Modeling

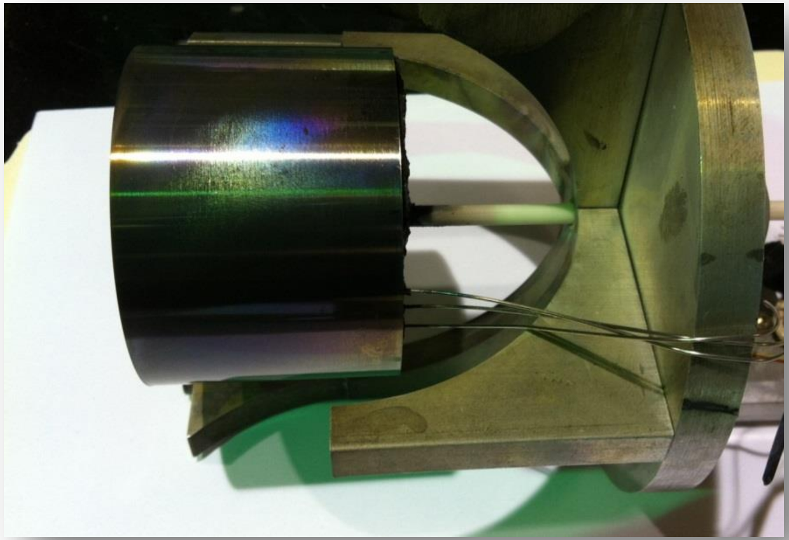


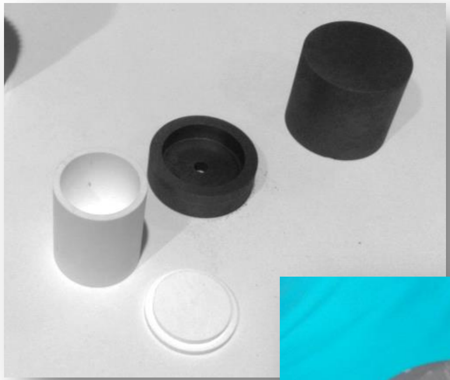
- 2D Axisymmetric about θ
- Radiation and convection boundary conditions
- Neglects PCM density change and void formation
- Latent heat handled by the "enthalpy method"

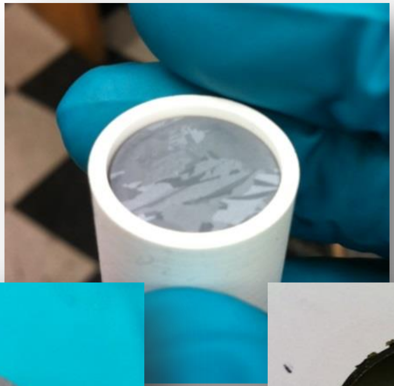


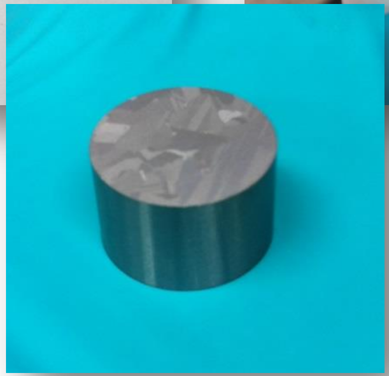
Experimental Testing

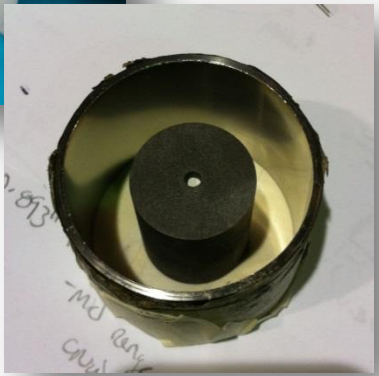


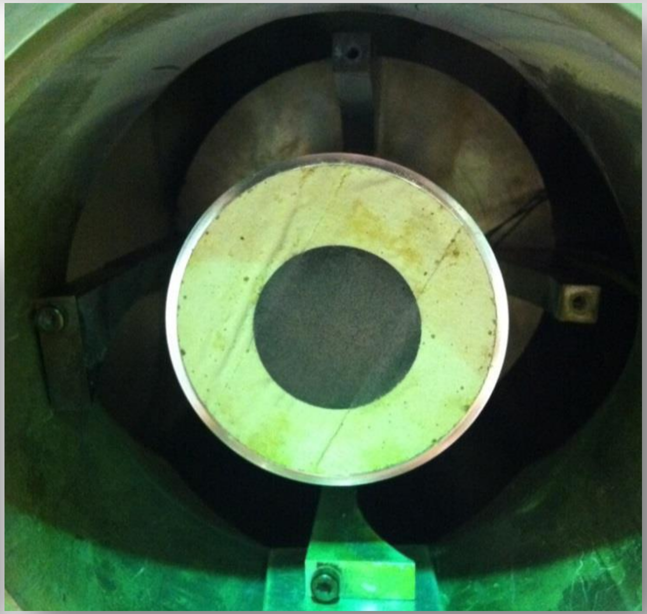








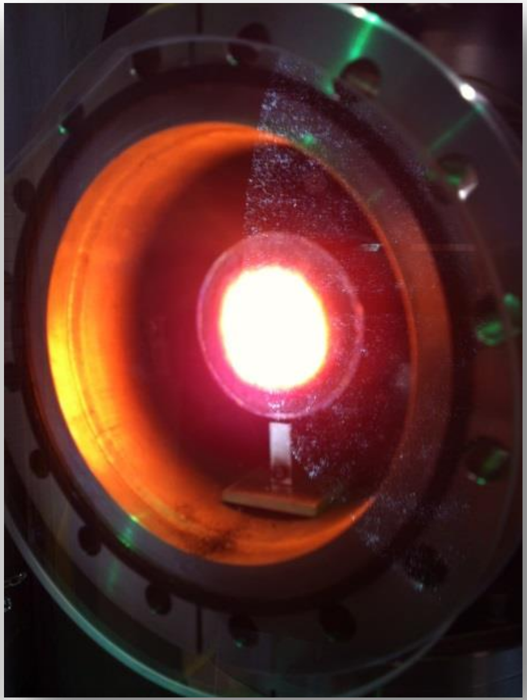




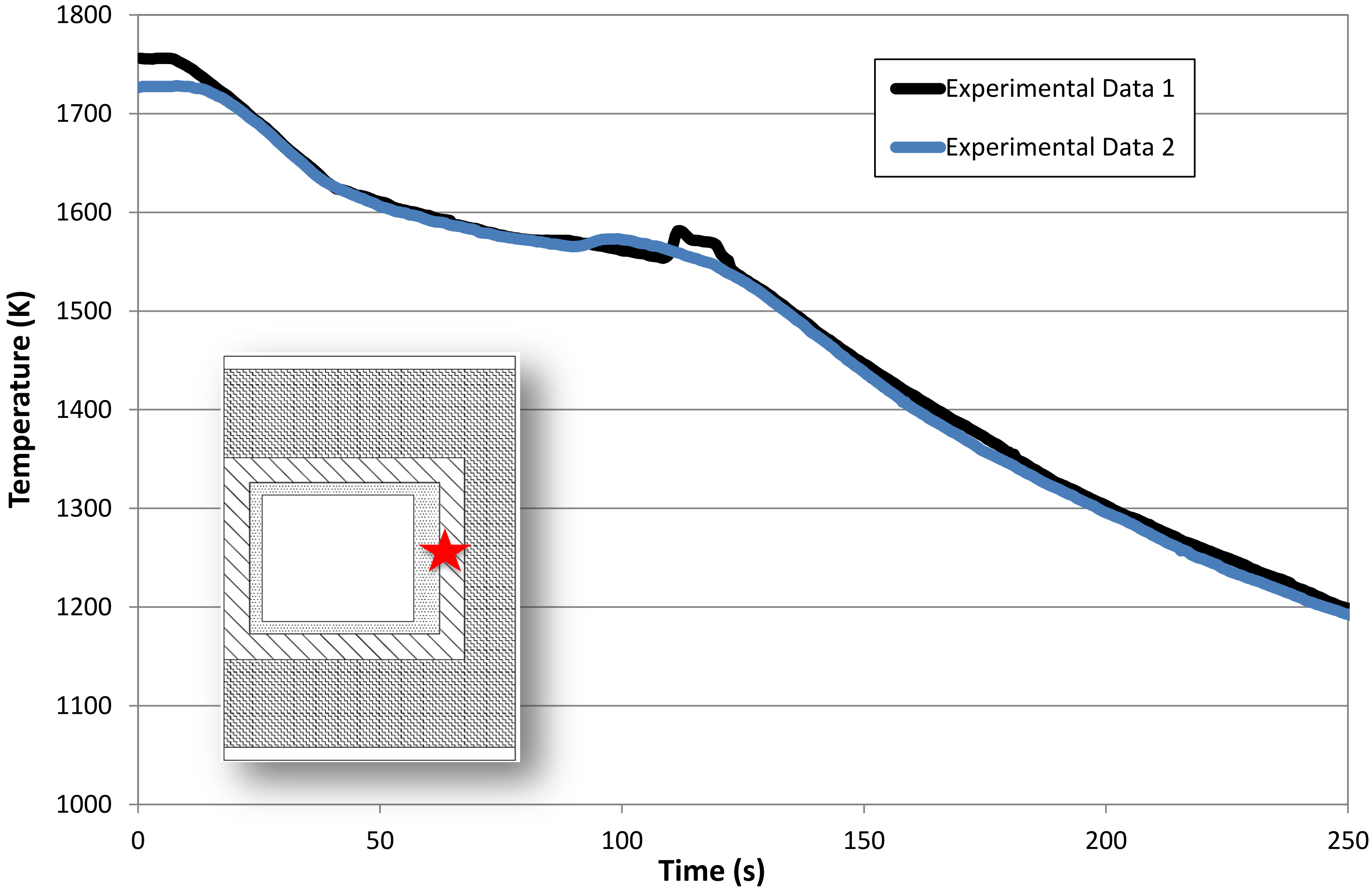
Experimental Testing

Testing Procedure

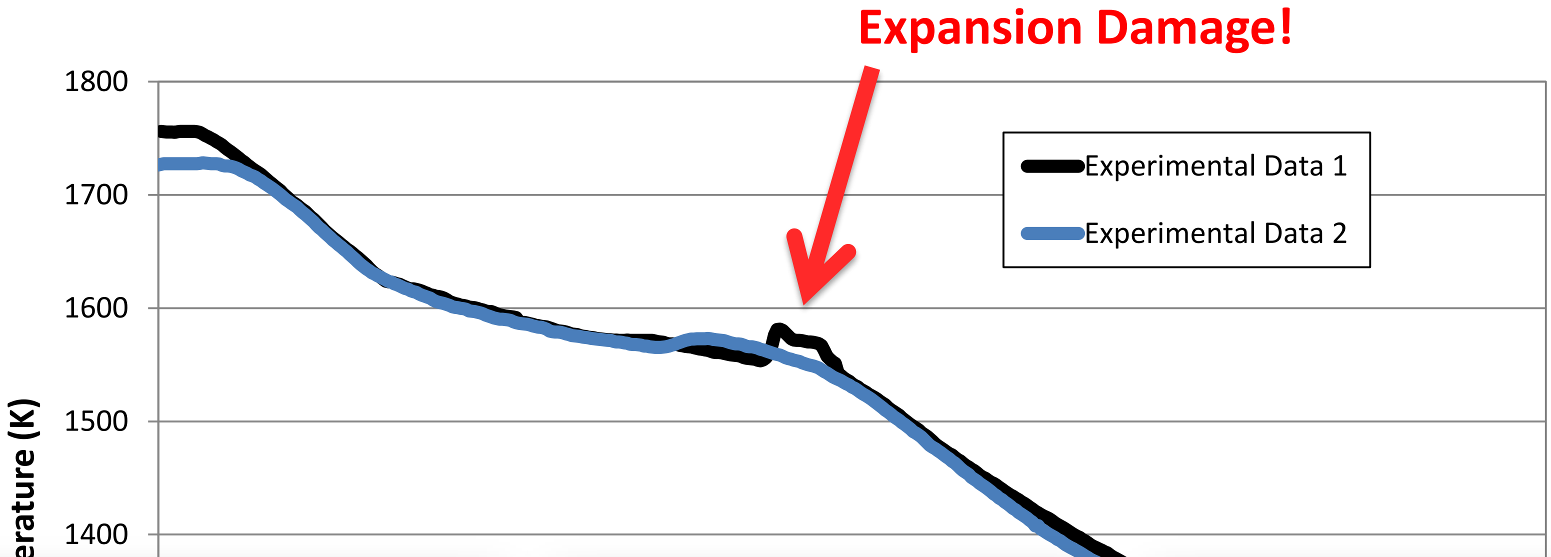
- Bake out at 300 °C and 30 mTorr to evaporate "proprietary water based binder" in the cast ZrO_2 ceramic
- Fill chamber with 150 Torr of Argon
  - Required to suppress $Zr0_2$ + C reaction
  - Prevents irreparable damage to quartz chamber window
- Gradually increase power until thermal equilibrium is achieved
- Use "shutter curtain" to quickly cut power and record cooling curve

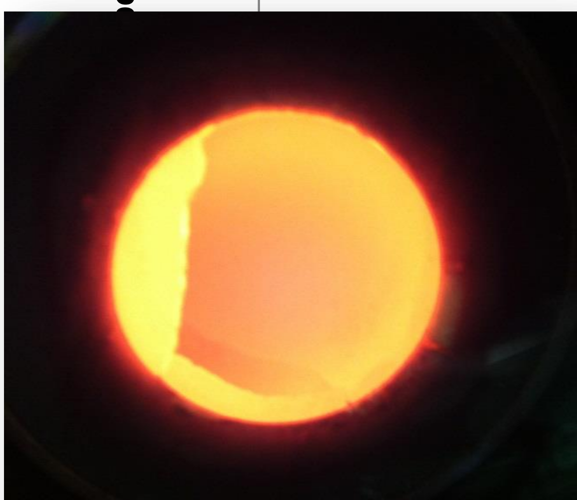


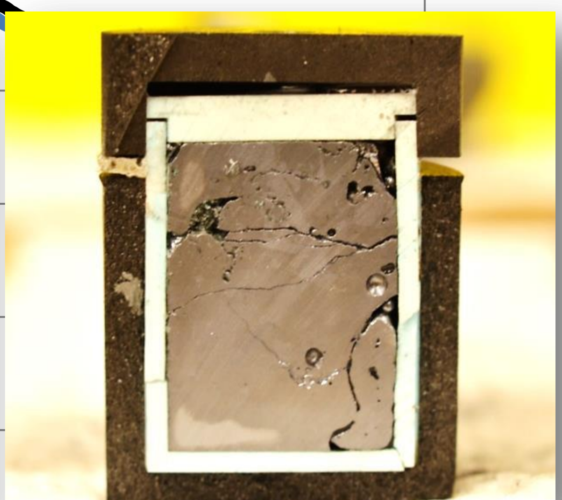
Experimental Data



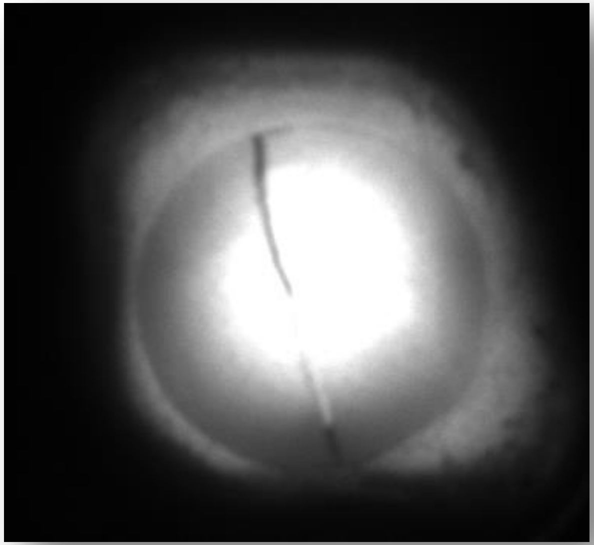
Experimental Data

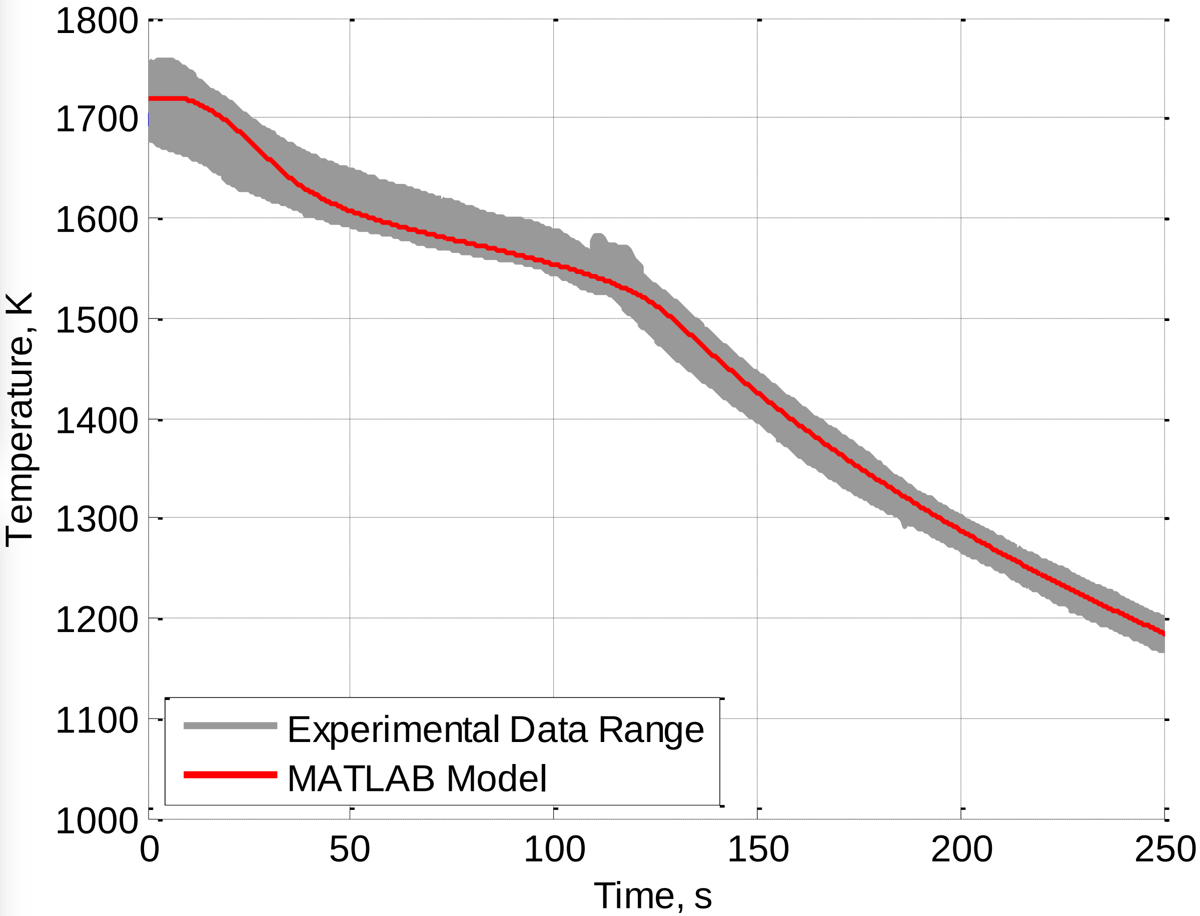




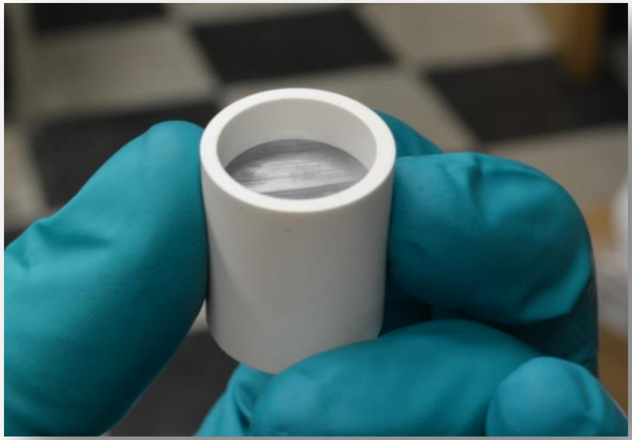


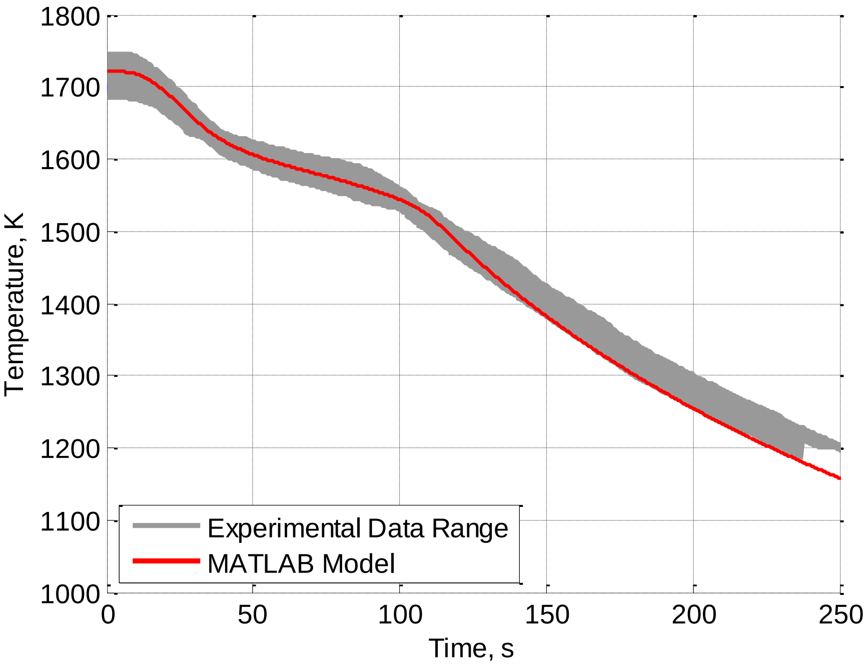
Experimental Data



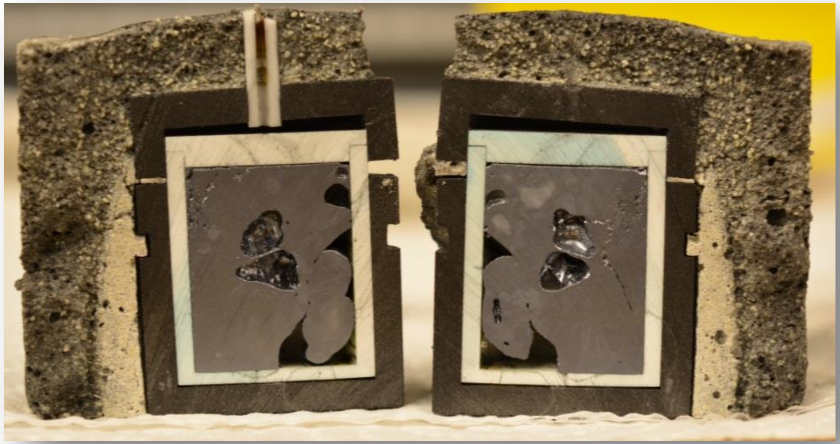


Damage Mitigation: Fill Factor

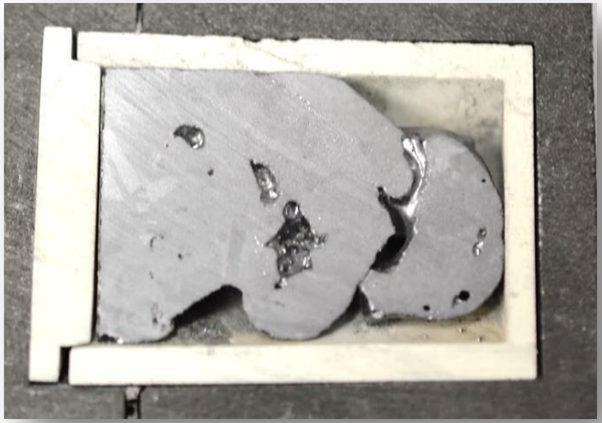


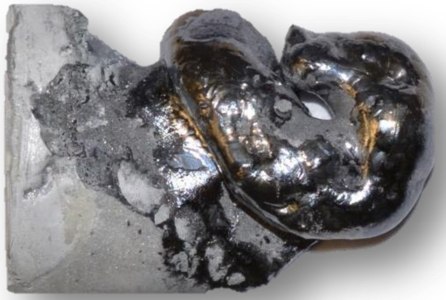


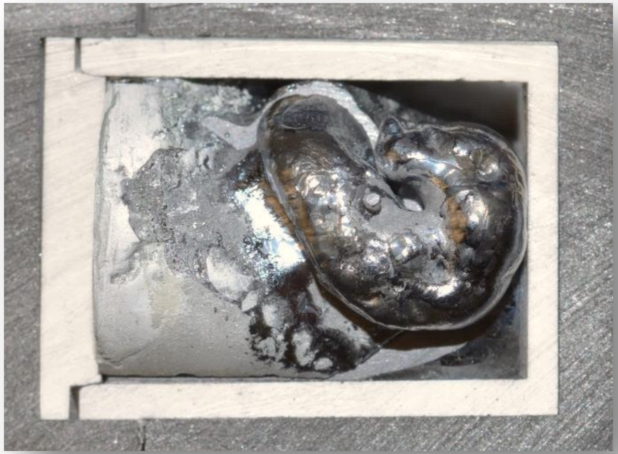
- Successful early tests using silicon powder and chips achieved "fill factors" of approximately 60%
- Tests were performed reducing fill factor from 100% to 80% in 5 % increments
- Audible cracking provided an indication damage during freezing
- No tests < 100% showed macro scale damage. However, all sections showed damage to the inner BN liner



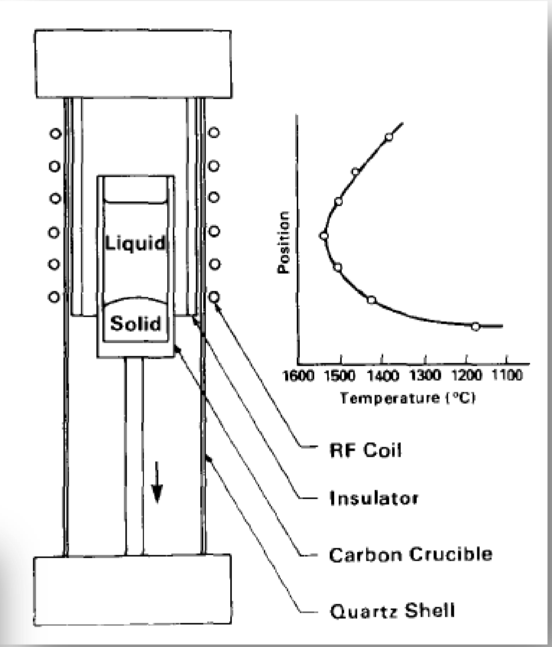
Damage Mitigation: Fill Factor



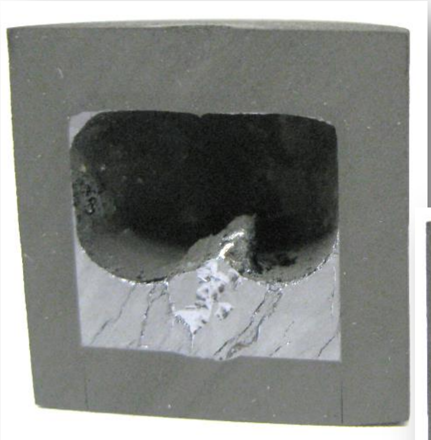


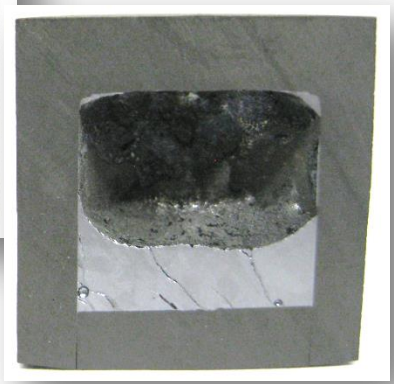


Damage Mitigation: HD Graphite



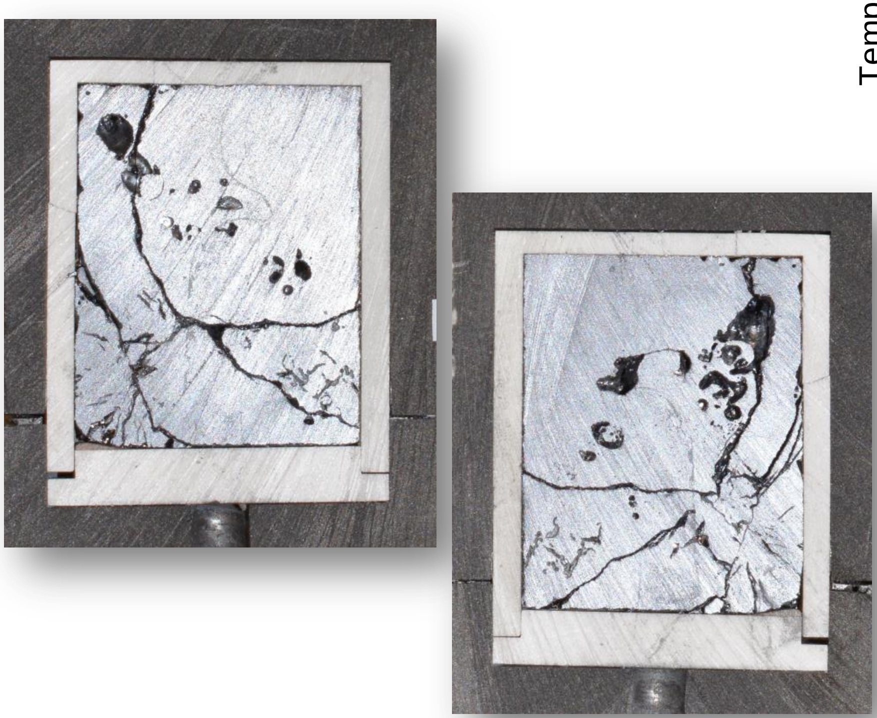
- Production of large silicon ingots precisely controls the phase front
- Graphite crucibles are used with contamination on the order of 20 *ppm*
- Graphite must be > 1.75 *g/cc* with a grain size < 50 *μm*
- Benefits from wetting behavior?

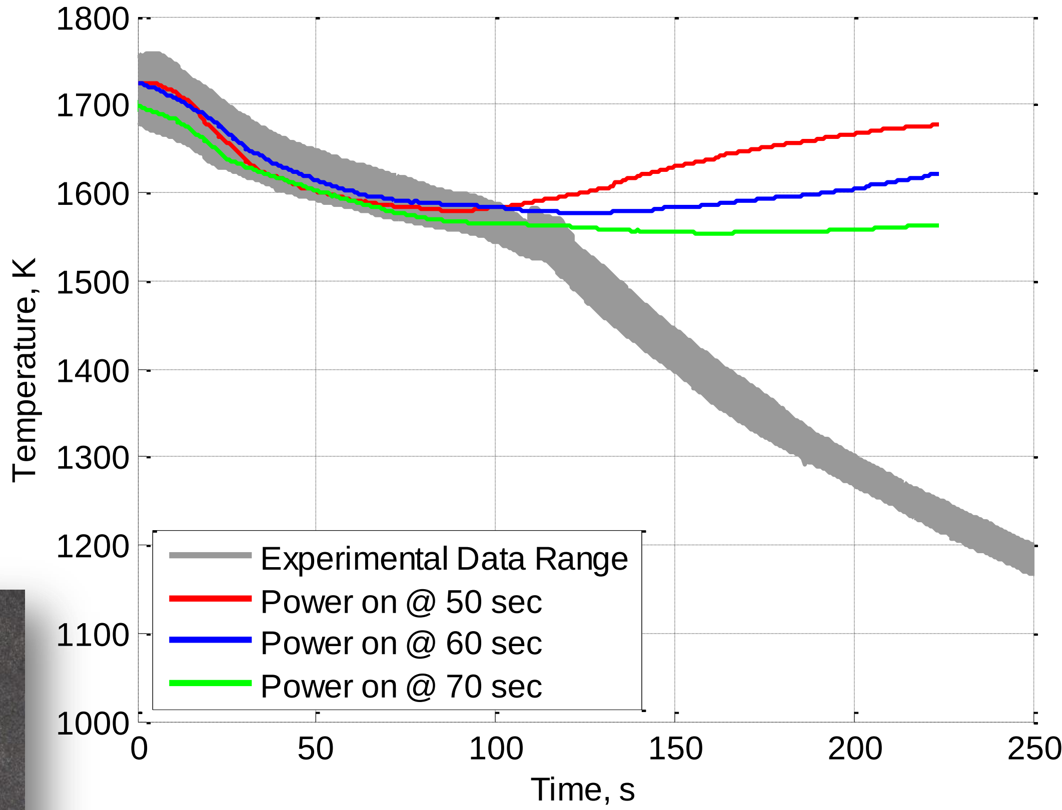




Damage Mitigation: Partial Freezing

- Only allow silicon to partially freeze?
- Experimentally problematic due to assured failure at the end of testing
- Duty cycle must be matched to eclipse period and power available must consider thermal inertia

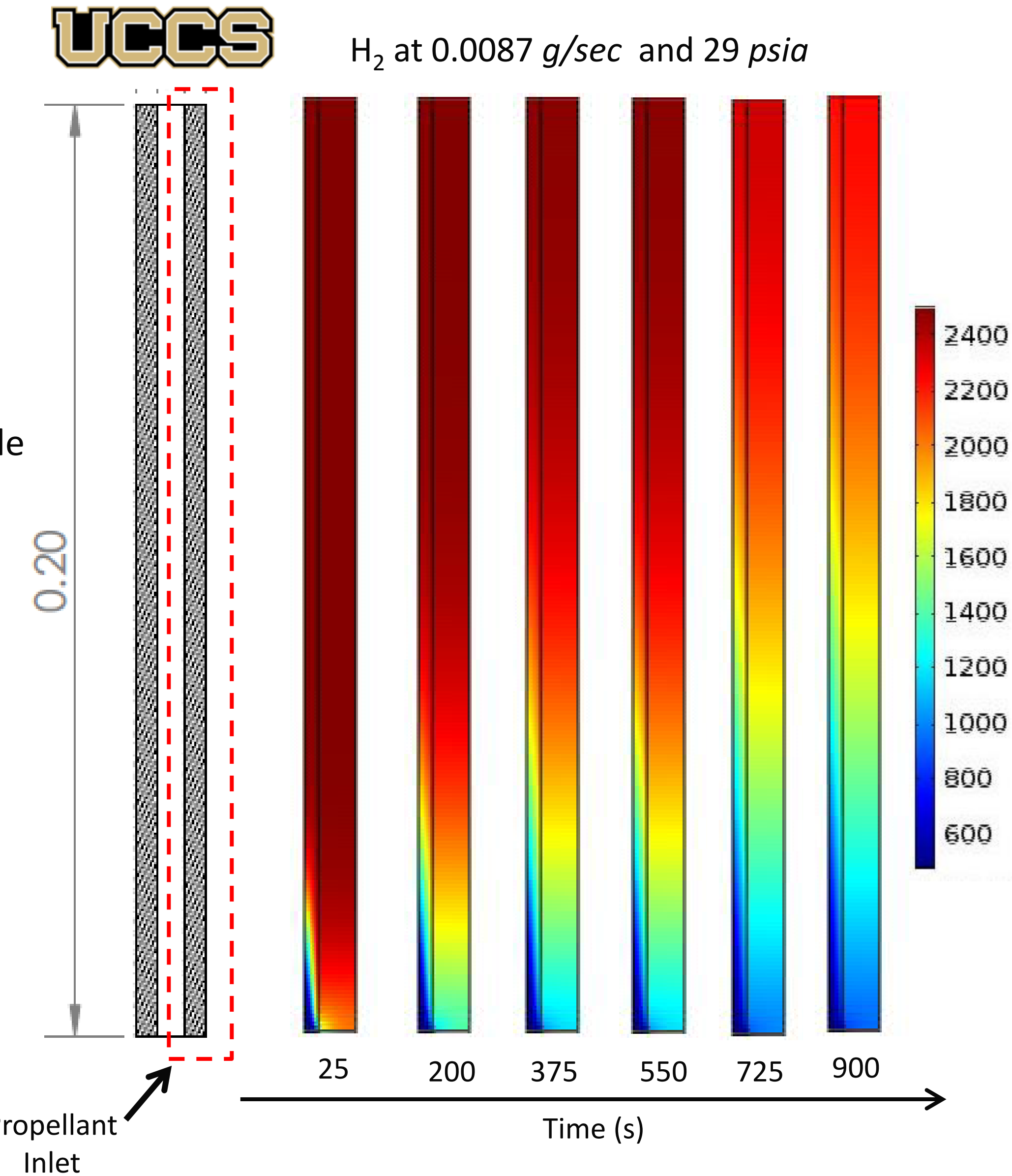




Future Work

Convective Coupling

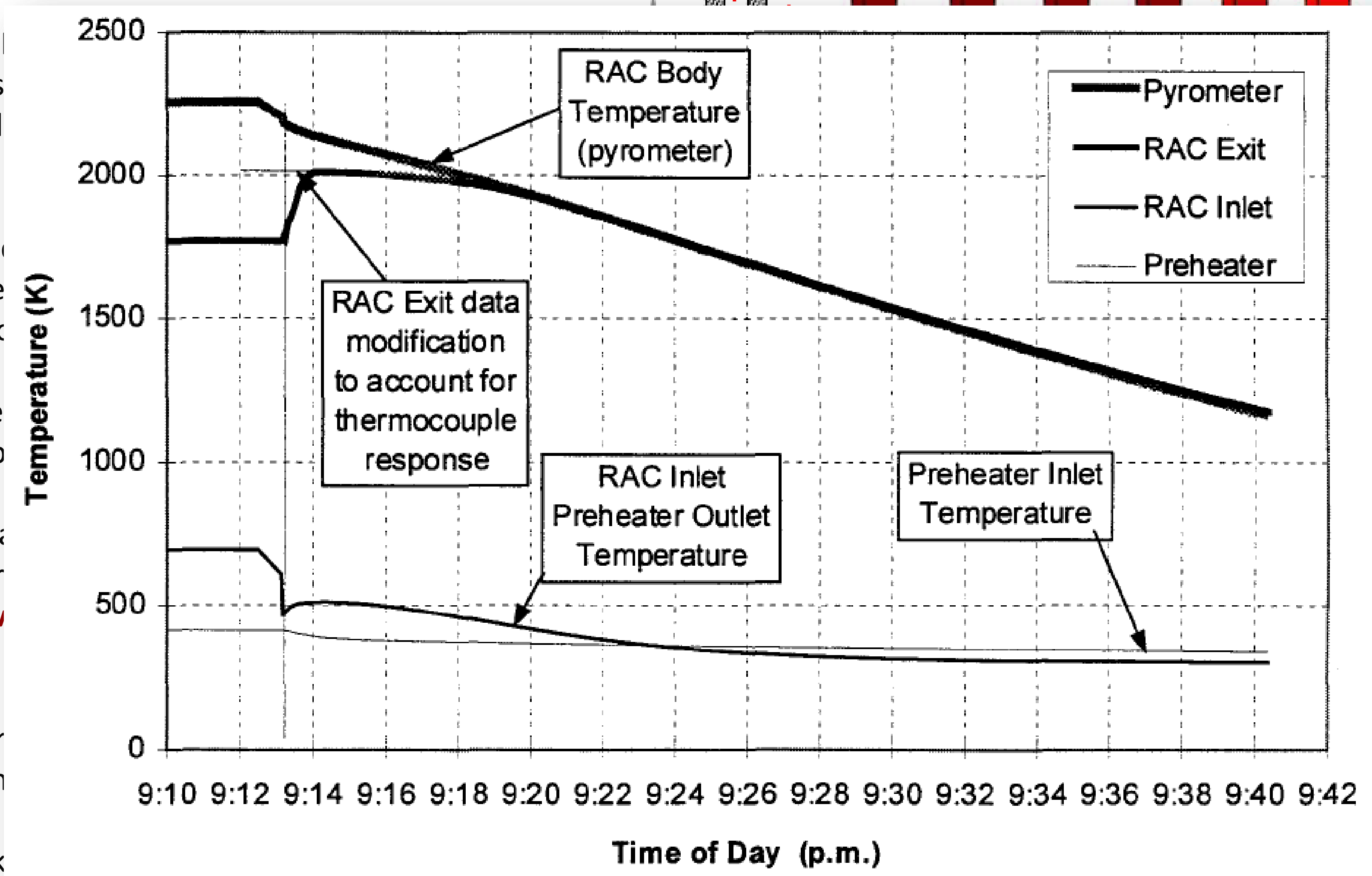
- The ISUS system was capable of maintaining a constant temperature with a sensible heat medium due to “extra length” being designed into the heat exchanger
- The design spec of the ISUS RAC has the potential for 0.72 MJ/kg with a 600 K ΔT (double the original design spec)
- In reality, achieves 0.46 MJ/kg if the steady output region is considered “usable”
- To date, no discussion of latent heat thermal energy storage discusses **advantageous convective coupling**
- Will use commercial multi-physics software (Star-CCM+) to replicate a ISUS heat exchanger channel and switch storage to latent heat
- Seek a quantification of convective coupling benefit

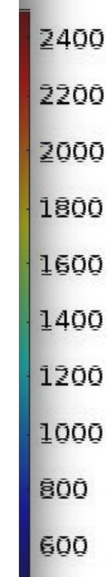


Future Work

Convective Coupling

H_2 at 0.0087 *g/sec* and 29 *psia*





- The cons med into
- The pote the c
- In re outp
- To da ener **conv**
- Will (Star chan
- Seek benefit

USC Viterbi School of Engineering

Conclusions

- Bi-modal solar thermal propulsion has the potential to dramatically extend the microsatellite operating envelope
  - > 1 km/s ΔV
  - Delivery time measured in ***days not years***
- Silicon and boron based thermal energy storage have been frequently mentioned in the literature but lack development due to schedule and funding constraints
- When complete, experiments will bring latent heat thermal energy storage for STP to a similar TRL level as sensible heat options
  - ***Volumetric expansion?***
  - ***Convective coupling?***
- Thorough experimental investigation into high temperature latent heat thermal energy storage will provide a road map for future solar thermal system designers

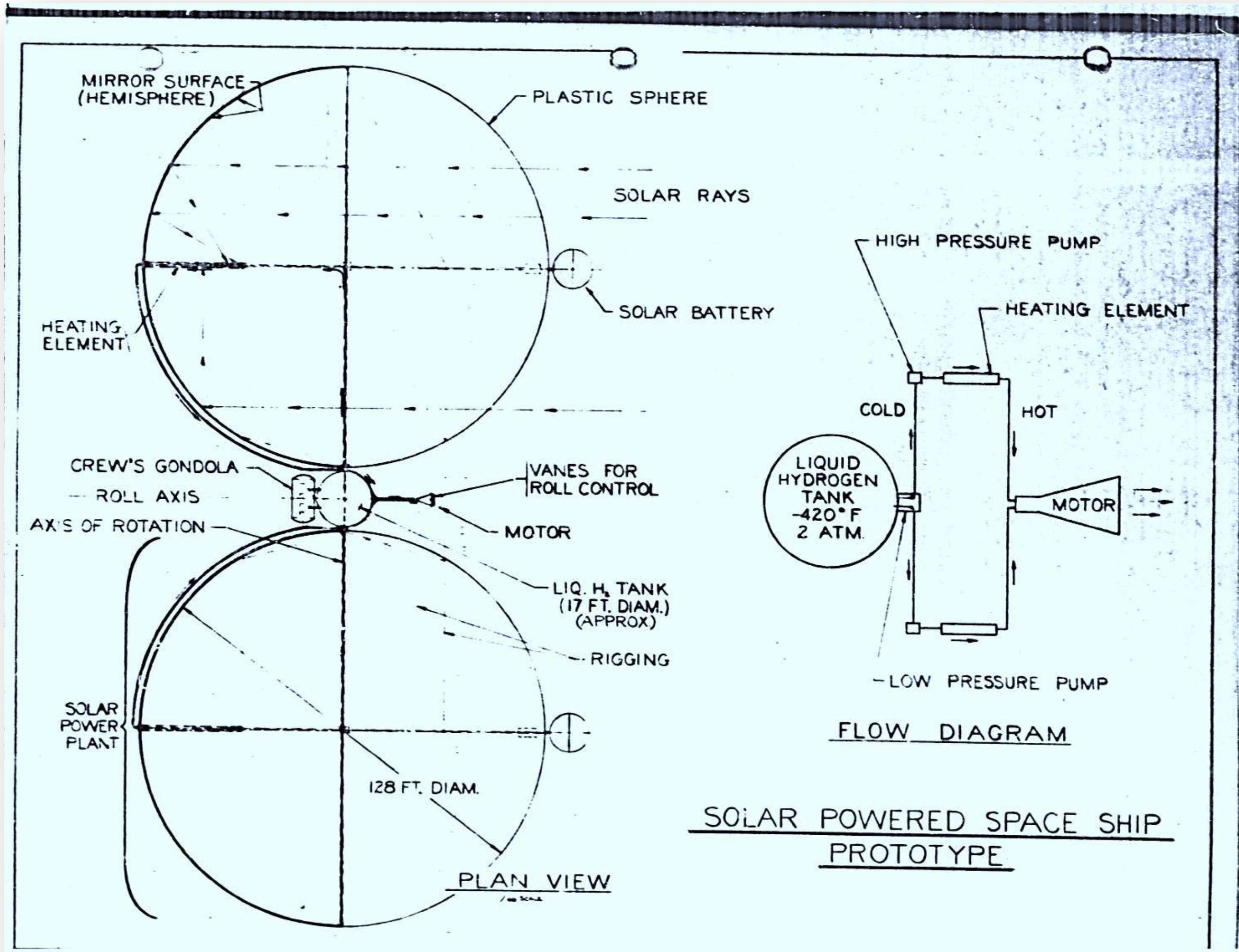
USC Viterbi School of Engineering

Supplemental Slides

■ ■ ■

Solar Thermal Propulsion Overview

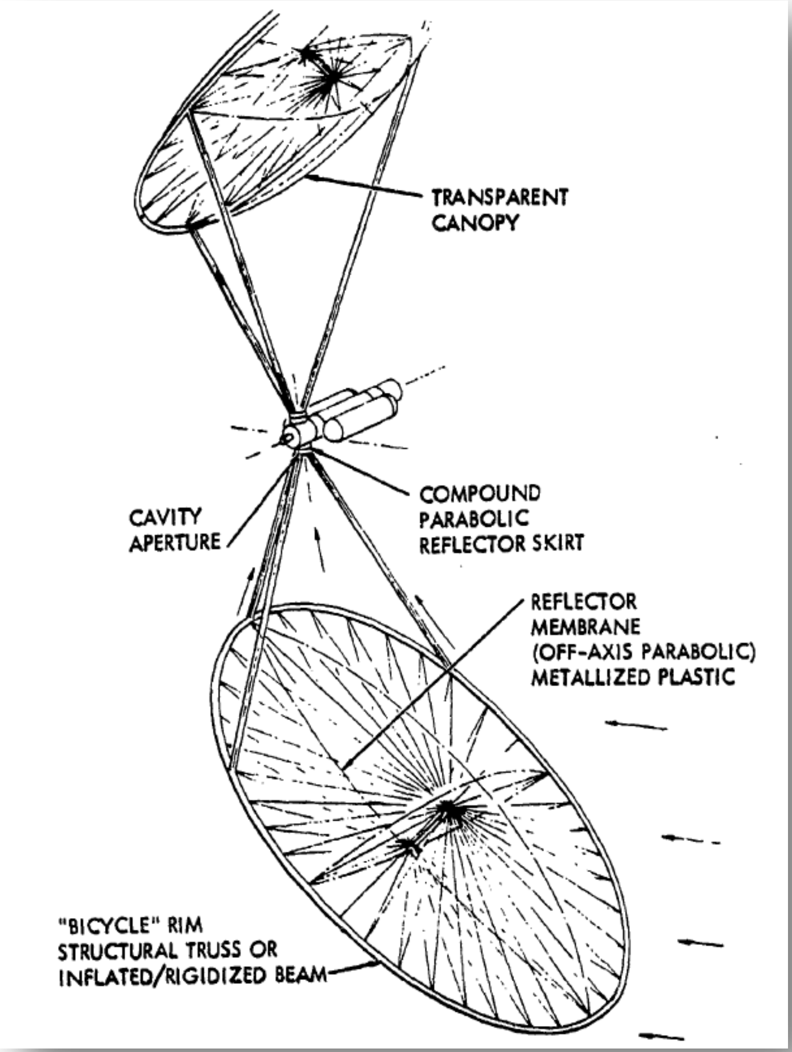
1956 — 1980s — 1990s — 2000s — Today



- "Solar Powered Space Ship" proposed by Krafft Ehricke
- 7500 *kg* spacecraft with a two man crew
- AFRPL funded investigation at Electro-Optical Systems (EOS) in 1963 produced solar heated H_2 at approx. 2300 K
- Work halted due to concerns about "awkward" vehicle design and integration issues
- Funding was shifted to a competing advanced concept

Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today



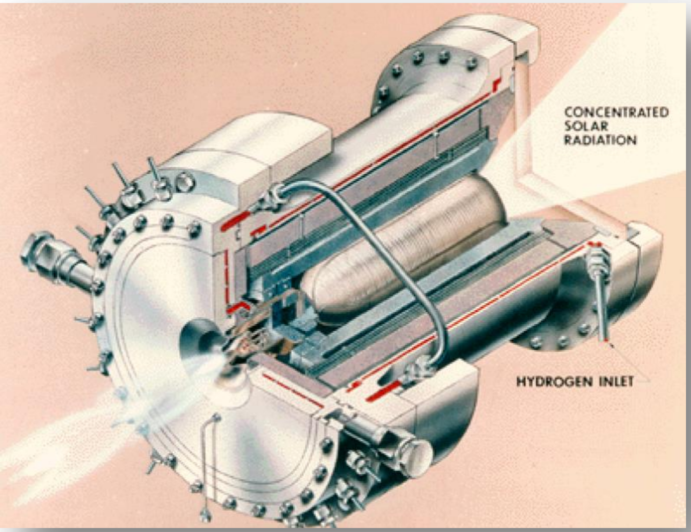
- Space Shuttle – "represents a national commitment to extended operations in space" *Selph 1981*
- 1979 Rockwell report, funded through AFRPL, concludes a solar thermal rocket is possible and recommends near term production
- Vehicle integration was greatly simplified by a centrally located solar receiver and inflatable concentrators
- Compared performance of **28,100 *kg***, shuttle launched spacecraft for LEO-GEO transfer

Engine Type	LO_2 H_2	Ion	Solar 1	Solar 2
ΔV (*m/s*)	4,270	5,850	5,850	4,800
Isp (*sec*)	475	2,940	872	872
Trip Time (*days*)	5	180	14	40
Payload to Geo (*kg*)	9,250	20,000	9,300	13,200

USC Viterbi School of Engineering

Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today



- AFRPL funded effort for experimental demonstration based on findings of Rockwell report
- Rocketdyne contracted to produce a solar thermal thruster using coiled rhenium tubing with a target exit temperature of 2705 *K*
- Solar furnace problems limited testing temperatures to approximately 1800 *K*
- AFRPL declared technology "feasible" but development was slowed in 1989 due to budget cut-backs
- Note that the design **does not** include a means of thermal energy storage

"…time spent traversing the Earth shadow results in a trip-time increase of approximately 10% at no increase in propellant expended."

Ethridge 1979

Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today

- A **bi-modal** nuclear thermal system capable of providing propulsive and electrical power was proposed in the early 1990s

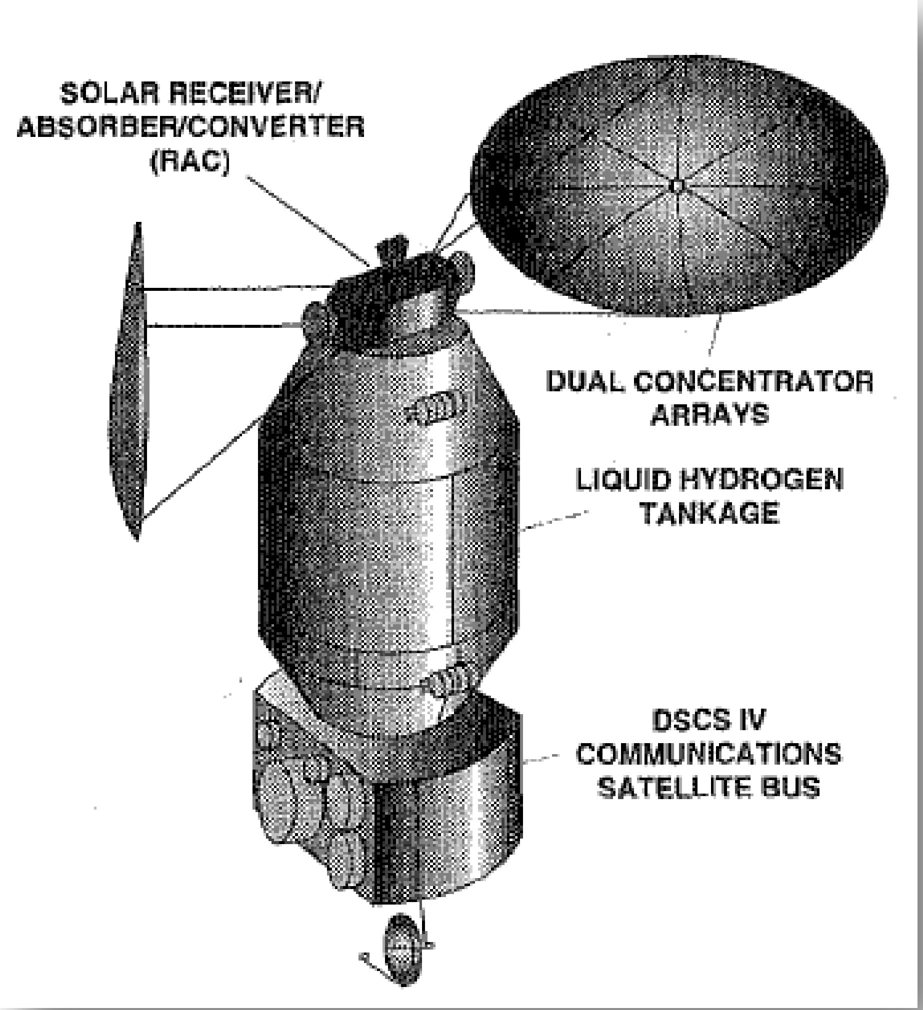
- Integrated upper stage design supplies electrical power to the payload after orbit transfer

- Reduced mass: potential for launch vehicle "step down"

Delta II 7925	**Titan IIG**
\$50M in 1995	\$18-30M in 1995
1800 kg to GTO	1000 kg to GTO

- Due to waning interest in nuclear thermal research, AFRPL considered the concept with a solar thermal architecture

- Sought to quickly reduce the cost of Air Force space operations using *existing* technology

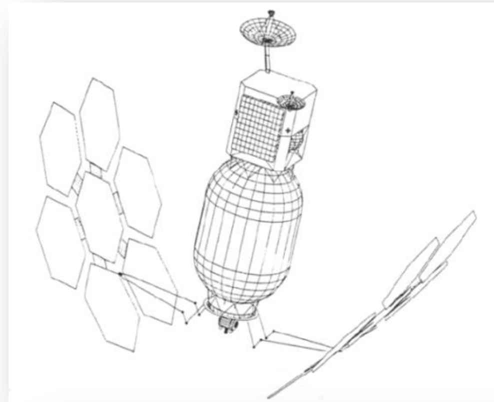


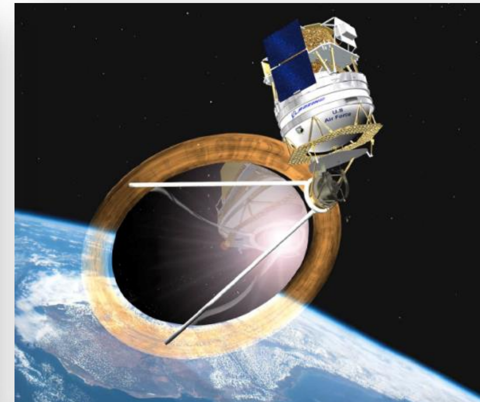
USC Viterbi School of Engineering

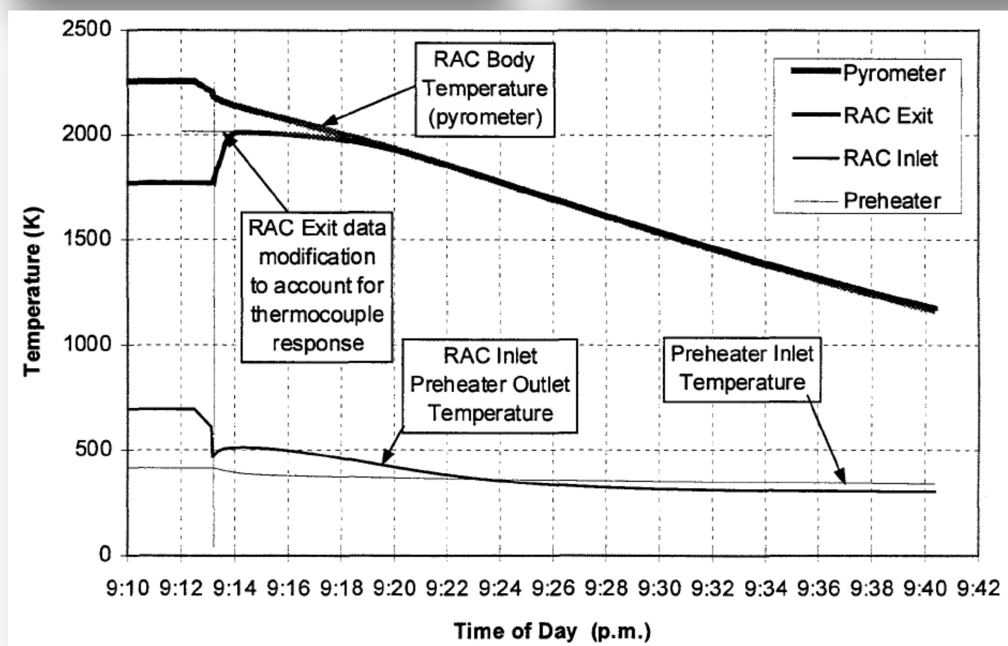
Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today

- Integrated Solar Upper Stage Program (ISUS) initiated in 1994
- ISUS program targeted a "militarily" useful payload on orbit by 1998 – *very optimistic*
- Performed a ground test of a prototype Receiver-Absorber-Converter (RAC)
- RAC incorporated sensible heat thermal energy storage – necessitated by the bi-modal design
- Succeeded in recording data for hot flow hydrogen testing
- Program closed in 1998 – followed by Boeing Solar Orbit Transfer Vehicle (SOTV) and the STP Critical Flight Experiment at NASA Marshall

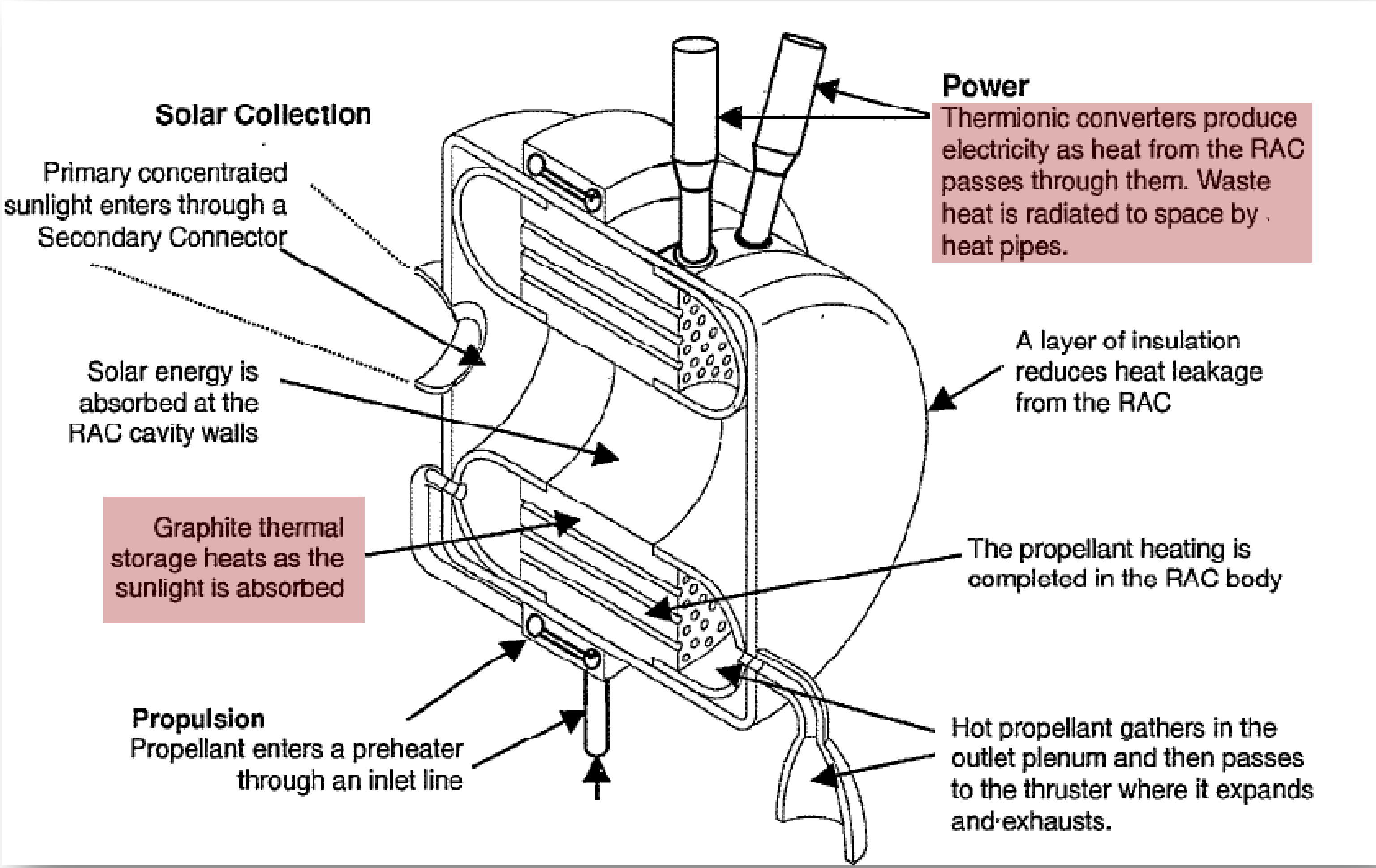






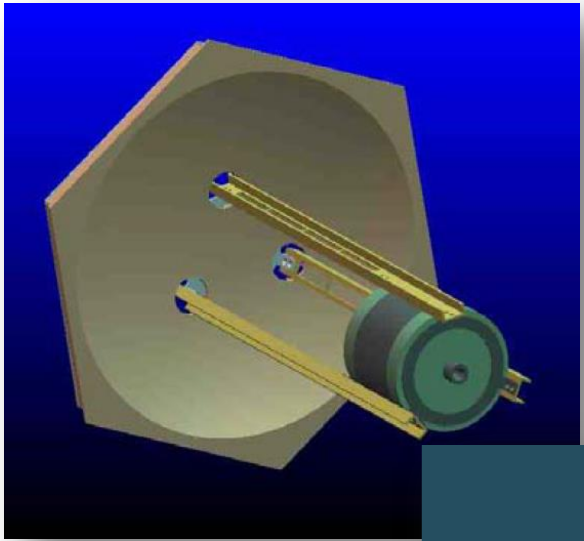
Solar Thermal Propulsion Overview

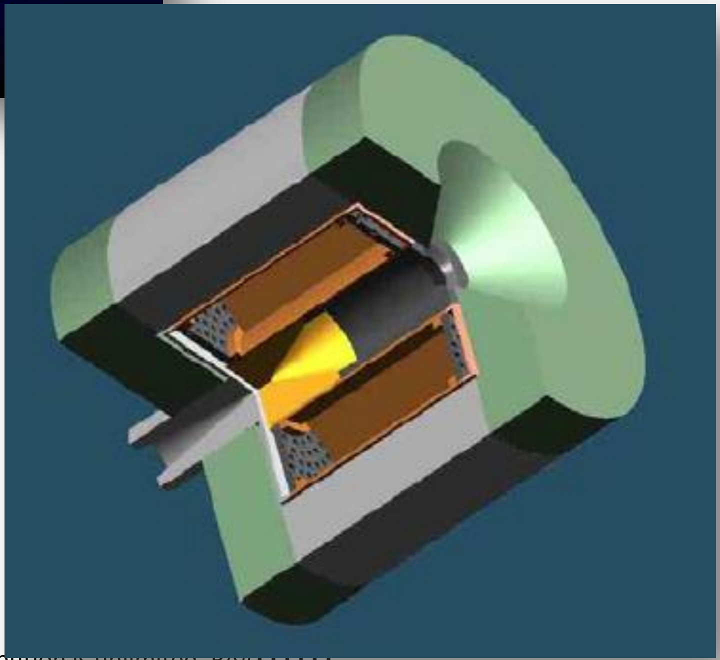
1956 — 1980s — 1990s — 2000s — Today



Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today



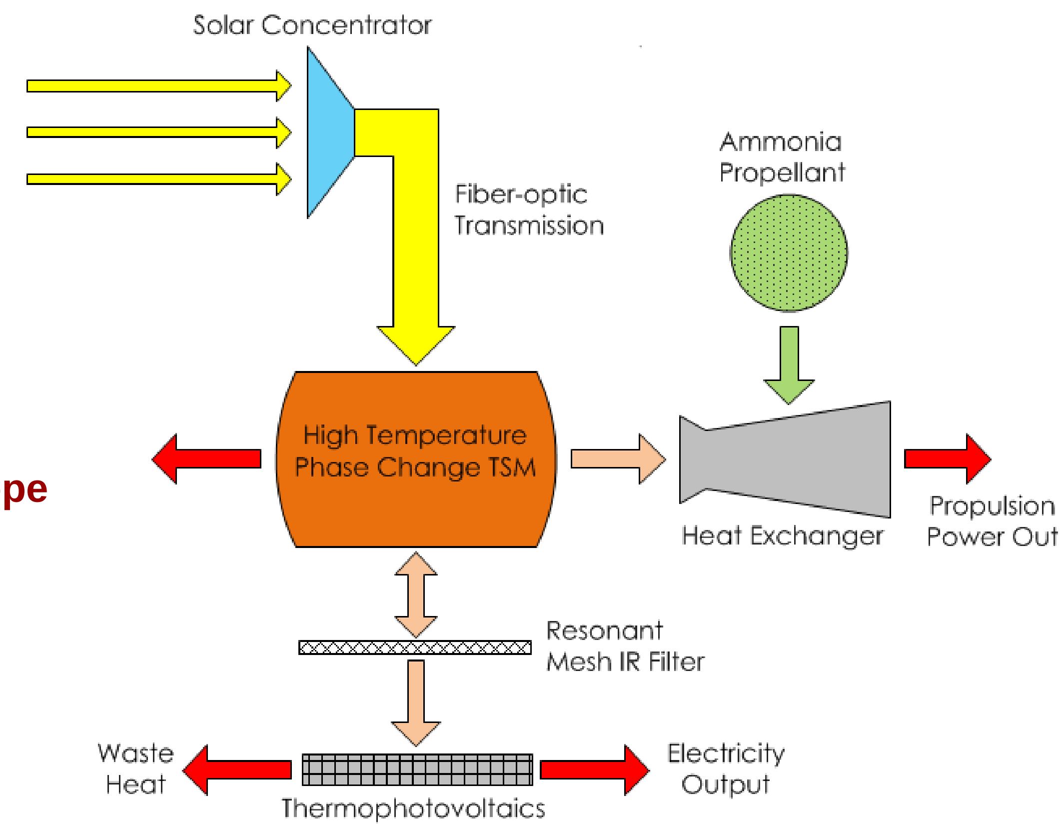


- Concept shifted to microsatellites (10-100 kg) in an effort to *finally* mount a space demonstration
- Project headed by Kennedy, a veteran of the ISUS program, at Surrey Space Center
- Proposed the use of non-cryogenic propellants such as N_2H_4 and NH_3 and "packed bed" sensible heat thermal energy storage
- Achieved experimental NH_3 temperatures approaching 2000 K
- Other small scale research efforts
  - Thin film concentrator and Mo receiver work at JAXA
  - Fiber optic coupling work at Physical Sciences Inc

Solar Thermal Propulsion Overview

1956 — 1980s — 1990s — 2000s — Today

- Drawing from Kennedy's microsatellite study, a review by the AFRPL advanced concepts group identified STP as a promising candidate for high performance microsatellite missions
- A ***bi-modal microsatellite*** configuration is proposed and further study is recommended
- Microsatellite scaling distinguishes STP
- Large ΔV (> 1 km/s) possible

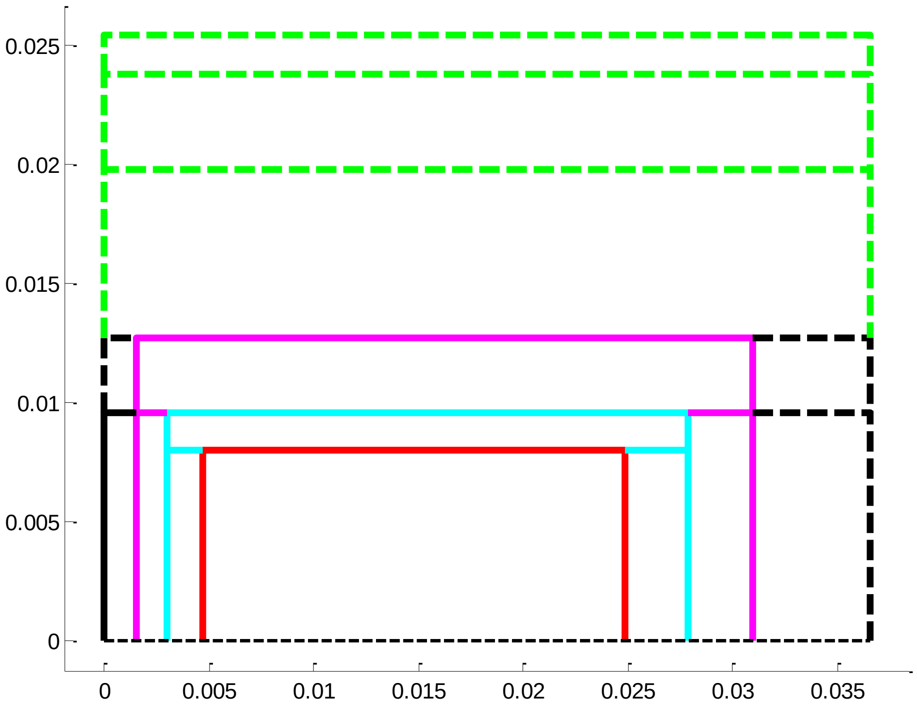


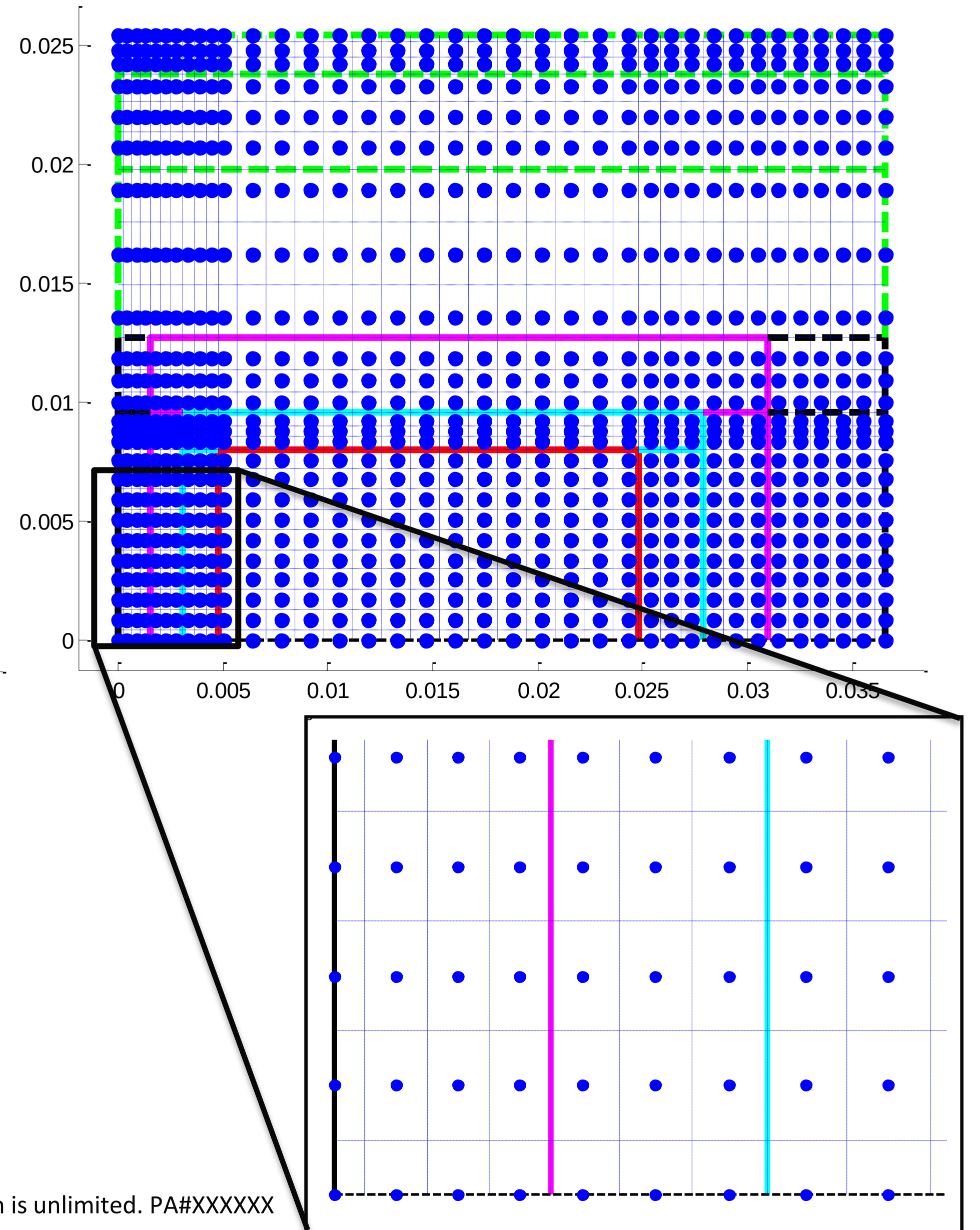
Expand the Microsatellite Operating Envelope

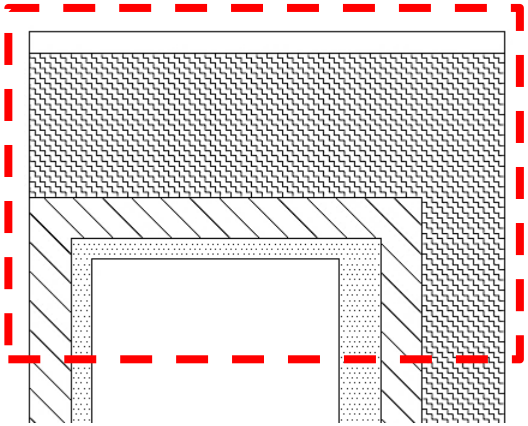
- Expand possible "piggy-back" launch options
- GEO Insertion: *~ 1760 m/s*
- Near Escape Missions: ~ *770 – 1770 m/s*

Possible with EP, however, STP offers a much shorter burn time and higher maneuverability

MATLAB Model

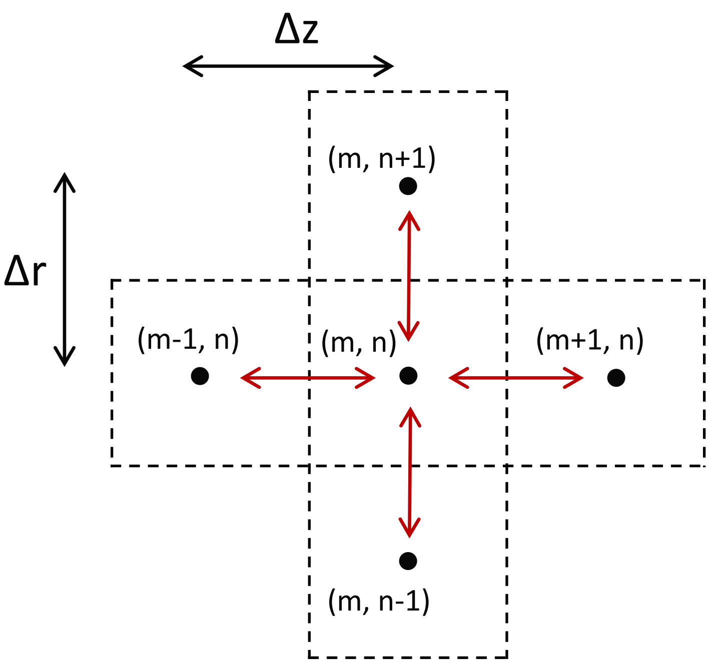


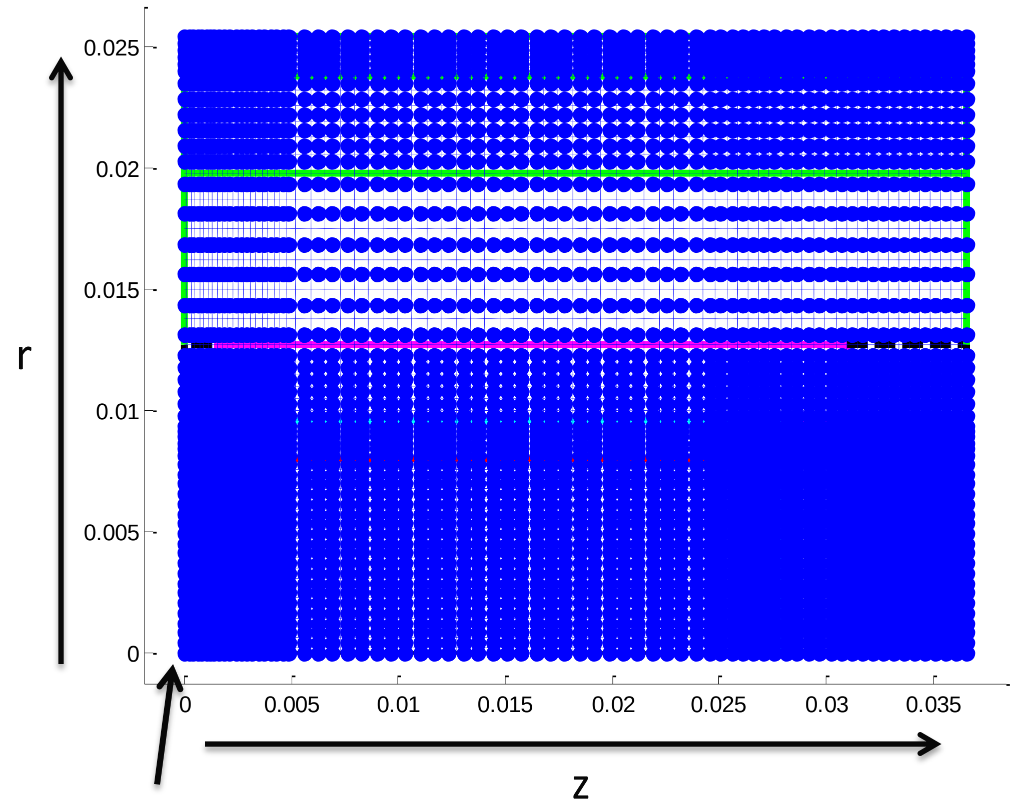


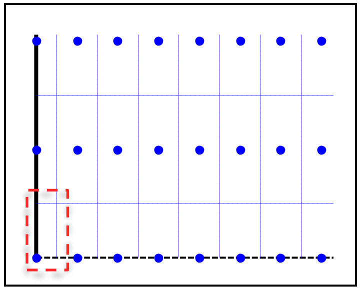


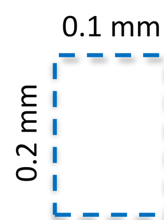
MATLAB Model

- 3700 Nodes
- dt = 0.00025 seconds
- Approx. 14 hours runtime for a 300 second simulation





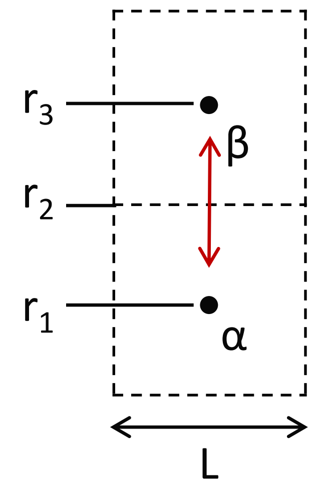




V = 1.3×10^{-5} cc
m = 2.65×10^{-5} g

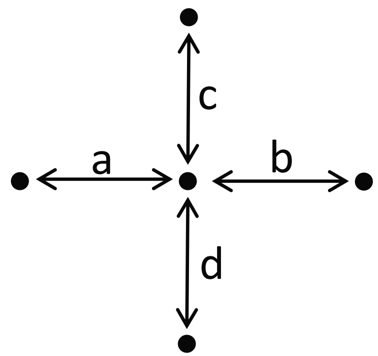
MATLAB Model

Conduction in the "r" Direction



$$q = \frac{\left(T_\beta - T_\alpha\right)}{\frac{\ln\left(r_2/r_1\right)}{2\pi L k_\alpha} + \frac{\ln\left(r_3/r_2\right)}{2\pi L k_\beta}}$$

All geometric terms are offloaded into coefficient matrices to speed computations

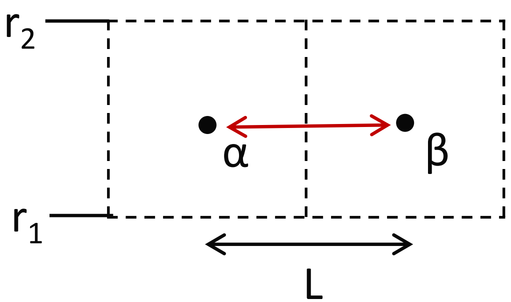


At Each Time Step

$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up}$$

$$\Delta T = \frac{q_{net}\,dt}{mc_p}$$

Conduction in the "z" Direction



$$q = \frac{A\left(T_\beta - T_\alpha\right)}{L\left(1/k_\alpha + 1/k_\beta\right)}$$

$$A = \pi\left(r_2^2 - r_1^2\right)$$

Node With PCM

$$\Delta T = \frac{q_{net}\,dt}{mc_p} + LatentHeat(rr, zz)$$

MATLAB Model

Radiation Boundary Condition

$$q_{rad} = -\sigma \varepsilon A \left(T_{node}^4 - T_{amb}^4 \right)$$

$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up} + q_{rad} + q_{conv}$$

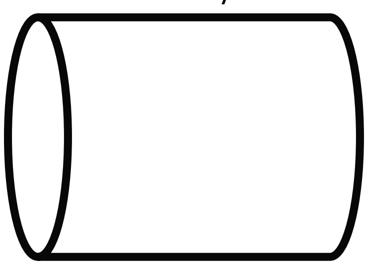
$$\Delta T = \frac{q_{net} dt}{m c_p}$$

Convective Boundary Condition

$$q_{conv} = -hA \left(T_{node} - T_{amb} \right)$$

Assume Long Horizontal Cylinder

Assume Vertical Plate



Vertical Plate → h ≈ 6.7 (W/m²K)

$$\mathrm{h} = \frac{k}{L} \left(0.825 + \frac{0.387 \mathrm{Ra}_L^{1/6}}{\left(1 + (0.492/\mathrm{Pr})^{9/16}\right)^{8/27}} \right)^2$$ *(Churchill and Chu)*

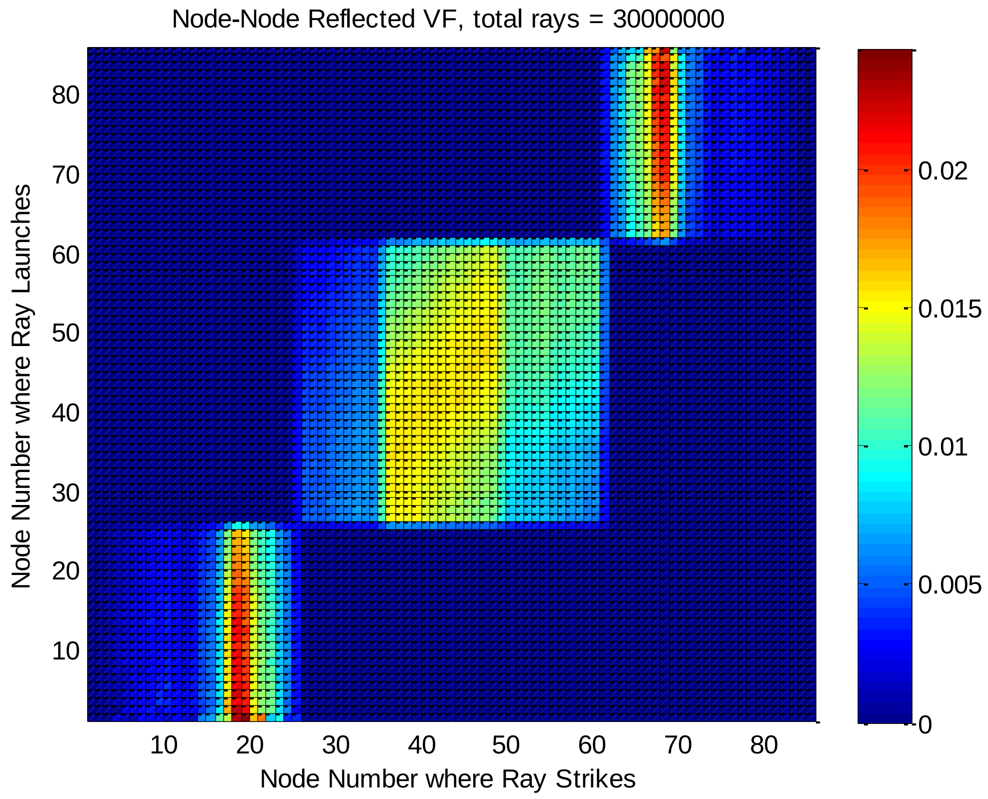
Assume laminar flow with Argon at 500 *K* and 150 *Torr* ($Ra_L = 10^6$)

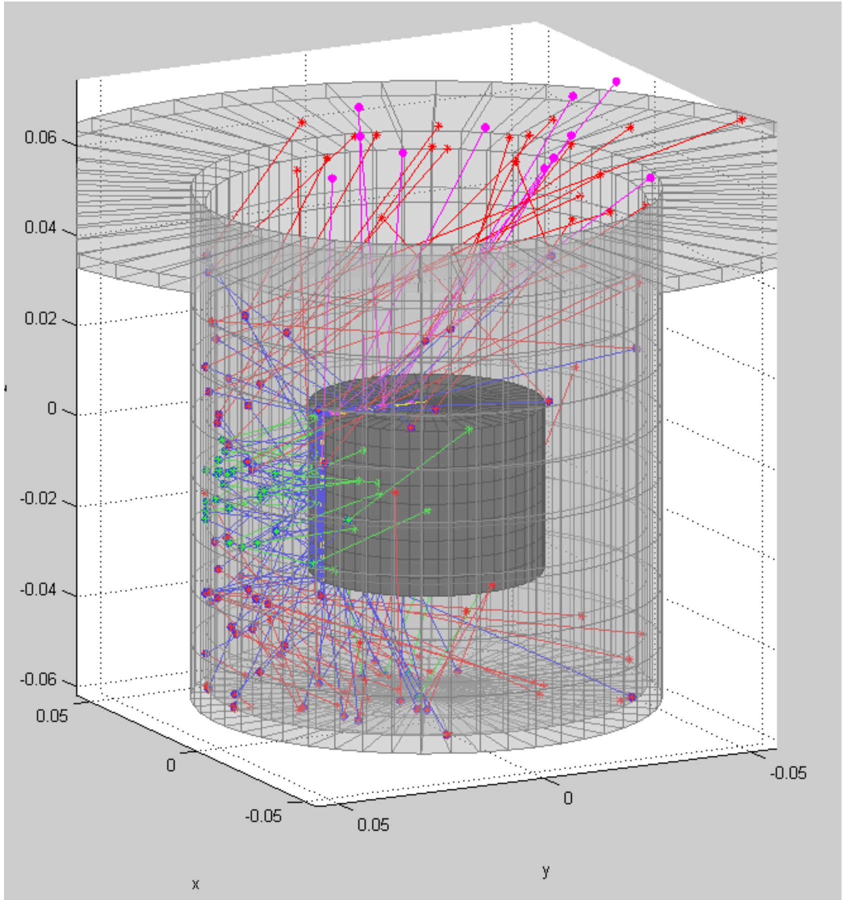
Horizontal Cylinder → h ≈ 5.7 (W/m²K)

$$\mathrm{h} = \frac{k}{D} \left(0.6 + \frac{0.387 \mathrm{Ra}_D^{1/6}}{\left(1 + (0.559/\mathrm{Pr})^{9/16}\right)^{8/27}} \right)^2$$ *(Churchill and Chu)*

Assume laminar flow with Argon at 500 *K* and 150 *Torr* ($Ra_L = 10^6$)

MATLAB Model

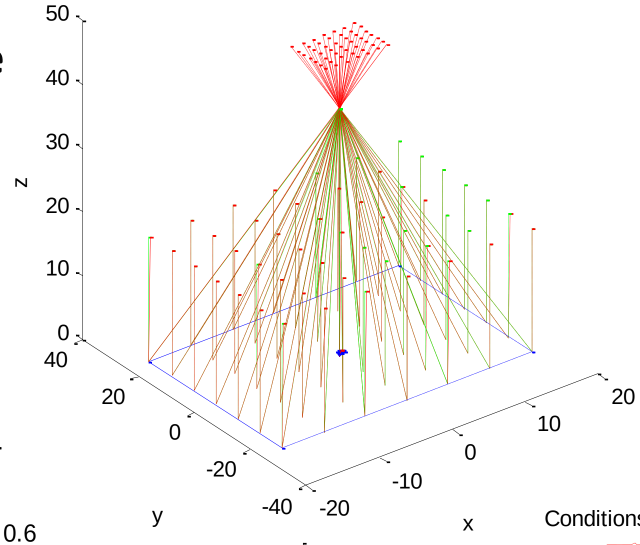




Pointing Error Calculations

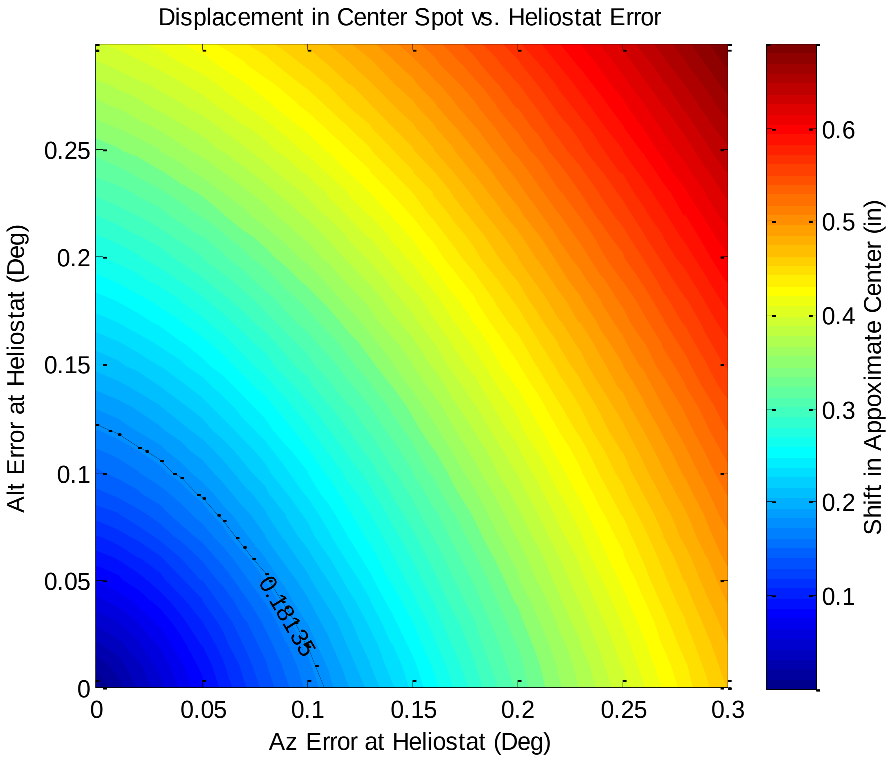
Accuracy Requirements in the Literature

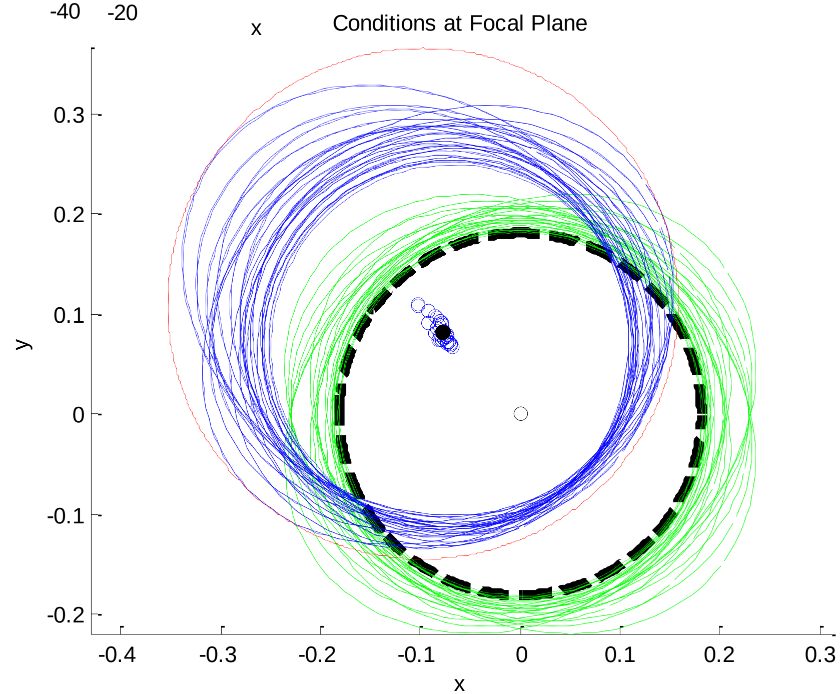
- ± 0.3° - *Hukuo 1957*
- ± 0.1° - *Ethridge 1979*
- ± 0.5° - *Holmes 1995*
- ± 0.1° - *Kennedy 2004*



Note idea image for a parabolic concentrator

$$d = 2f\sin(\theta_{sun}/2)$$

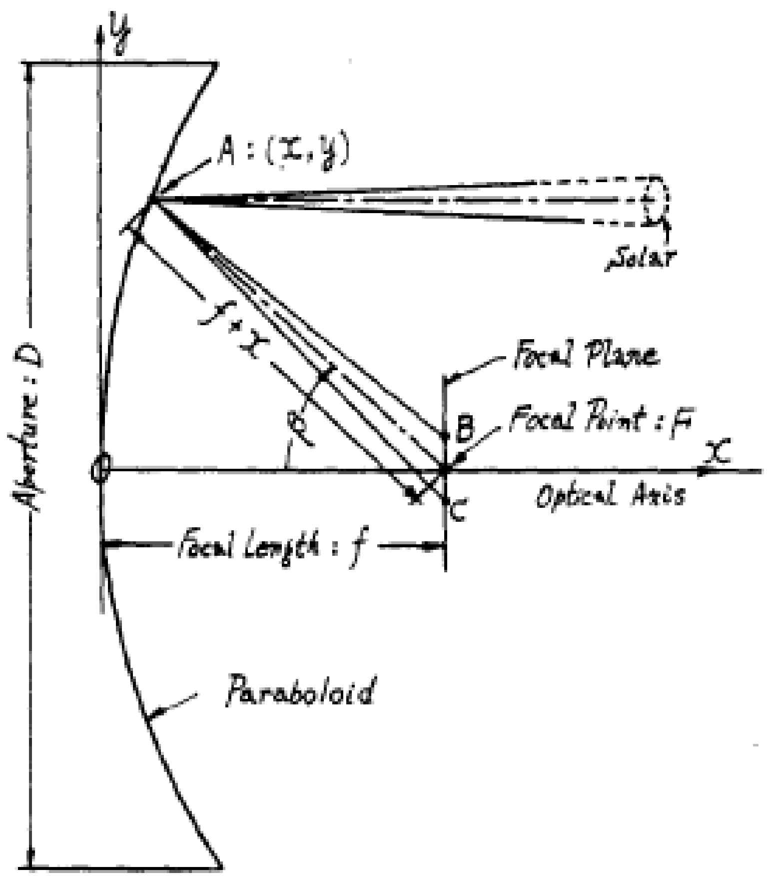




Pointing Error Calculations

Hukuo and Mii 1957

FIG. 1 — Section of a parabolic mirror.



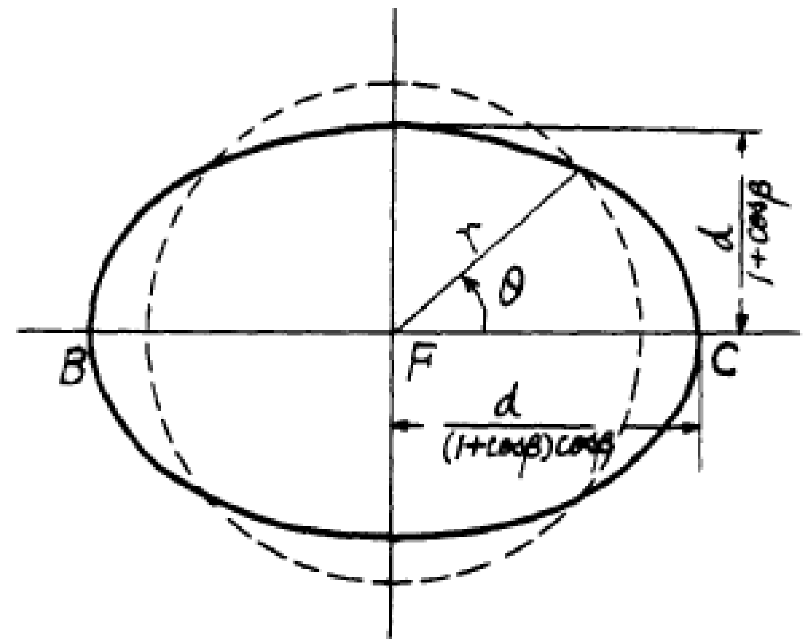
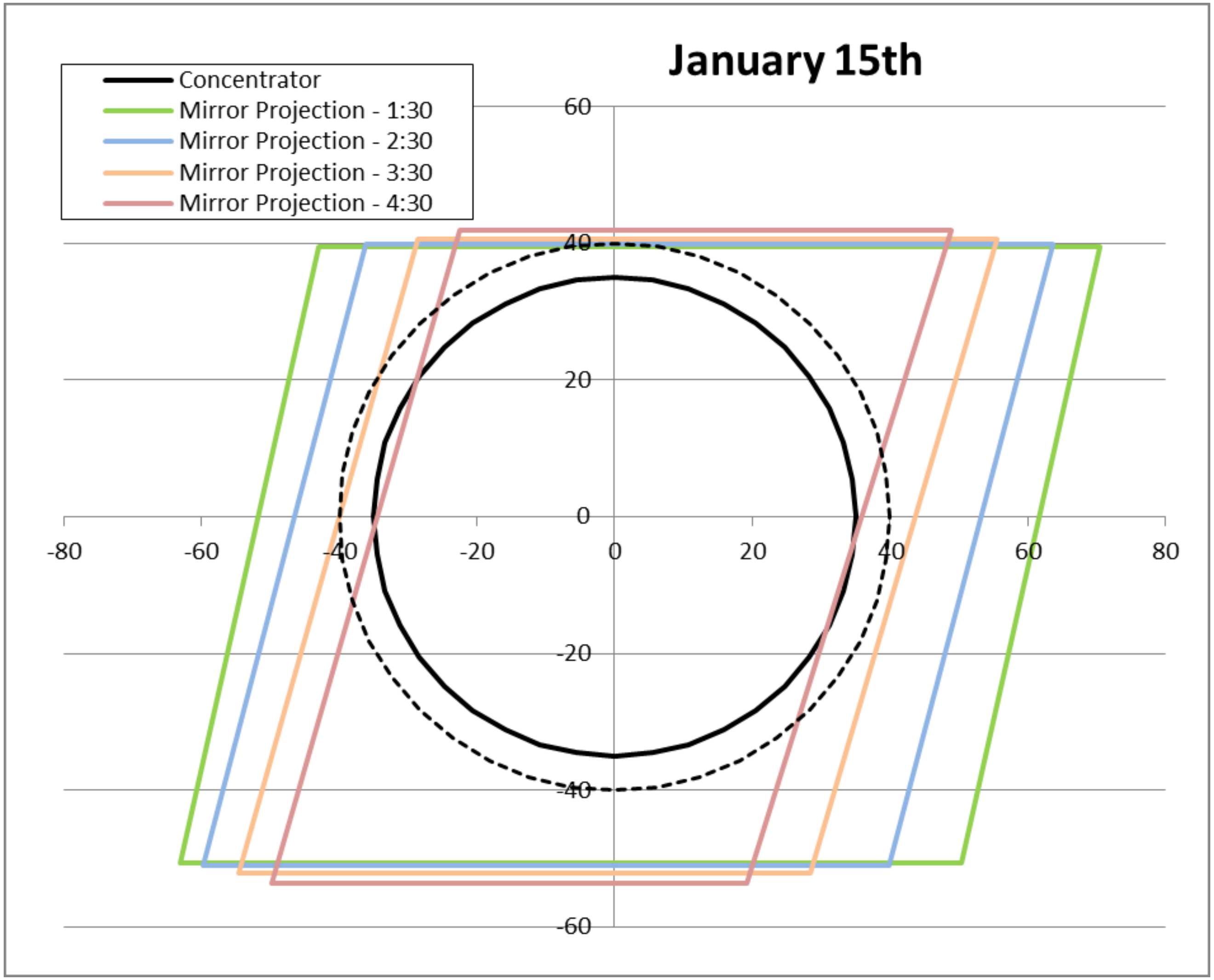
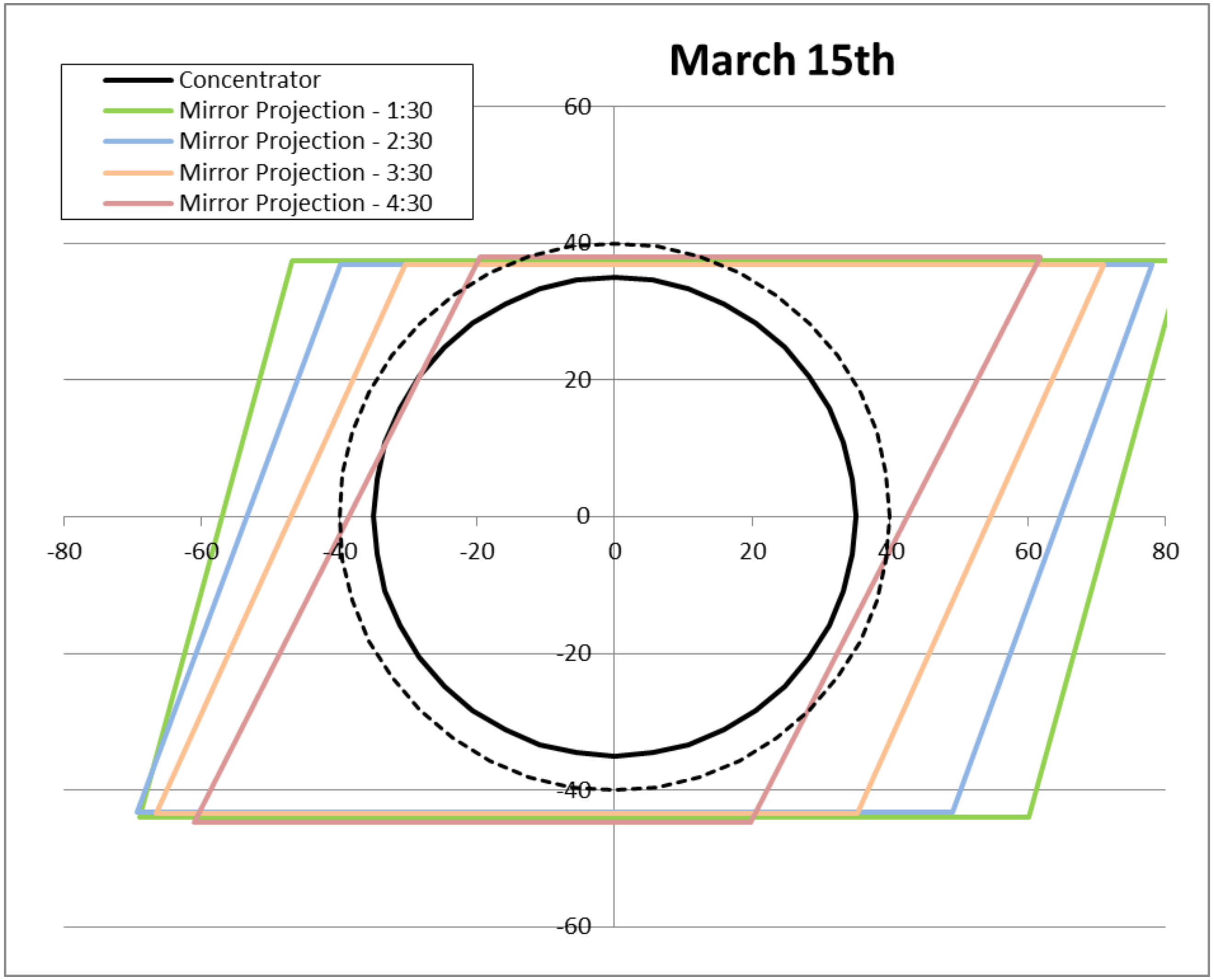


FIG. 2 — Solar image produced by a ray which is reflected by the paraboloid with the angle β.

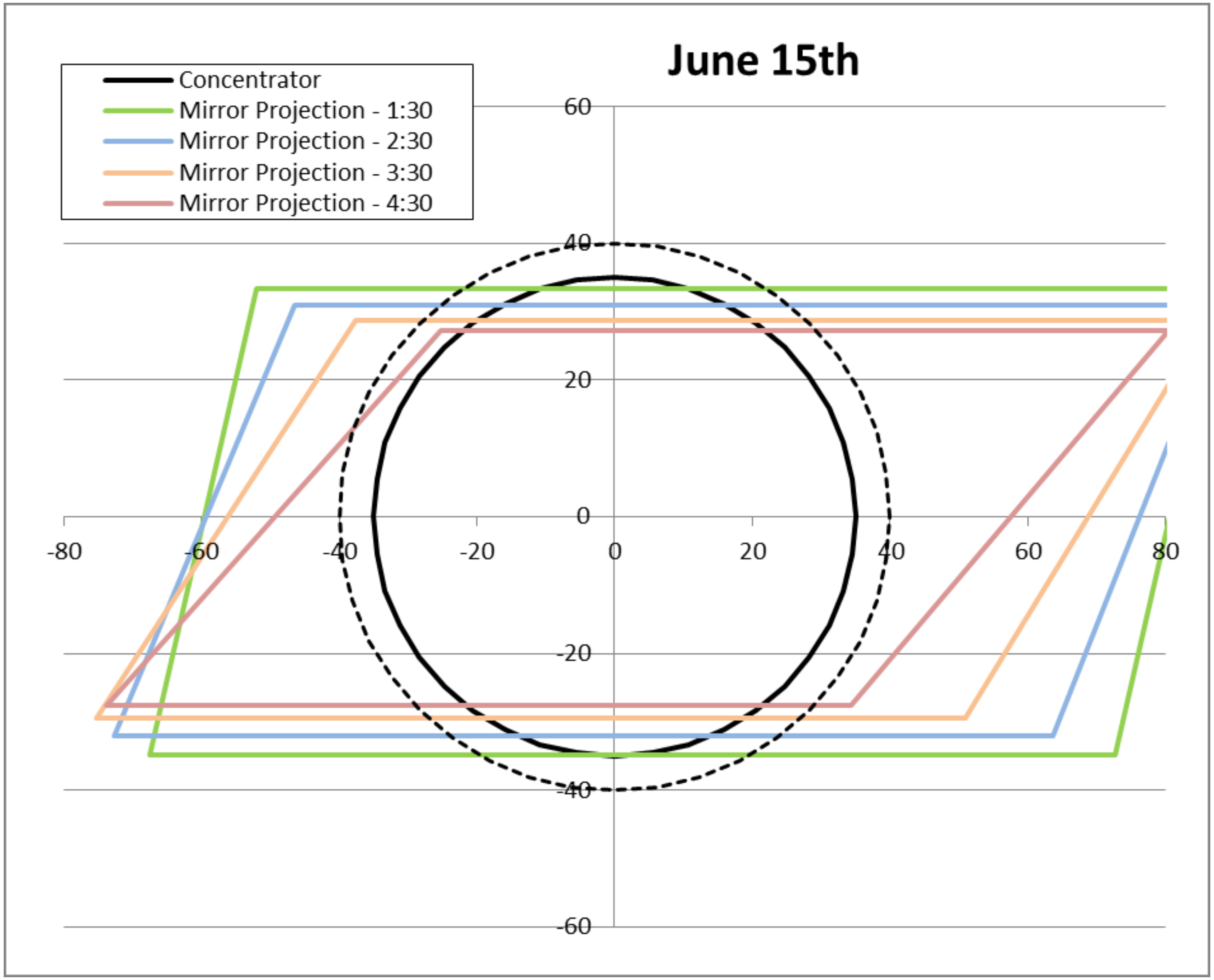
Heliostat Coverage



Heliostat Coverage

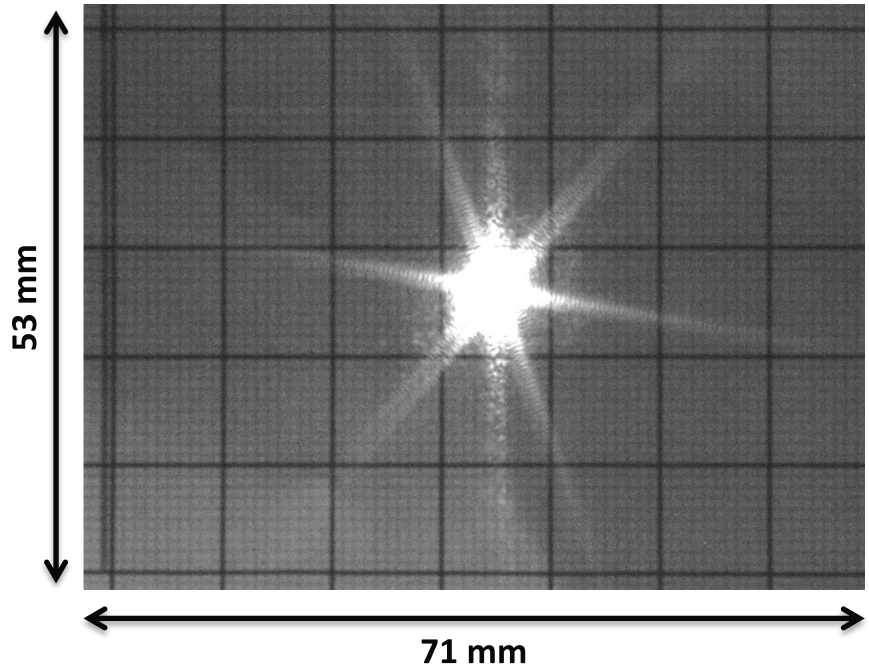


Heliostat Coverage



CCD Diagnostic Method

- Read pixel intensities from CCD after subtracting representative "dark frame"
- Convert using black body calibration from *counts/μs* to *W/m²nm* at 980 *nm*
- Account for reflectivity of pseudo-Lambertian surface
- Convert from *W/m²nm* to *# of Suns*
  - Weight against filter band pass
  - Use ASTMG173 data to scale 980 *nm* values with the full spectrum
  - Multiply by ASTMG173 standard insolation to get pixel reading in W/m^2
- Compare to locally measured insolation to get map of concentration ratios



Sony ICX445 CCD - 1.2 MP

16-bit mono output format

Images captured at 640 x 480

Tech Comparison Metrics

Solar Thermal w/o Energy Storage	Chemical Thrusters	Electric Propulsion
• Eliminated PCM and TPV • Reduced solar collector size • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV	• Astrium Hydrazine Monoprop • Commercially available 1 N and 20 N models • Isp: 220-230 s • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV	• XHT-100 Hall Effect Thruster • 95 W power draw • Isp: 750-1000 s • 3 – 10 mN Thrust • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV

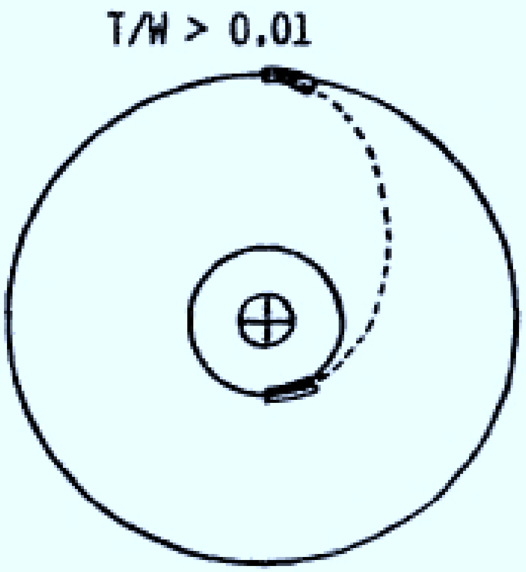
Identical Mass Fractions ($M_{Propulsion\ \&\ Power}$ = 58%)

Total ΔV and Delivery Time are Primary Comparison Metrics

Ethridge Orbit Calculations

TWO IMPULSE

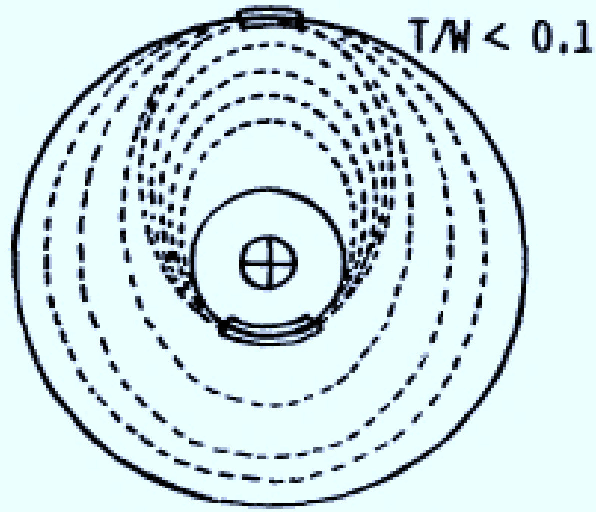
ONE PERIGEE BURN
ONE APOGEE BURN



LEO TO GEO
$14000 \leq \Delta V \leq 17000$ FPS
TRIP TIME < DAY

MULTI IMPULSE

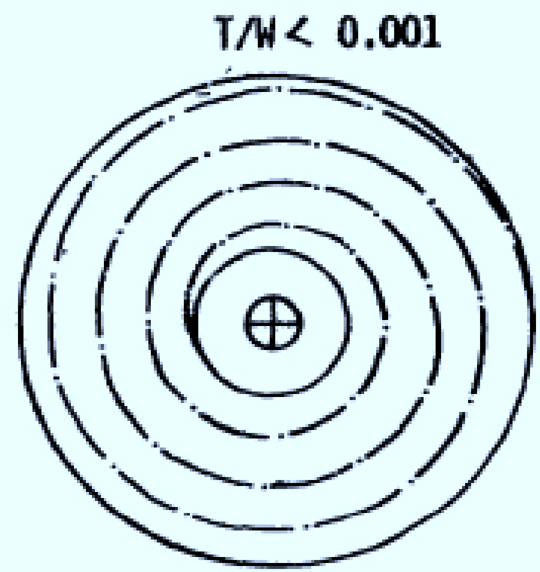
MORE THAN ONE PERIGEE BURNS AND MORE THAN ONE "INSERTION" BURNS NEAR FINAL APOGEE



LEO TO GEO
$14000 \leq \Delta V \leq 19200$ FPS
TRIP TIME > DAYS

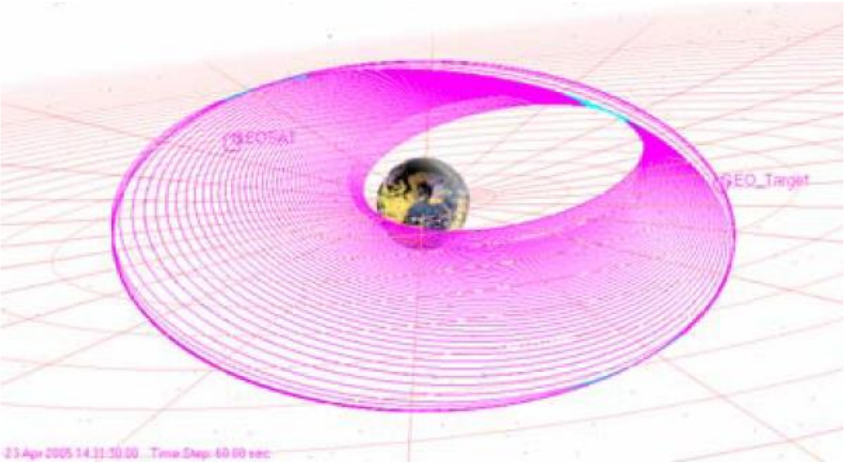
CONTINUOUS BURN

SPIRAL TRAJECTORY



LEO TO GEO
$\Delta V \approx 19200$ FPS
TRIP TIME > WEEK

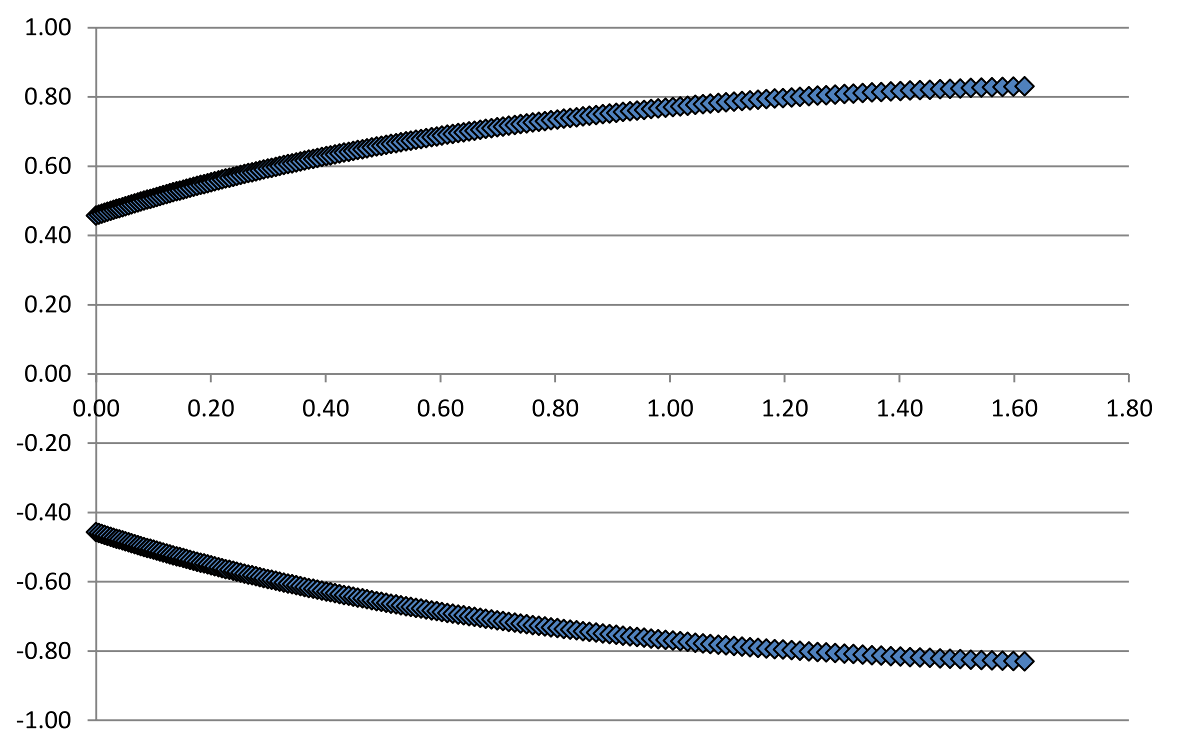
Kennedy Orbit Calculations



- 10% “On Time”
- 100 kg satellite
- Launch from Ariane 5 into GTO (350 x 35,717 km - 7°)
- Transfer to 0° at 116 °E
- Assumes ½ N thrust and 400 s I_{sp}
- 48 kg for *JUST* solar thermal engine and propellant

Start Date	1 April 2005, 00:00:00.00 (Julian Date 2453461.5)
End Date	6 May 2005, 09:11:16.96 (JD 2453496.88)
Elapsed Time	35 days, 9 hrs., 11 min.
Number of Maneuvers	58 (51 apogee kicks, 7 plane changes at node crossings). Two-orbit “hold” of 42 hrs., 20 min. introduced after apogee kick 48 to attain proper orbital phasing at GEO
Total Velocity Change	1,761 m/s
Propellant Consumption	36.184 kg
Final Mass	63.816 kg
Engine “On-Time”	80 hrs., 33 min.

Secondary Concentrator



- Defined by parametric equations given by *Welford and Winston 1978*
- CAN NOT be used to increase power due to low f/d ratio for the concentrator
- CAN be used to increase concentration ratio

Diameter	Max Angle	Minimum Diameter	% Area Increase	Max Ratio	Minimum Spot	Spot Change	**C Ratio Change**
70	33.0	1.66	0%	3.24	0.914	0.84	5%
75	35.162	1.81	15%	2.99	1.046	1.09	-16%
80	37.7	2.09	32%	2.67	1.220	1.49	-29%

Ammonia and Hydrazine

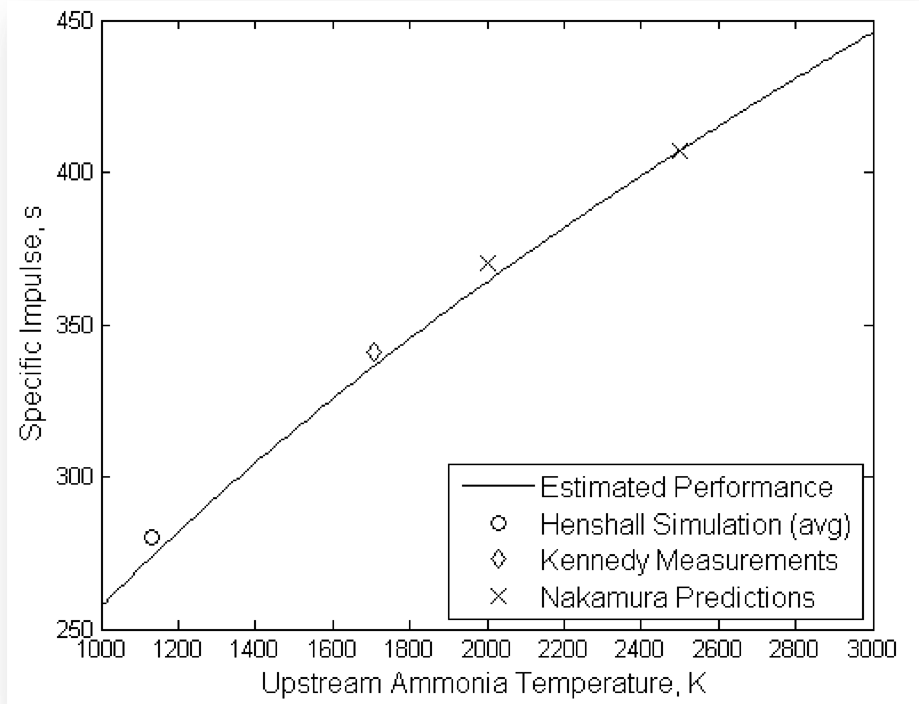
$3N_2H_4 \rightarrow 4NH_3 + N_2 - 336\ \text{kJ}$

$4NH_3 \rightarrow 2N_2 + 6H_2 + 184\ \text{kJ}$

Net 1.6 MJ/kg

α_D	Isp
0	253
0.2	274
0.4	289
0.8	312
1	322

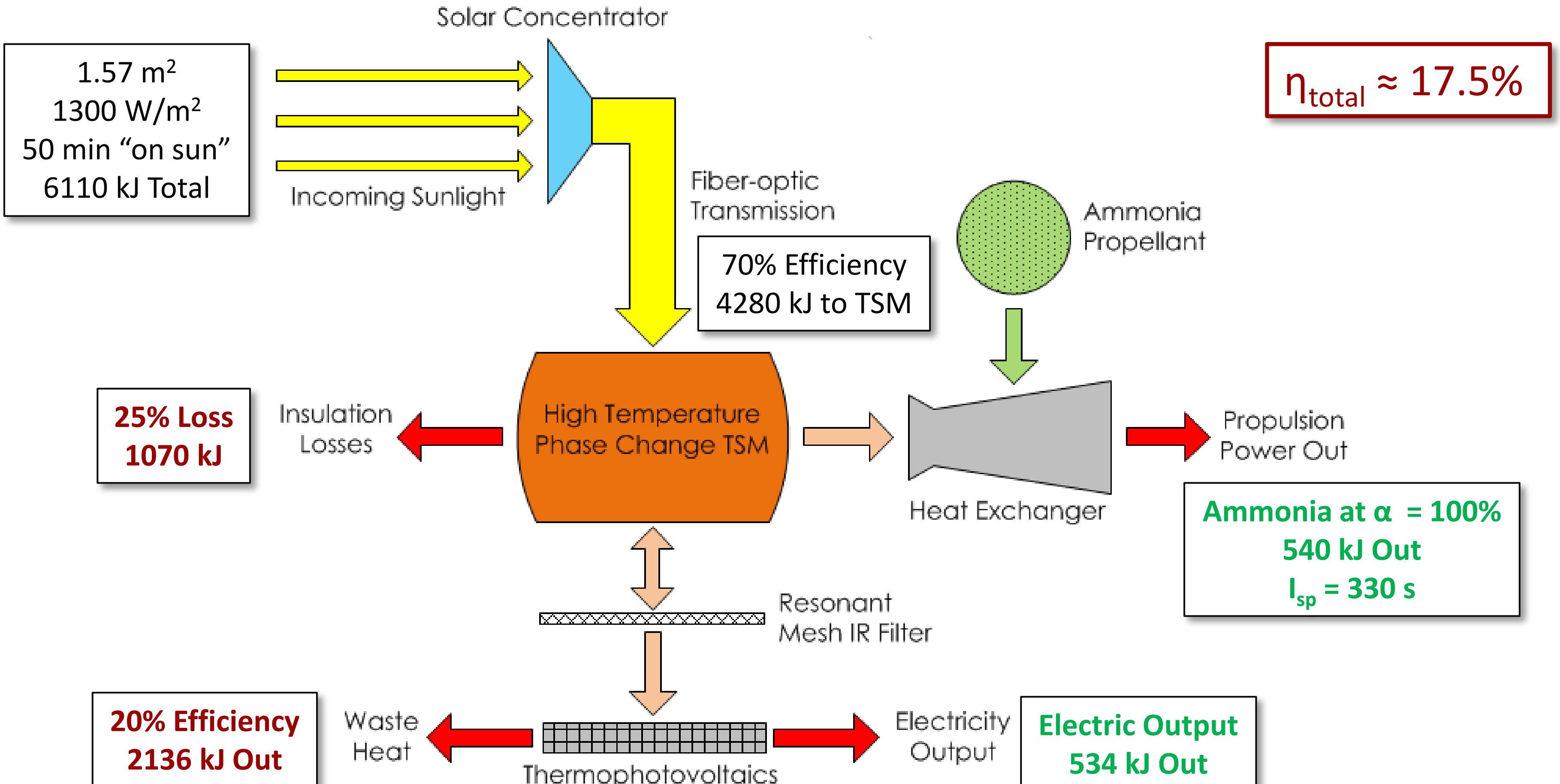
- Incomplete dissociation will lower performance
- Equilibrium calculations for 1500 K solar thermal thruster (*Colonna et. al. 2005*)
- Note, hydrazine thrusters typically have $\alpha_D \approx 55\%$



$$V_e = I_{sp} g_o = \sqrt{\frac{T_o R}{M} \frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_o}\right)^{(\gamma-1)/\gamma}\right]}$$

Energy Values

For each 200 km Orbit



Tech Comparison Metrics

- Satellite is sized for a 200 km circular orbit
  - Storage sized for approx. 36 min eclipse
- Assumes 20% total electrical system efficiency
- Assumes 70% thermal collection efficiency
- Approximates impulsive burn profile with a 5% firing rule