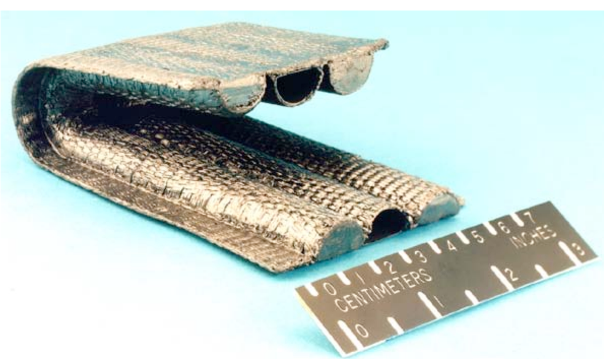
Heat-Pipe-Cooled Leading Edges for Hypersonic Vehicles

Workshop on Materials and Structures for Hypersonic Flight
University of California Santa Barbara
July 12-13, 2006



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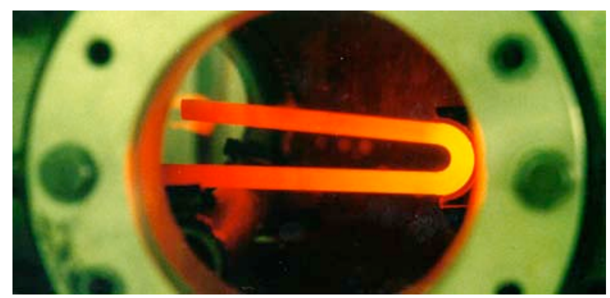
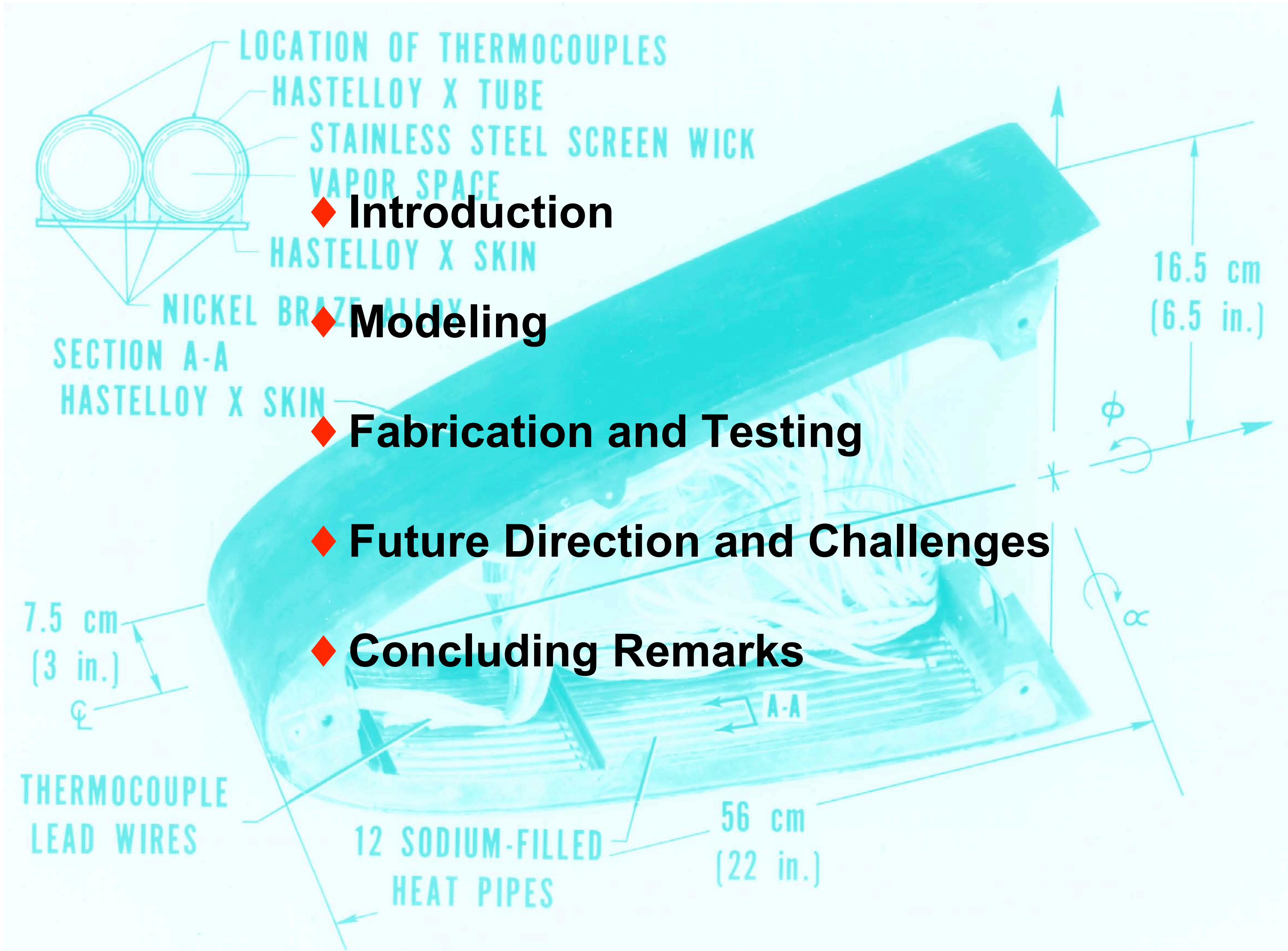


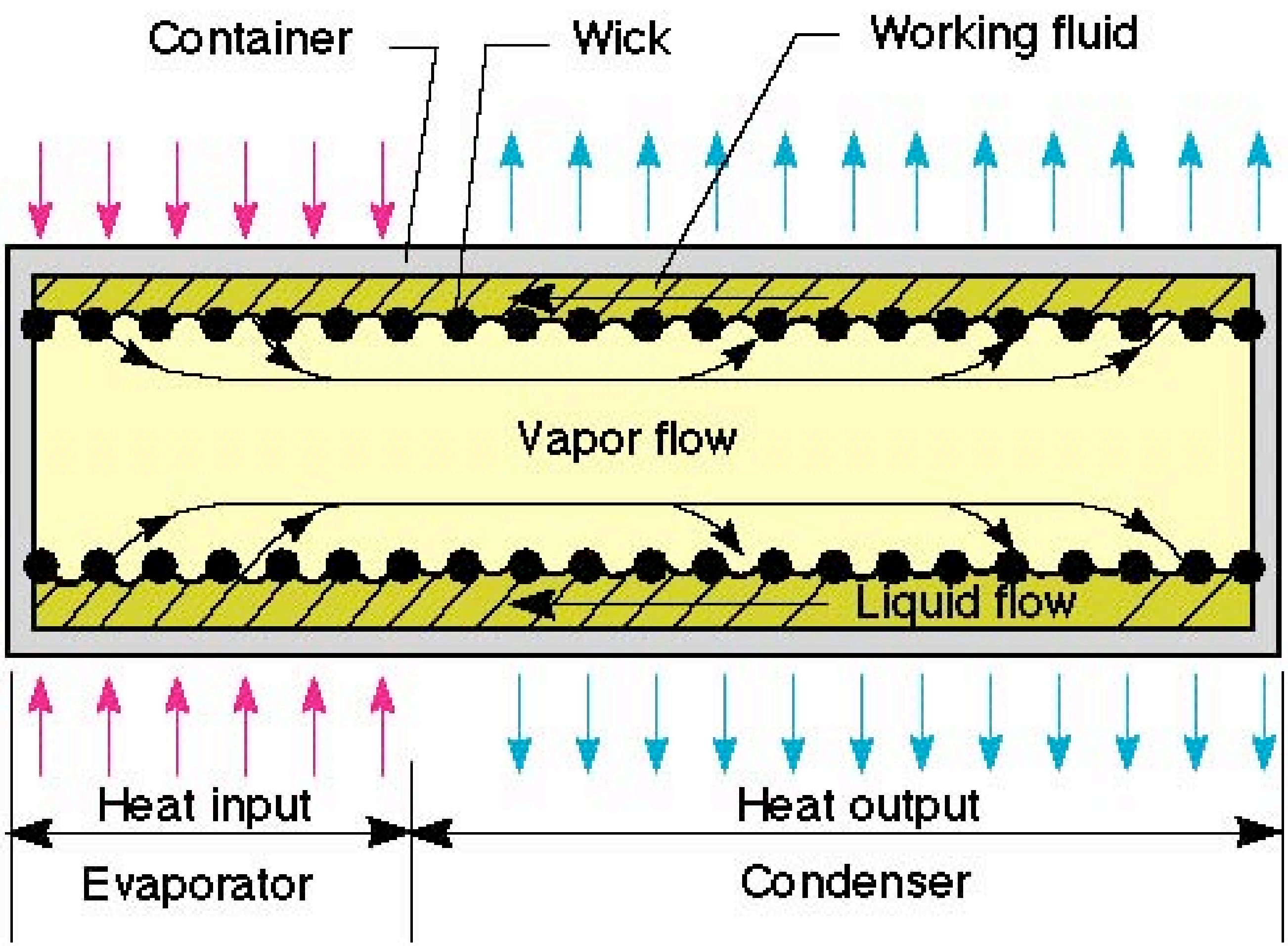
Agenda



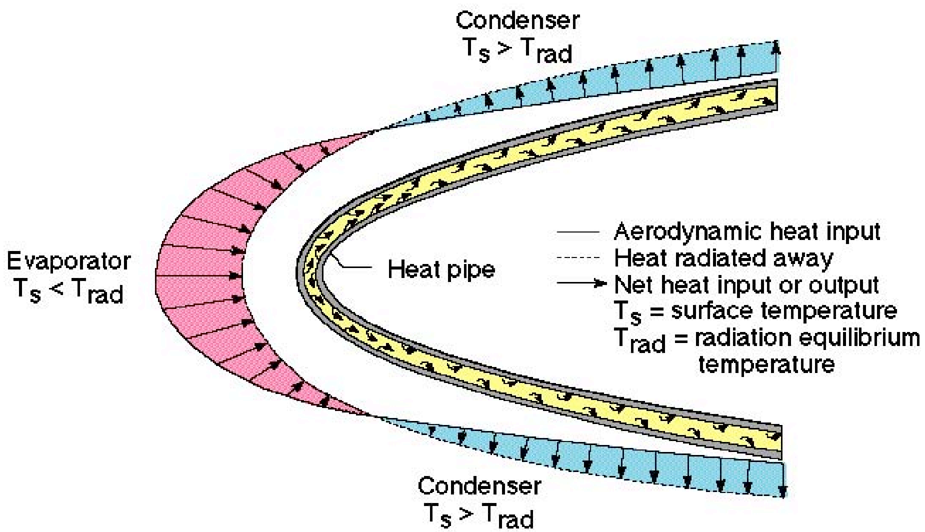
- Introduction
- Modeling
- Fabrication and Testing
- Future Direction and Challenges
- Concluding Remarks

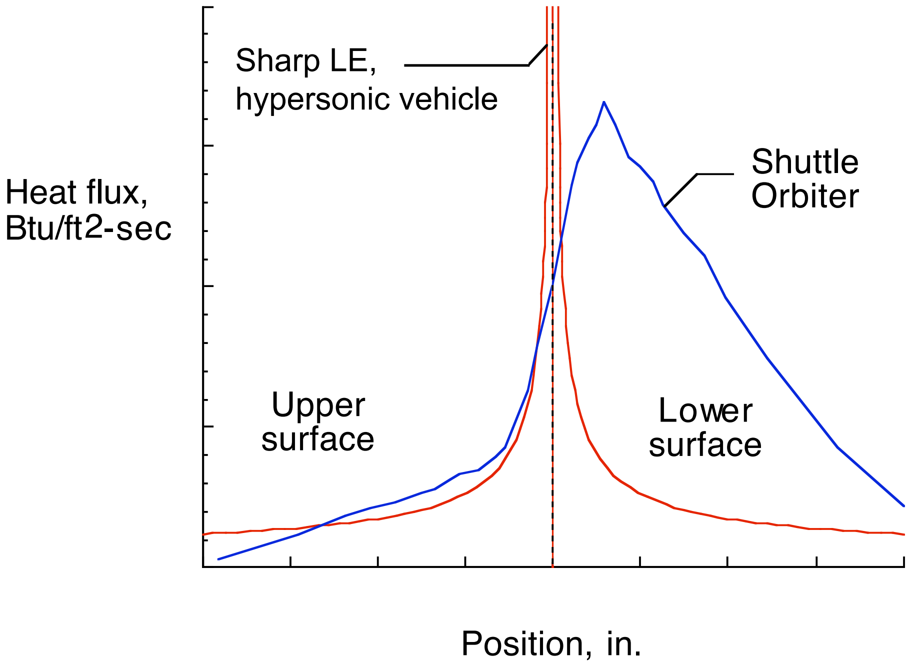
Heat-Pipe Operation

- Heat pipes transfer heat isothermally by the evaporation and condensation of a working fluid.



Leading-Edge Heat-Pipe Operation





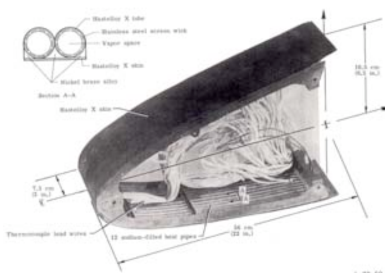
Heat Pipe Cooled Leading Edge History

Cal Silverstein-1971
R=0.5”
Mach 8 Cruise Aircraft

Merrigan/Seng
1989
Bench -scale
Nose cap

1970 | 1980 | 1990

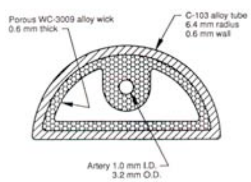
NASP



C. Camarda
1978
½ scale Space Shuttle Design, Fab/Test
Hastelloy x/Na

Boman & Elias
1990
Hastelloy-X/Na Heat pipe

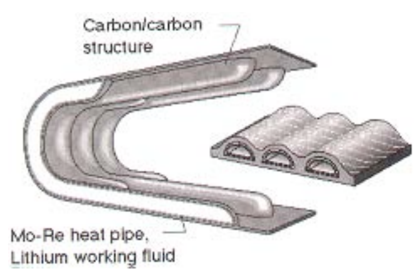
C. Wojcik
1991
Nb-Zr/Li



C. Silverstein
2001
- Hypersonic
- Engine Cowl
- Mach 6 test

LMSSC_ AFRL/VA
2005
Superalloy/Li;
Superalloy/Na; Mo-Re/Li

1991 | 1998 | 2005/6



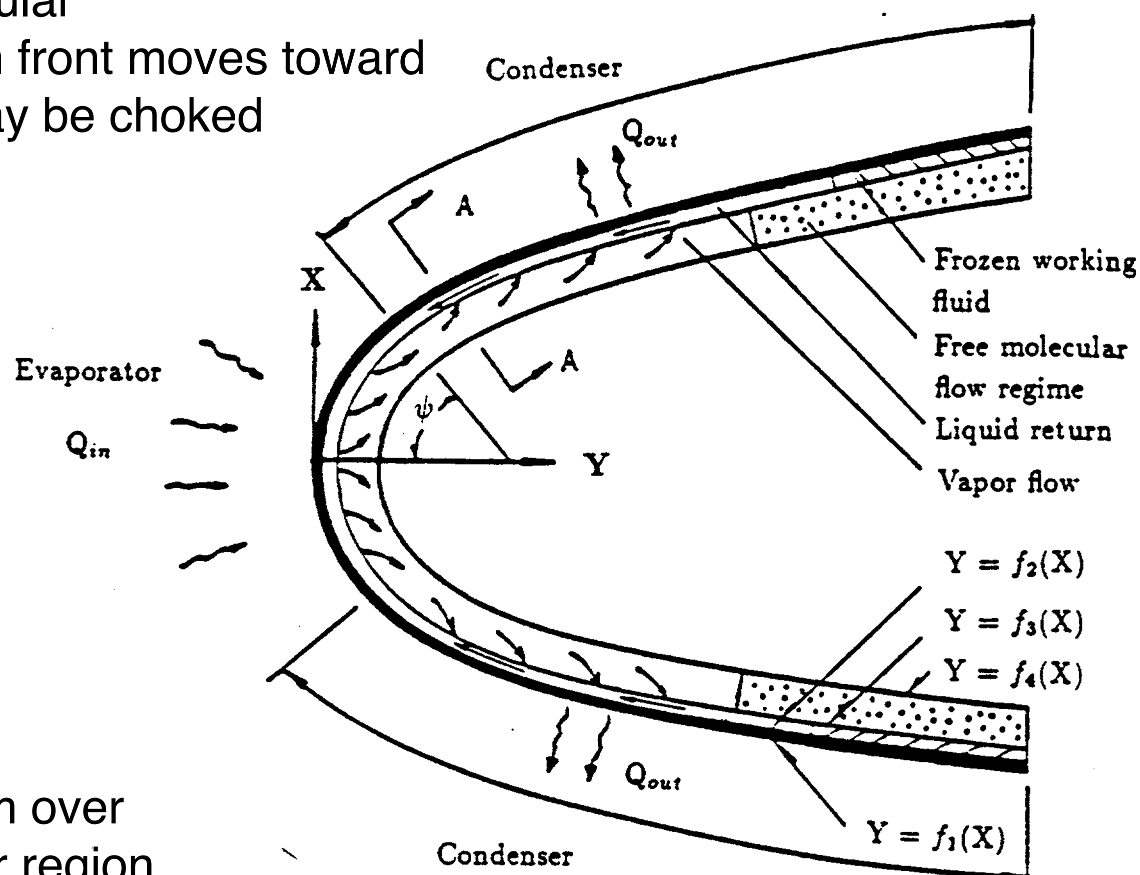
D. Glass et. al.
1999
- (Mo/Re)/Li Heat Pipe
  Embedded in C-C
- Fab & Test

Agenda

- Introduction
- **Modeling**
- Fabrication and Testing
- Future Direction and Challenges
- Concluding Remarks

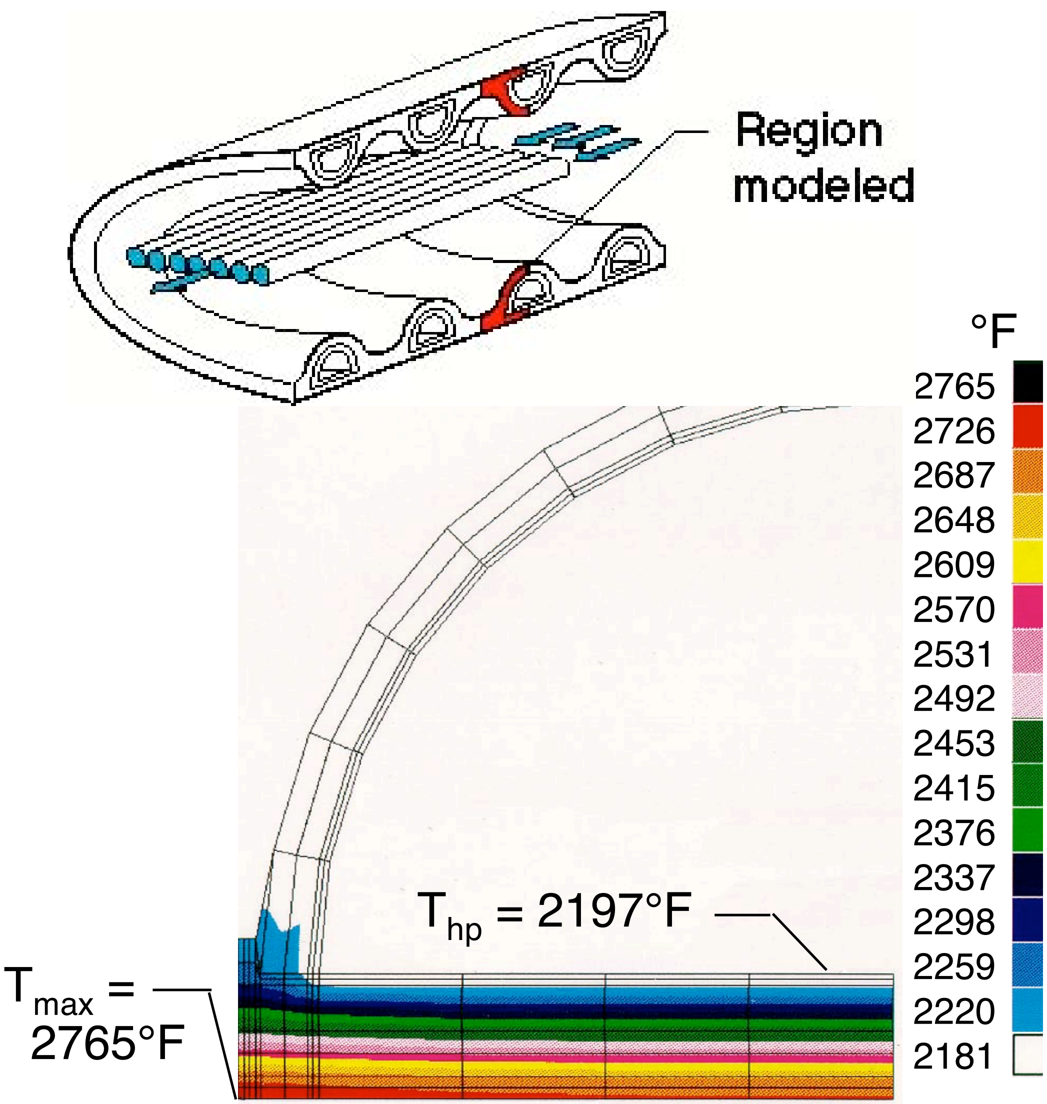
Heat-Pipe Modeling

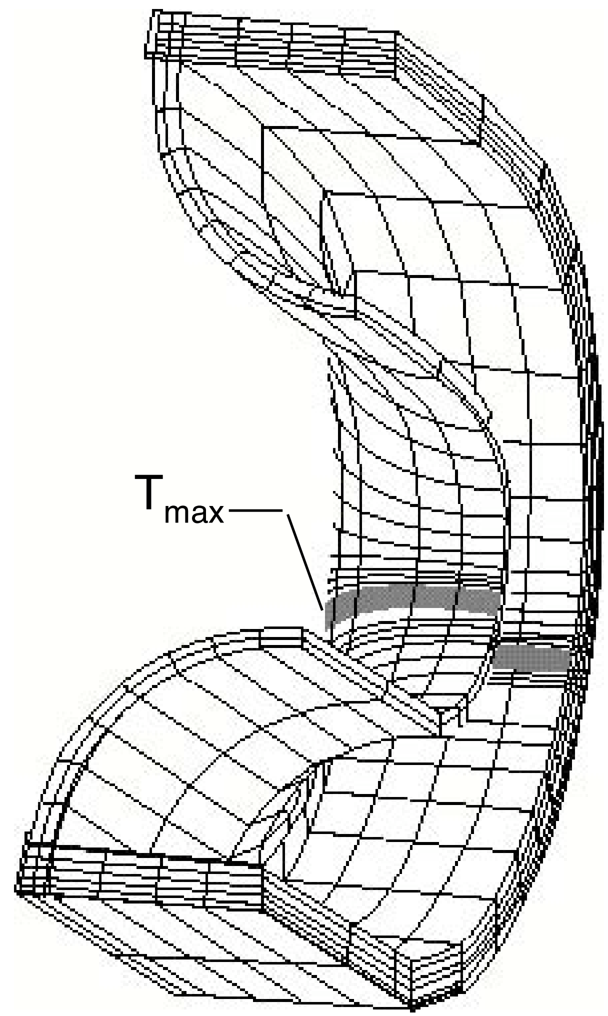
- Conduction, convection, or radiation coupling to environment
- Container - conduction only
- Wick/working fluid - conduction and heat of fusion
- Vapor
  - Phase I - free molecular
  - Phase II - continuum front moves toward cooler end. Flow may be choked at end of evaporator



  - Phase III - continuum over entire length in vapor region Sonic limit not encountered

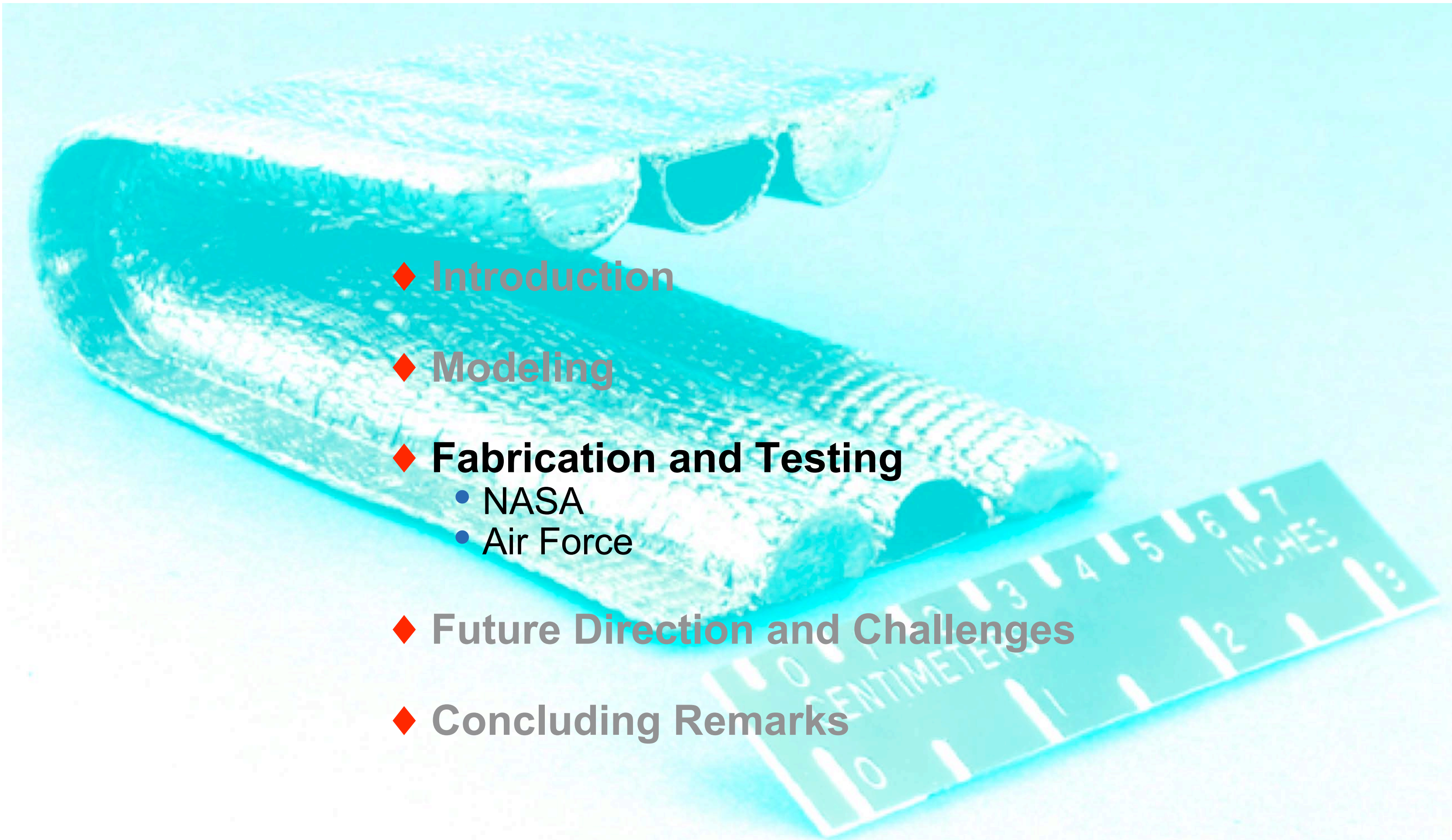
Heat-Pipe-Cooled Leading Edge Finite Element Analysis





3-D finite element model (non linear properties)

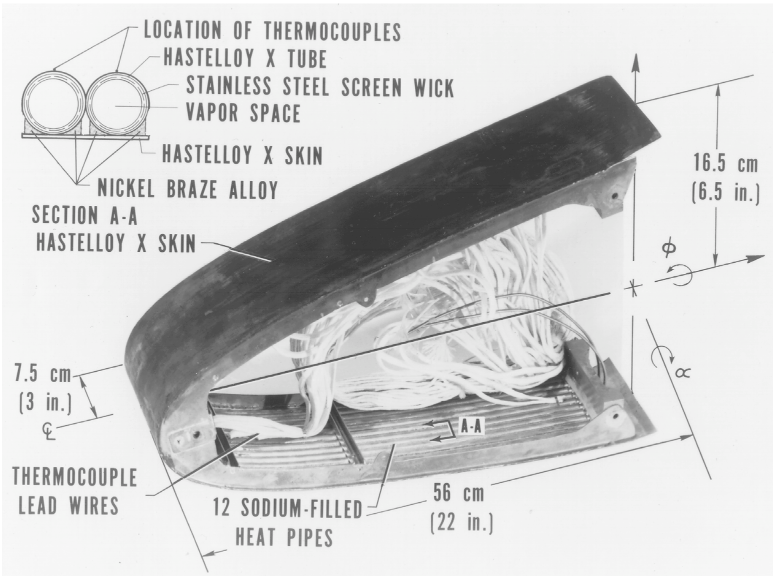
Agenda



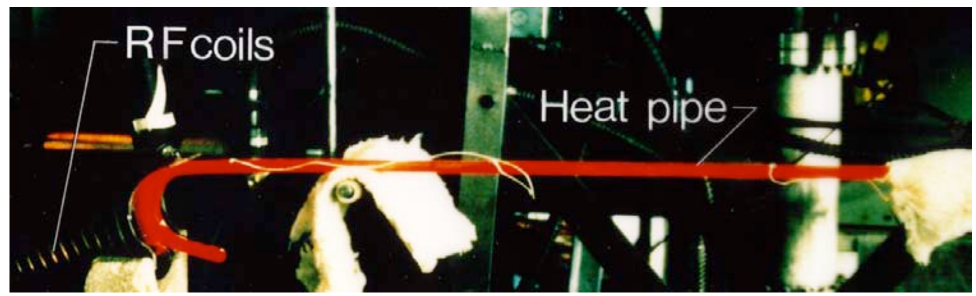
- Introduction
- Modeling
- **Fabrication and Testing**
  - NASA
  - Air Force
- Future Direction and Challenges
- Concluding Remarks

NASA Langley Heat-Pipe Leading-Edge Experience

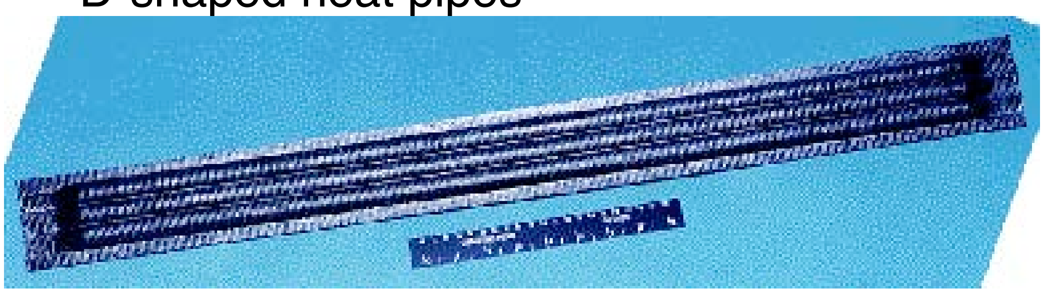
- Experience in design, analysis, integration, and testing



- Shuttle
  - Hastelloy-X
  - Na working fluid
  - Circular heat pipes

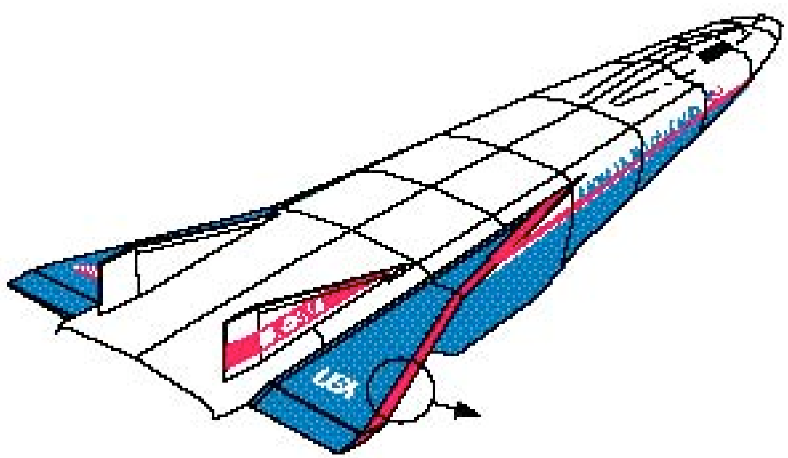


- NASP
  - Mo-Re embedded in C/C
  - Li working fluid
  - D-shaped heat pipes

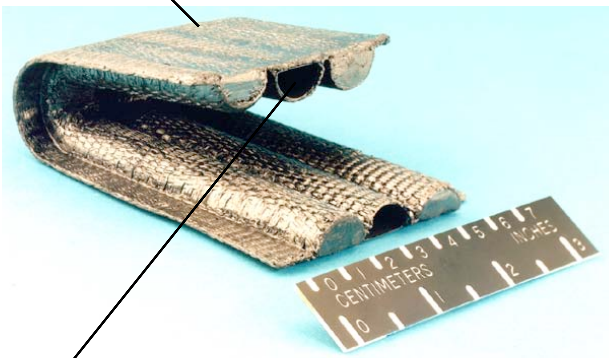


- Advanced STS
  - Hastelloy-X
  - Na working fluid
  - Rectangular heat pipes

NASP Carbon/Carbon Heat-Pipe-Cooled Wing Leading Edge

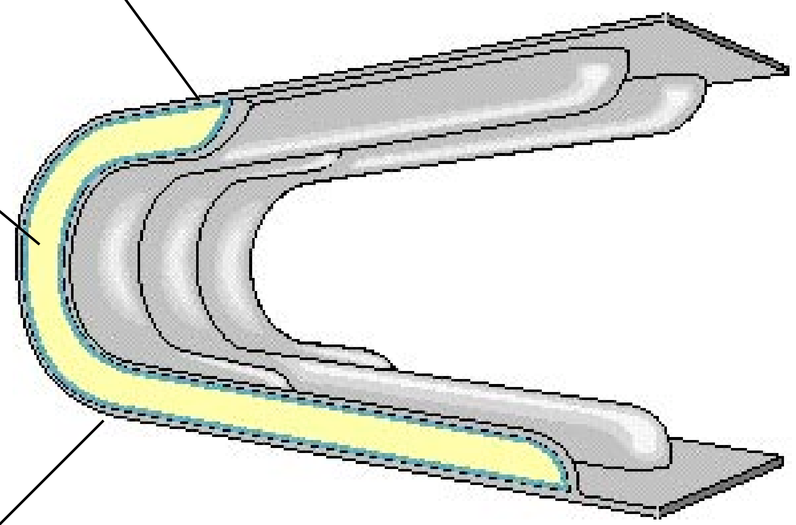


Heat pipes passively reduce leading-edge temperatures to reuse limits of composite



Description of Heat-Pipe-Cooled Wing Leading Edge

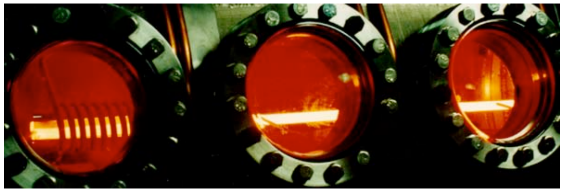
- Heat-pipe container
  - 0.010 in. arc cast Mo-41Re
    - High strength
    - High use temperature
    - Lighter than W-Re or pure Re
    - Ductile at room temperature
    - Weldable
- Heat-pipe working fluid
  - Lithium
    - 17 psia vapor pressure at 2500°F (1370°C)
    - Compatible with refractory metals
- Refractory composite structure
  - C/C or C/SiC (3-D woven fabric)
    - High use temperature
    - Lightweight
    - 0.010 in. SiC oxidation protection coating
    - CVD coating for minimization of coating temperature



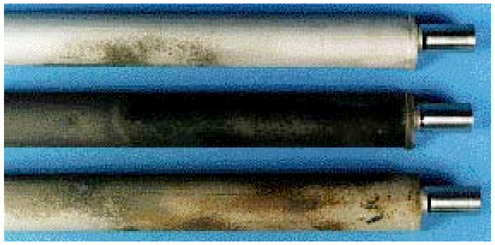
Heat-Pipe-Cooled Leading Edge Development

- Numerous small specimens to study various issues

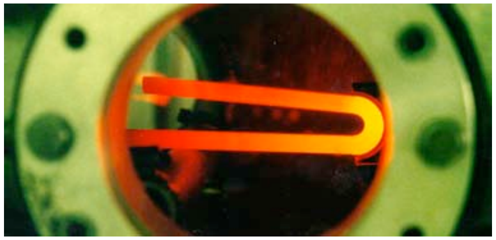
- Design validation heat pipe
  - 36-in-long straight heat pipe
  - Operated up to 2460°F (1350°C)
  - Throughput of 3.1 Btu/sec (3.3 kW)
  - Radial heat flux of 141 Btu/ft^2-sec (160 W/cm^2)
  - Developed leak due to difficulties with welded thermocouple



- Three straight heat pipes
  - 28-in-long
  - Operated up to 2300°F (1260°C) and 155 Btu/ft^2-sec
  - Embedded in carbon/carbon
  - Testing to be performed at NASA LaRC

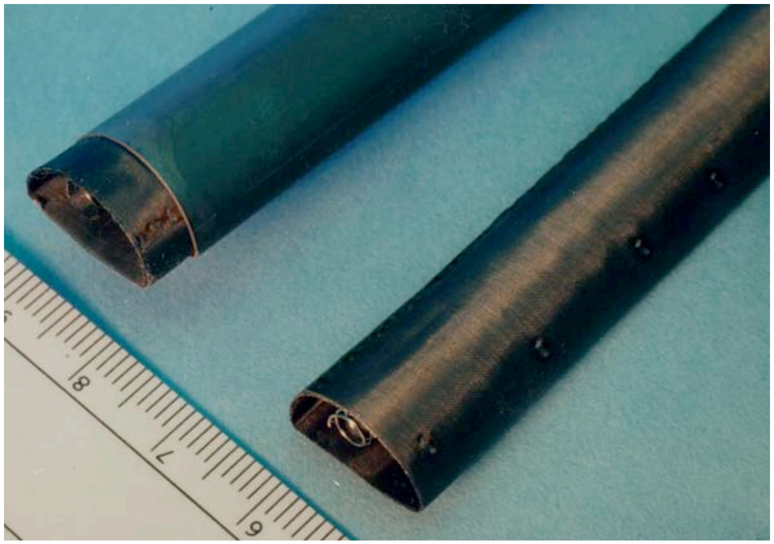


- J-tube heat pipe
  - 30-in-long
  - Nose and wick fabrication issues resolved
  - Transient performance tests at LANL



Heat-Pipe Fabrication and Testing

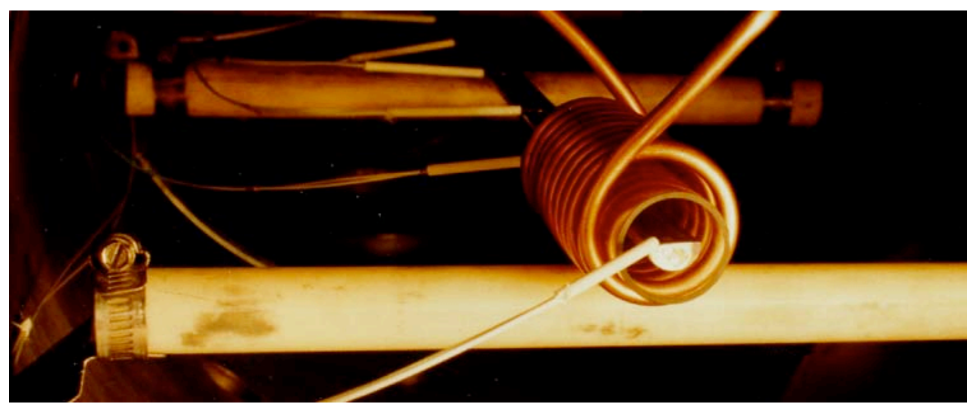
Design Validation Heat Pipe



- Container: 0.01-in. arc cast Mo-41Re, 0.3-in. radius
- Wick: 4 layers of 400 x 400 Mo-5Re screen

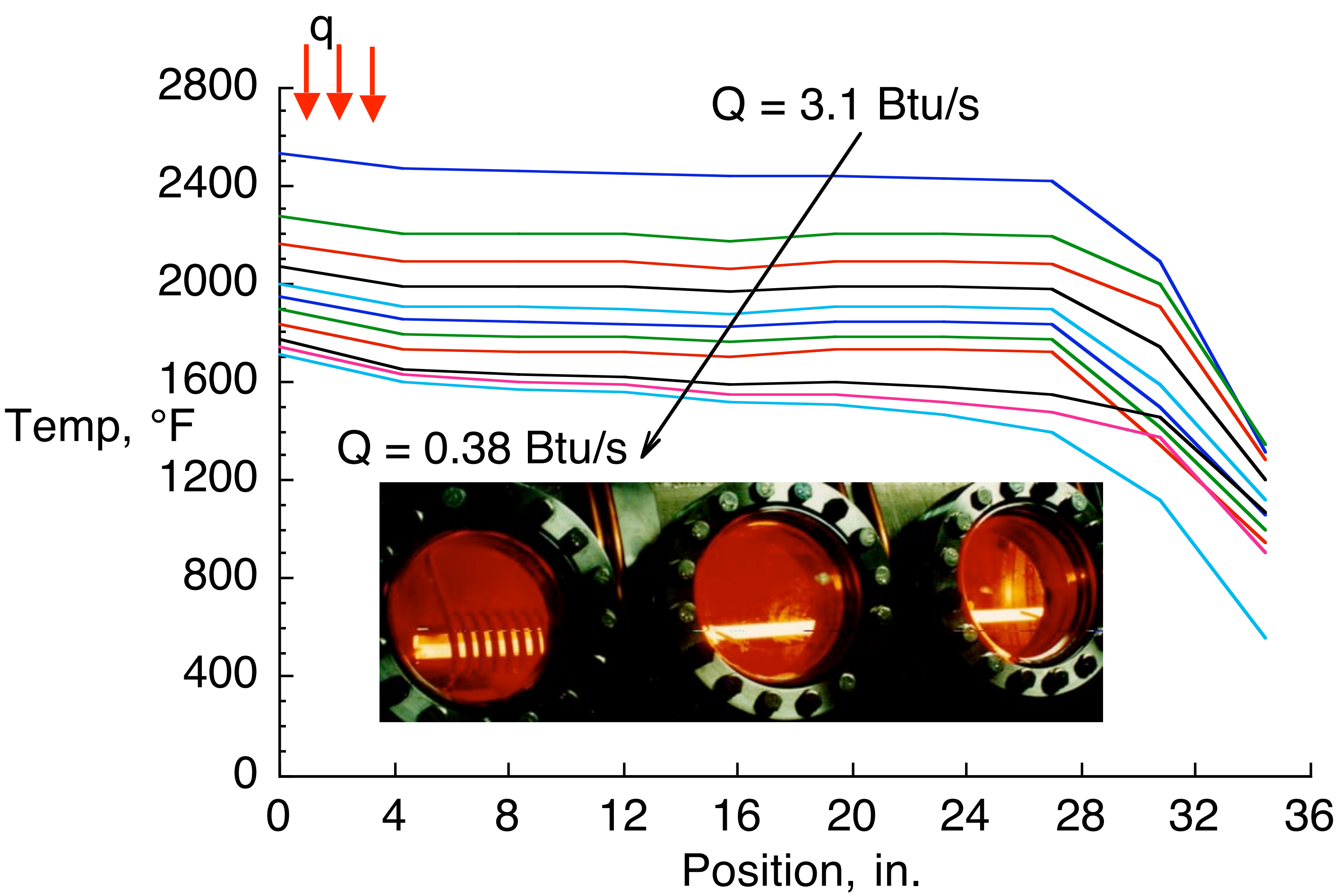
- Artery to reduce liquid pressure drop
  - 0.1-in. diameter, 400 x 400 mesh screen
  - Located on non-heated surface
  - Spring in artery for support
  - One end closed, pool at other end

- Heat pipe with thermocouples and induction heat coils



Steady State Heat-Pipe Operation

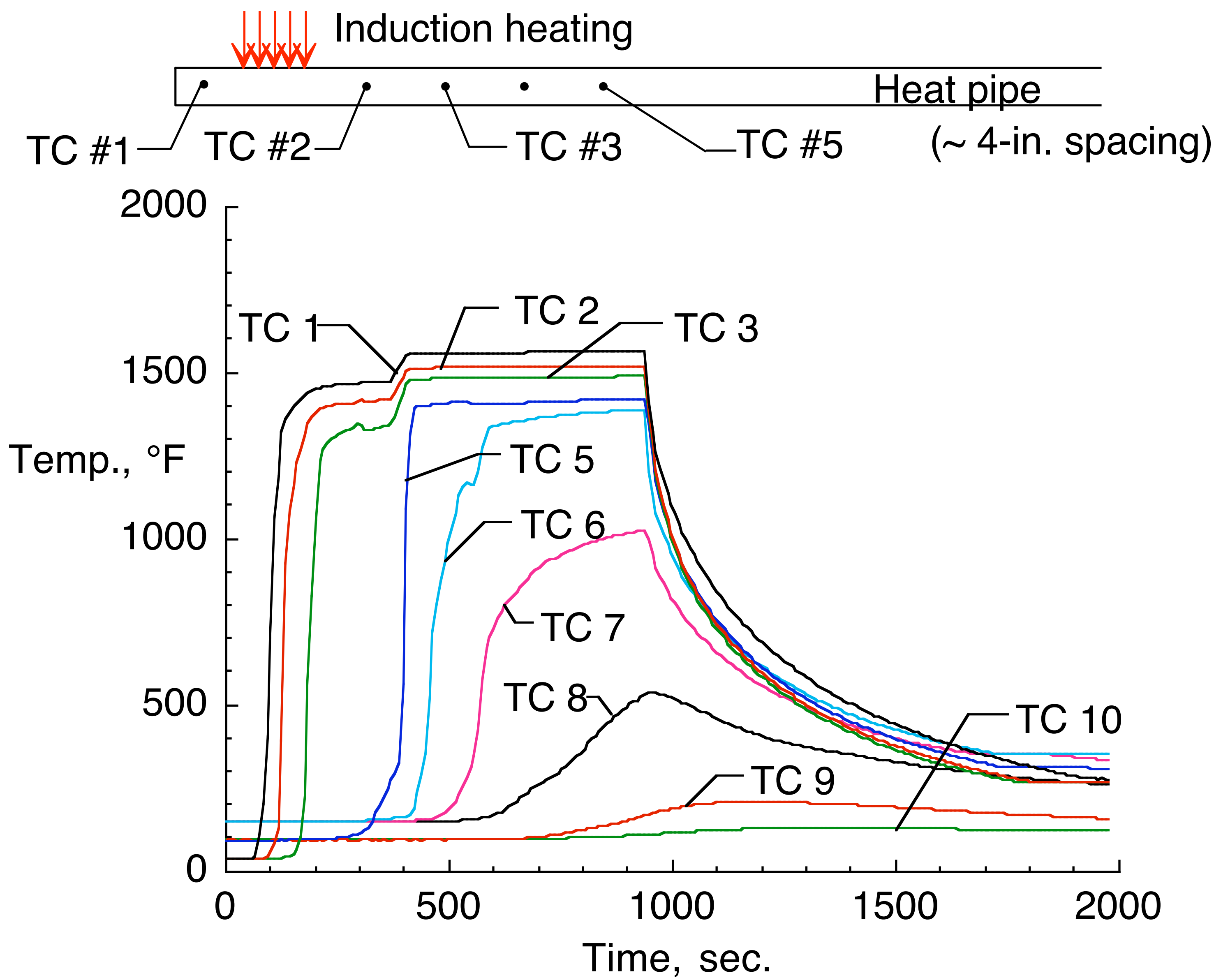
Design Validation Heat Pipe



Note: Thermocouples ~ 4 in. apart.

Heat-Pipe Start-Up From the Frozen State

Design Validation Heat Pipe



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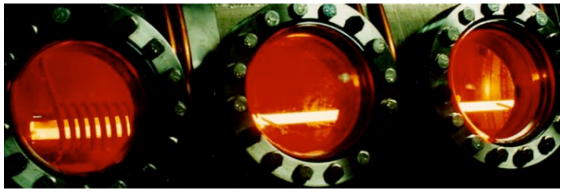

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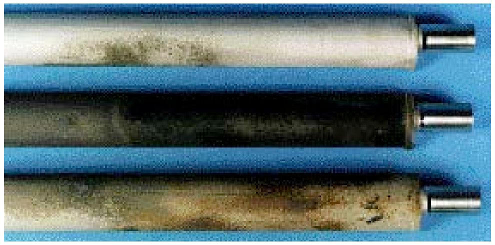

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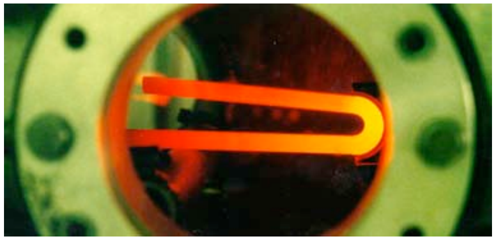
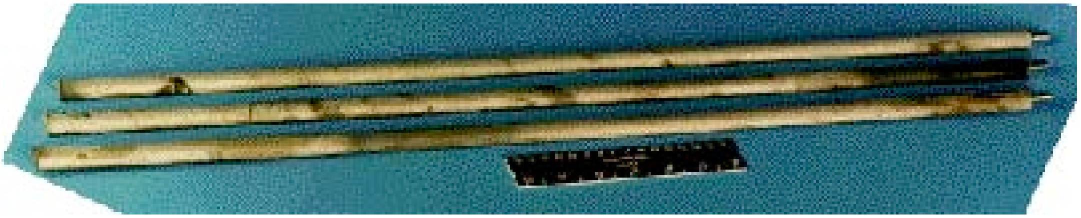


Comparison of the Three Heat Pipes

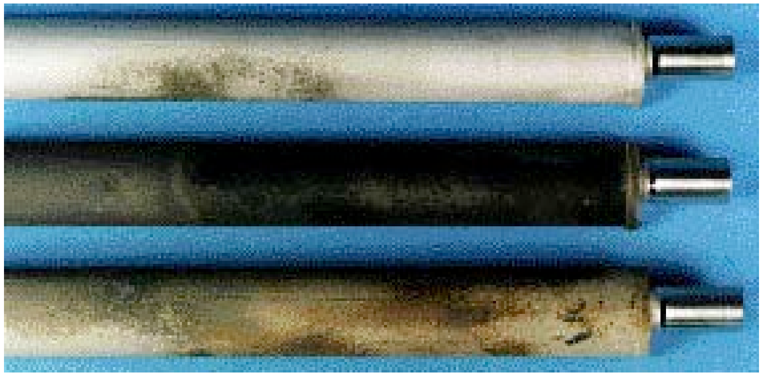
Three Straight Heat Pipes

	Lithium, lb	Wet in
Heat pipe #1	0.0099	42 hrs @ 1650-1740°F
Heat pipe #2	0.0088	70 hrs @ 1650°F
Heat pipe #3	0.018	47 hrs @ 1650°F



28-in long

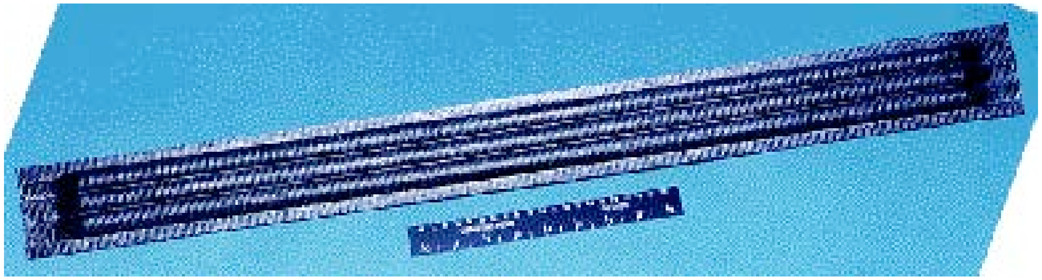
- Heat pipe #1
  - 2300°F, 155 Btu/ft^2-s over 1.5 in.
  - Nearly fully isothermal

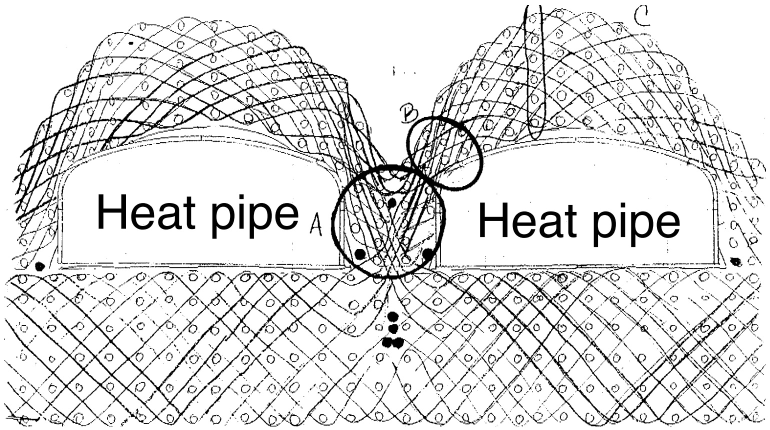


- Heat pipe #2
  - 2420°F
  - @ 2075°F, non-condensible gas over last 6 in. of heat pipe
- Heat pipe #3
  - Never operated properly

Heat Pipes Embedded In Carbon/Carbon

Three Heat Pipes in C/C



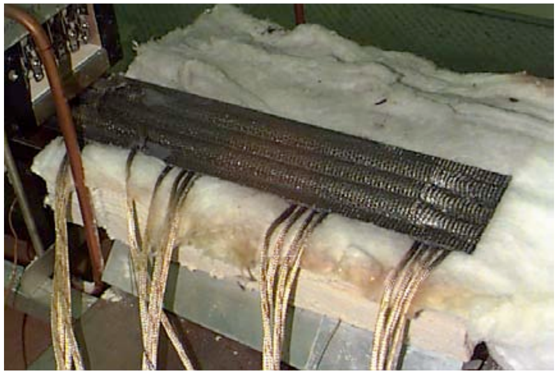


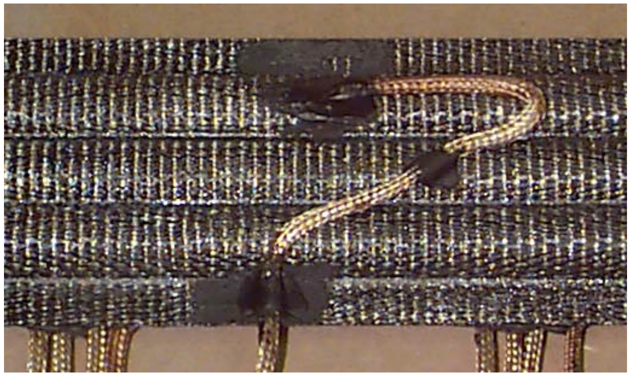
Hot spot

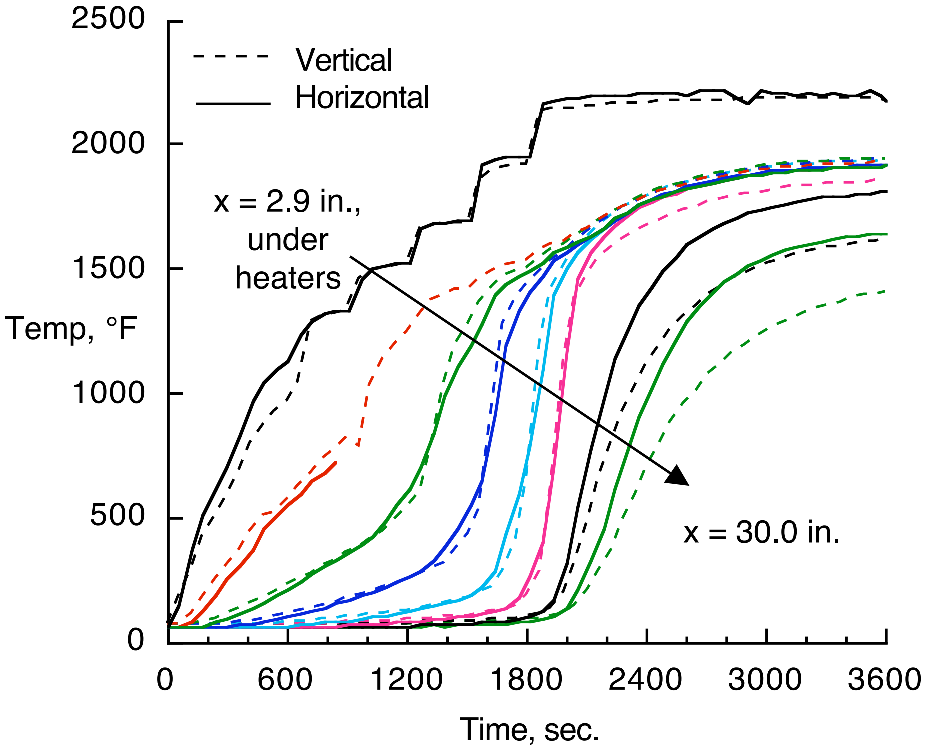
- Three Mo-Re heat pipes
- 3-D woven preform with T-300 fibers in a carbon matrix
  - increase through-the-thickness thermal conductivity
  - eliminate delaminations with 2-D C/C due to CTE mismatch
- No oxidation protection coating on C/C, therefore must test in an inert environment

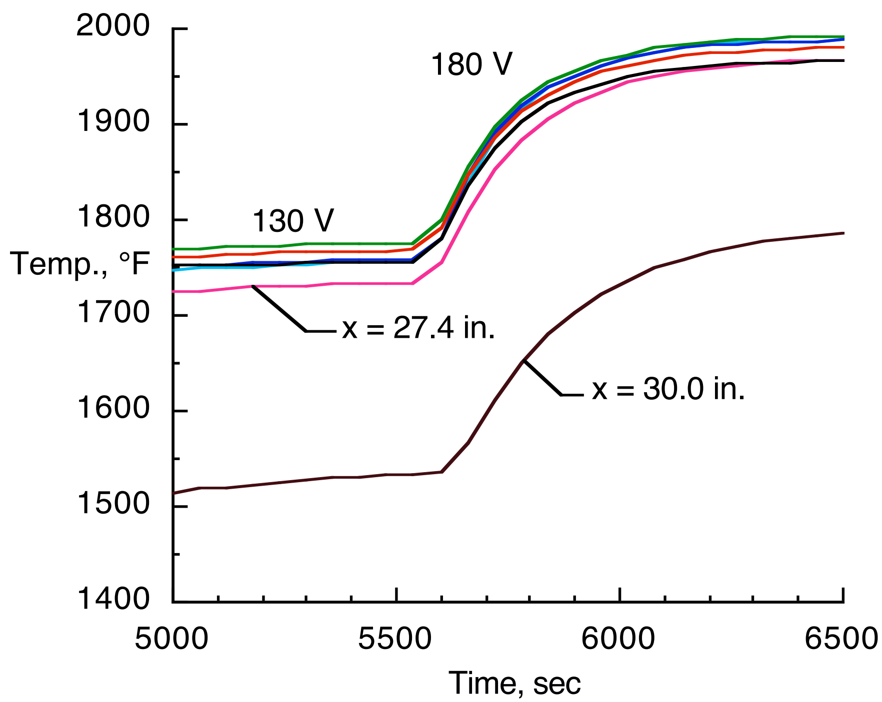
C/C Heat Pipe Transient Testing

Three Heat Pipes in C/C



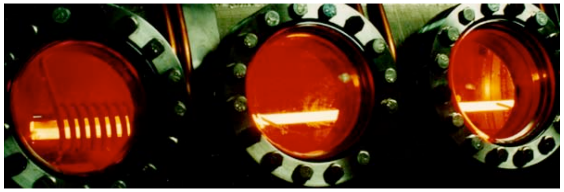






Heat-Pipe-Cooled Leading Edge Development

- Numerous small specimens to study various issues



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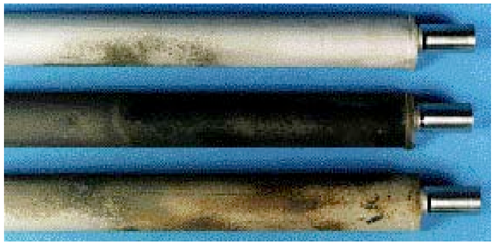

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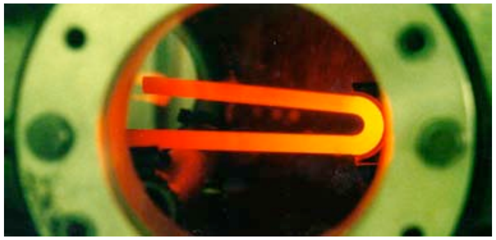

- J-tube heat pipe
  - 30-in-long
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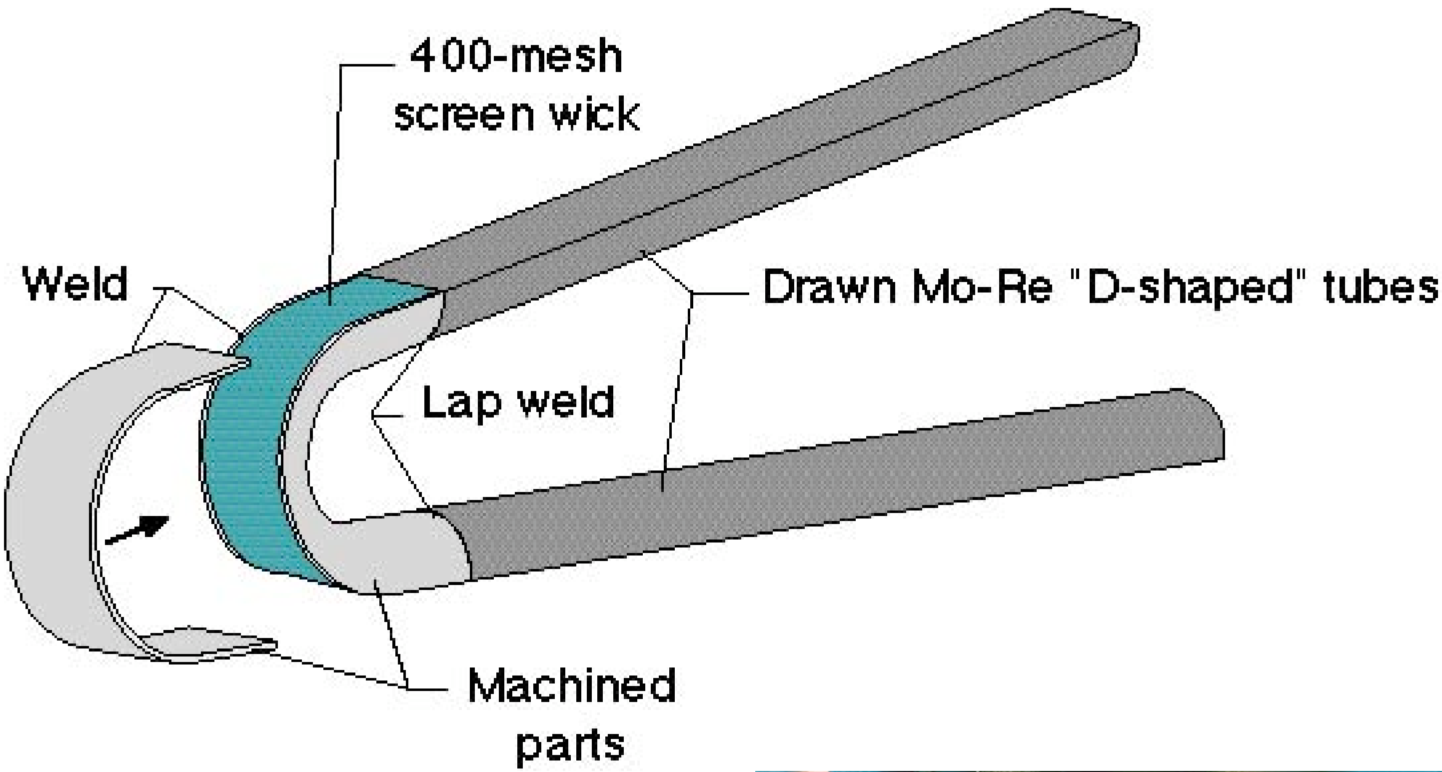
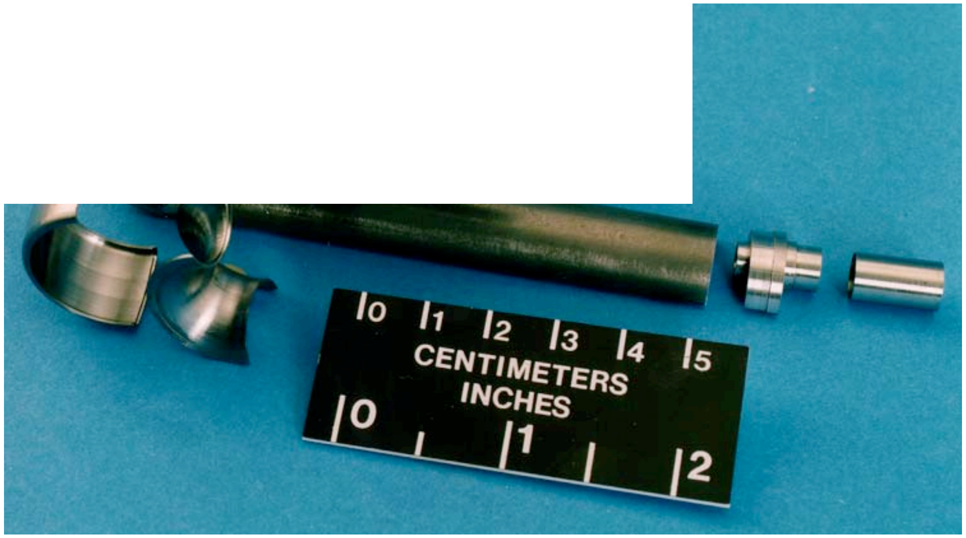
Machine and Weld Nose Region

J-Tube Heat Pipe



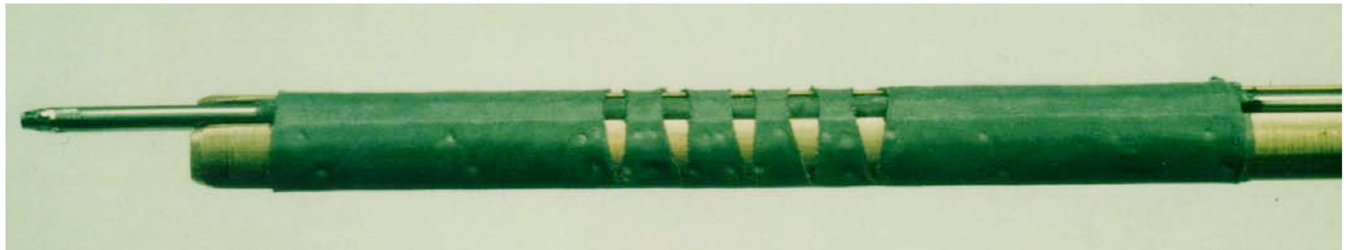
Photograph of nose parts

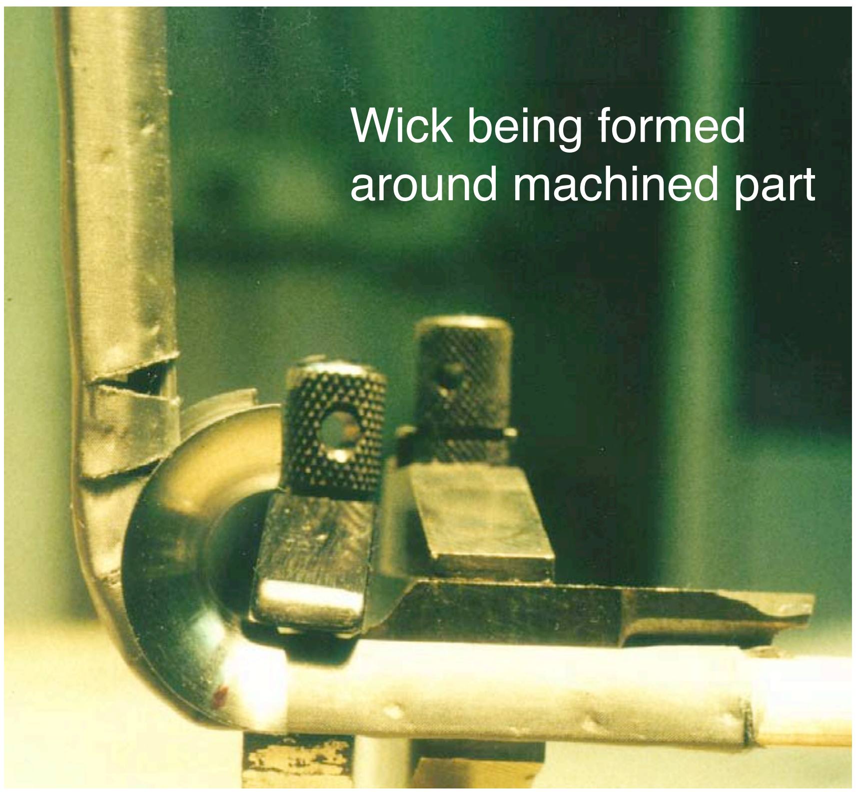


Curved Wick Fabrication

J-Tube Heat Pipe

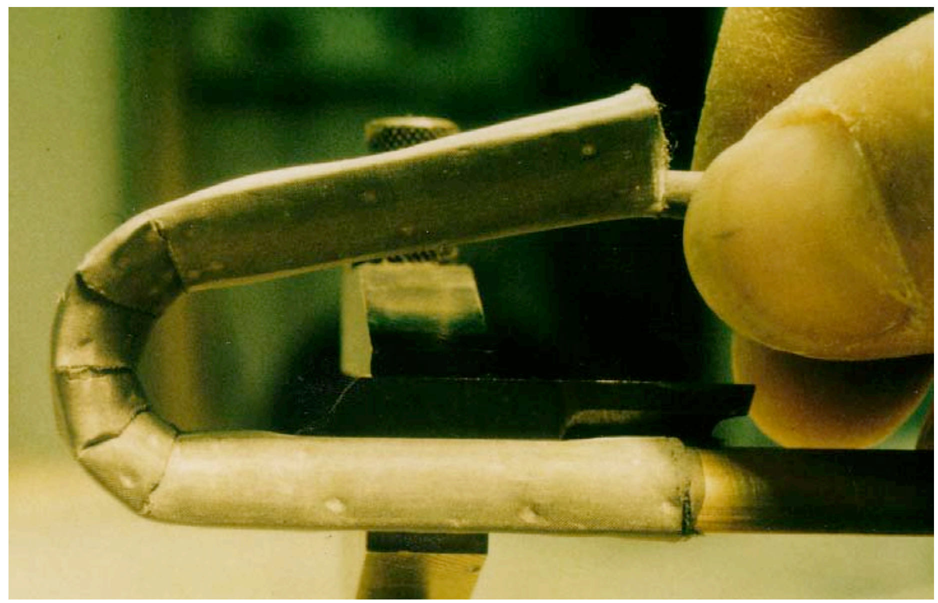
Wick formed on mandrel





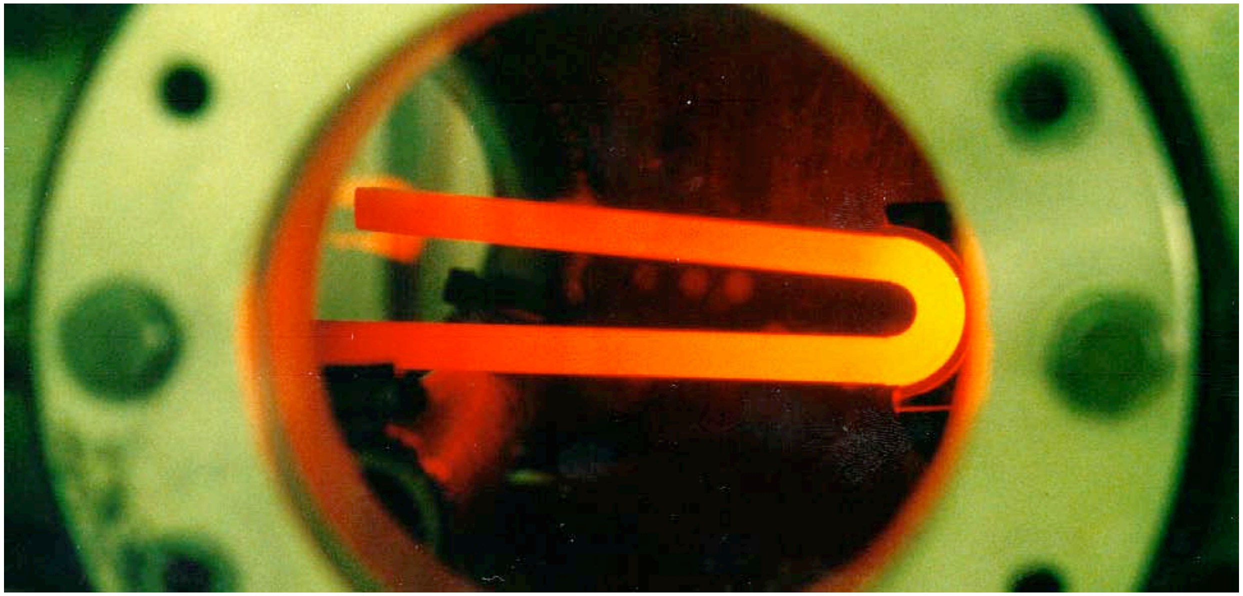
Wick being formed around machined part

Nose portion of wick



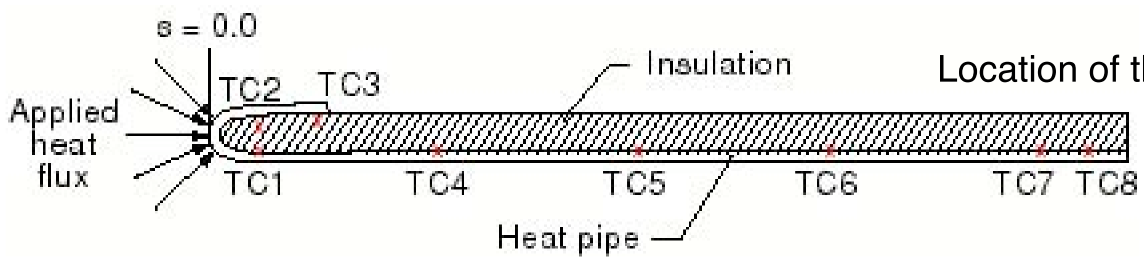
RF-Induction Heating of J-Tube Heat Pipe

J-Tube Heat Pipe

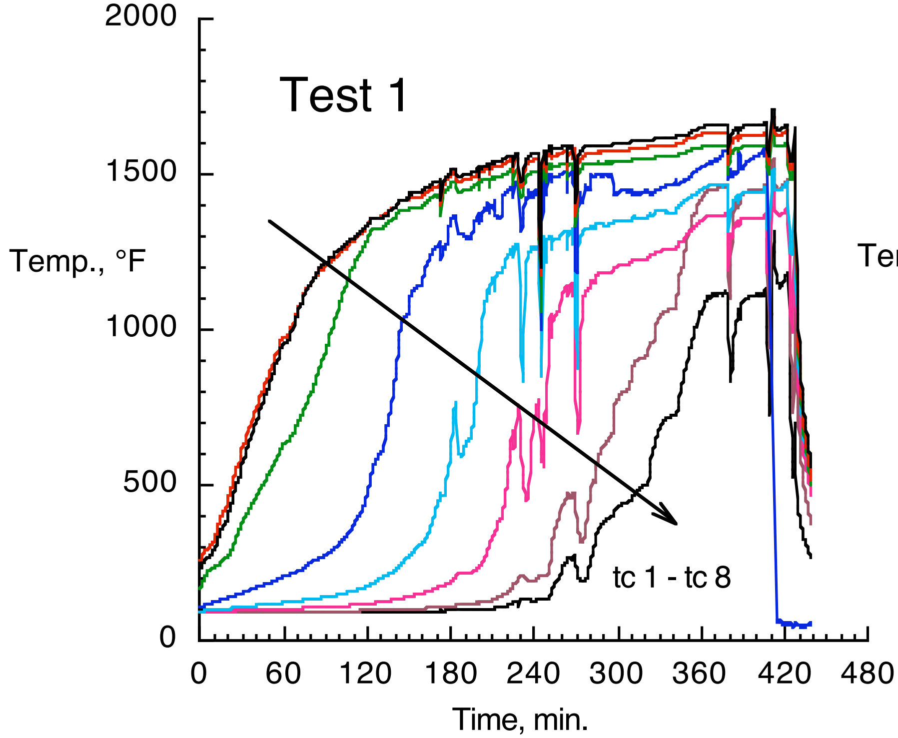


- RF-induction coil/concentrator heating of nose region on outer surface
- Test specific issue: Hot spot in nose region
  - Test
    - Curved surface not insulated, thus higher throughtput required
  - Flight vehicle
    - Curved surface is “insulated”

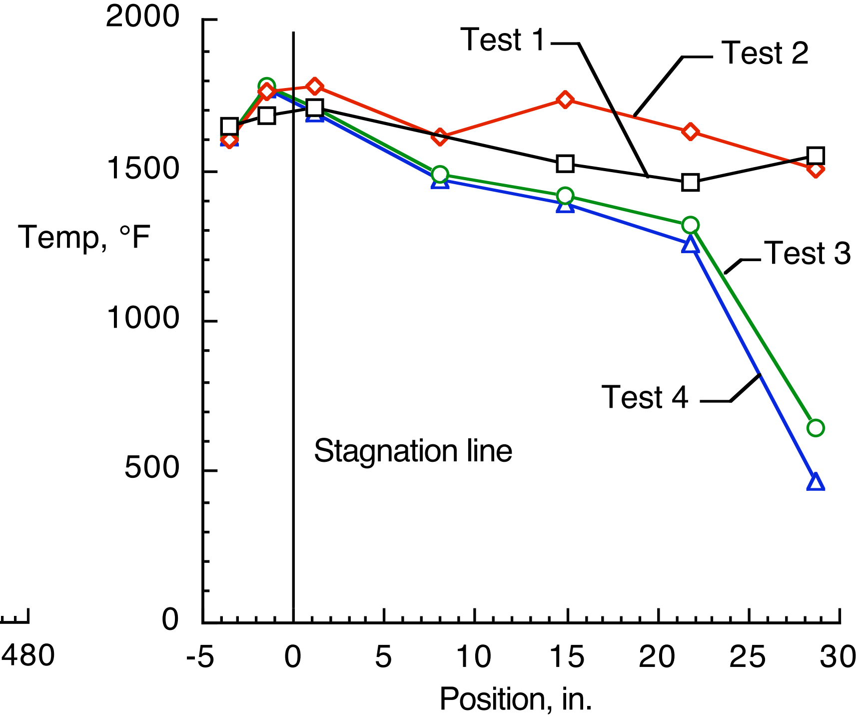
J-Tube Heat-Pipe Checkout Tests



Location of thermocouples

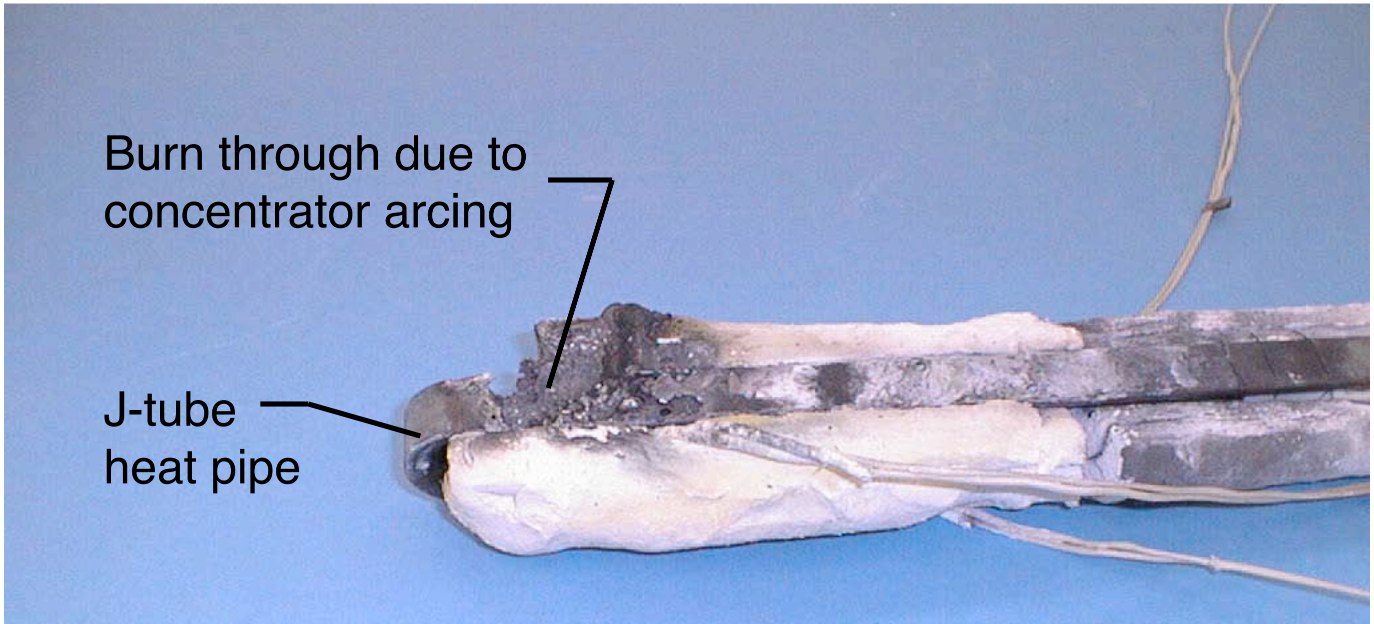


Start up of J-tube heat pipe



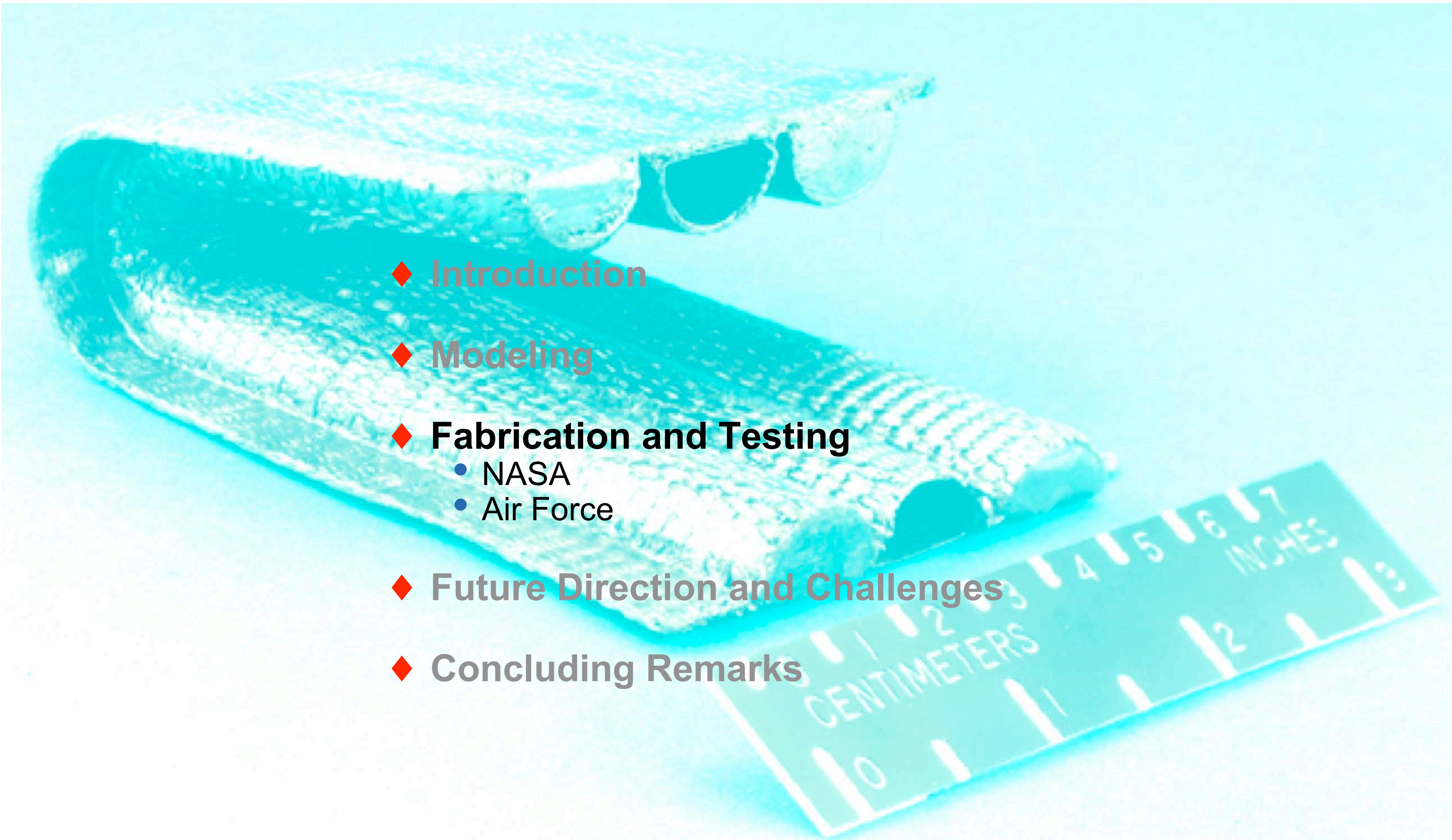
Maximum temperature distribution
(not steady state)

Test Induced Failure of Heat Pipe



- Nominal operation during 4 tests
- Test induced failure (concentrator arcing) during test 4
  - Insulation outgassed during test (~0.1 Torr)
  - Ionization between heating coil and heat pipe

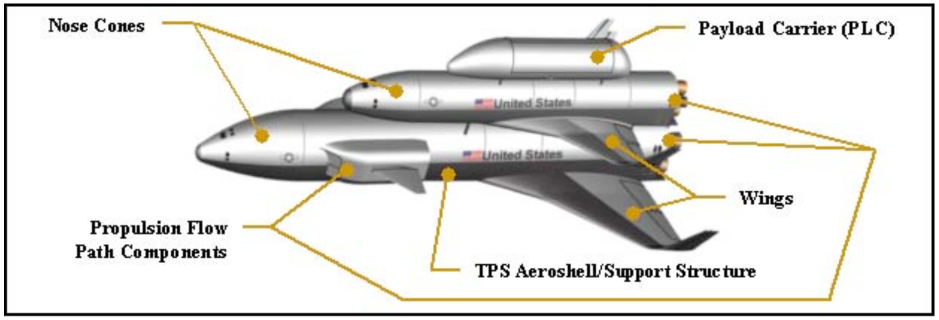
Agenda



- Introduction
- Modeling
- **Fabrication and Testing**
  - NASA
  - Air Force
- Future Direction and Challenges
- Concluding Remarks

Overview: Heat Pipe Cooling for SOV Leading Edges AFRL/Lockheed Martin

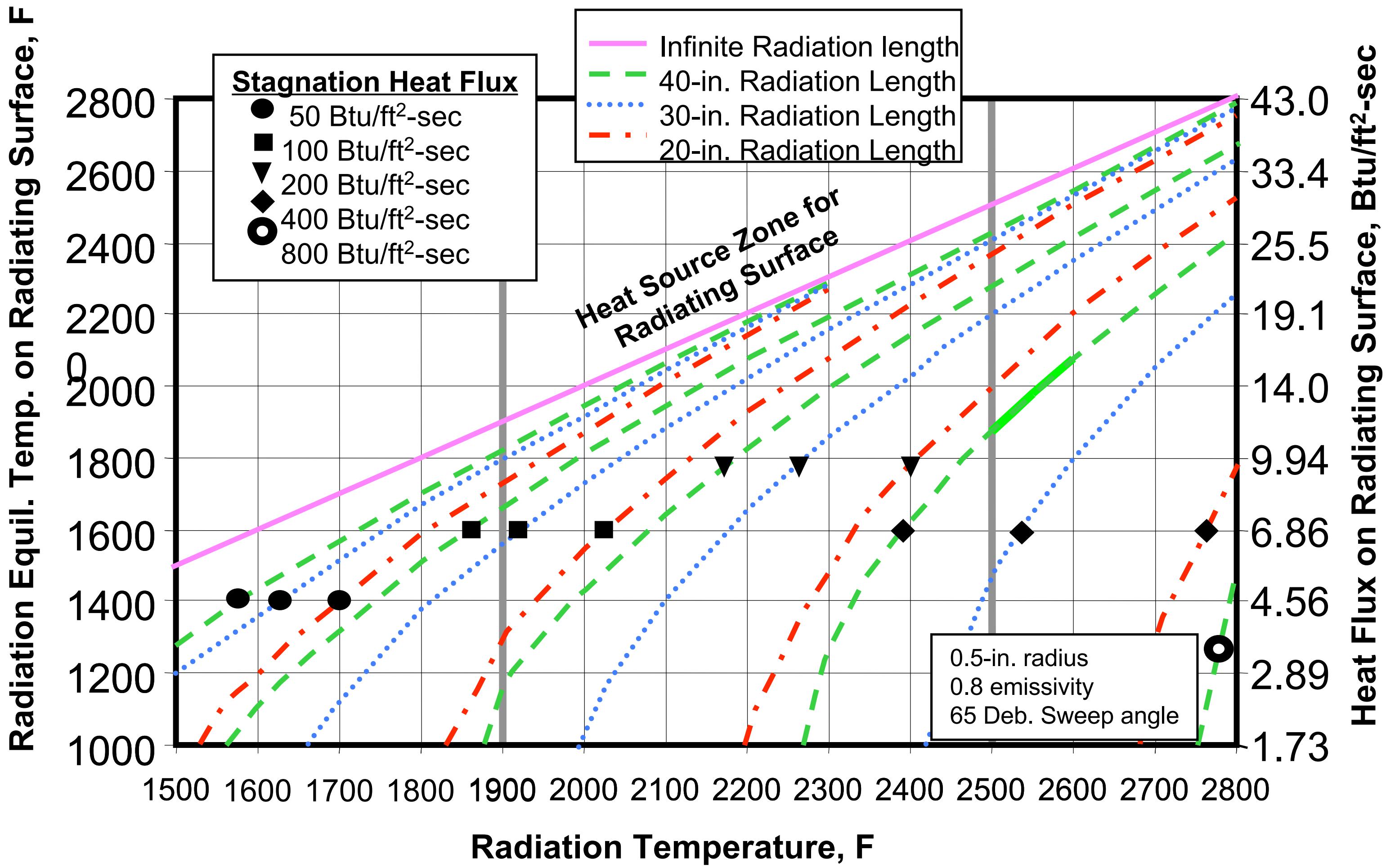
- **Identify Specific Operational Requirements, and SOV Configuration**
  - Generated Performance Maps (Assuming Typical Requirements, and Configuration)
- **Using LM-TSTO Orbiter Requirements, Developed Heat Pipe Cooled Leading Edge Designs for Moderate to High Heat Flux Cases**
  - Heat Pipe Design Option
    - Modular Mo-Re Alloy Heat Pipe
    - Developed Processing approaches for Mo-Re/Li Heat Pipe Design
  - Heat Pipe Design Option
    - Modular Superalloy/ Li Heat Pipe
    - Successfully Designed, Fabricated, and Tested
- **Developed Heat Pipe Design Solutions for Hypersonic Vehicles**
  - Sharp Hybrid Leading Edge Designs
  - Cowl Inlet Cooling (Fabricate and Test Superalloy/Na Heat Pipe)



* First Superalloy/Li Heat Pipe

Performance Map for Heat Pipe Leading Edge Cooling

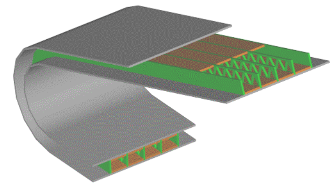
- **Generated Relationship Between the Cooling System Temperature and Radiation Length and Aerothermal Environment for Different Leading Edge Radii**



Technical Assessment of Key HPCLE Design Options

- **Key Design Options Very High Temp.**
  - Modular Mo Alloy/Li Heat Pipe
  - Modular (or D) Mo-Re/Li Heat Pipes Embedded in C-C or C/SiC
  - Modular (or D) Mo-Re/Li Heat Pipe Design

Modular Mo-Re/Li Heat Pipe



Embedded C-C (Mo-Re D shaped)/Li Heat Pipe

- **Key Design Options High Temp**
  - Superalloy/ Li Heat Pipe
- **Trade Study Criteria**
  - Materials Cost
  - Machining
  - Joining
  - Heat Pipe Durability
  - Thermal Performance
  - Structural Performance
  - System Weight
  - Life Cycle Cost
  - Manufacturing Yield
  - Start-up Risk
  - Atmospheric Protection Risk
  - Repair/Rework
- **Other System Level Concerns**
  - Impact From Atmospheric Debris
  - Oxidation Resistance
  - Thermal Contact Resistance
  - Robustness in Flight of Ground
  - Toxicity of Li, in Case of Leak
  - Manufacturing and Ease of Integration
  - Comparison with Passive and Actively Cooled Designs

Air Force Program Summary

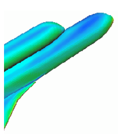
- **Developed Performance Maps Providing HPCLE Design Solutions**

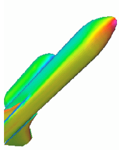
- **Based on Analysis for TSTO-Based SOV Configuration**
  - # 1 Modular Mo-47%/Li Heat Pipe
  - # 2 Modular Superalloy/Li Heat Pipe

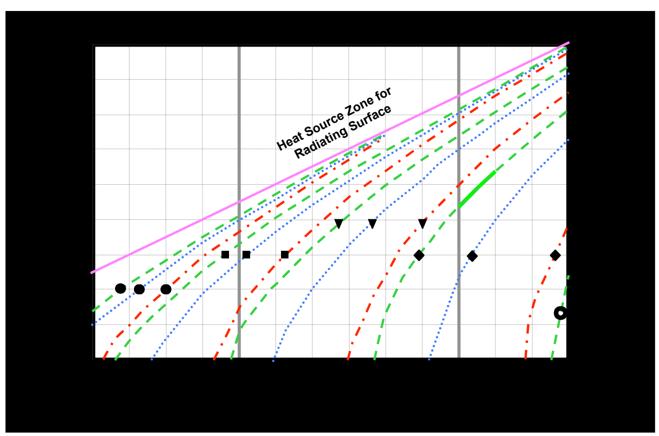
- **Performed Superalloy/Li Heat pipe Life Compatibility Tests**
  - Successfully Demonstrated ~401 Hours Life

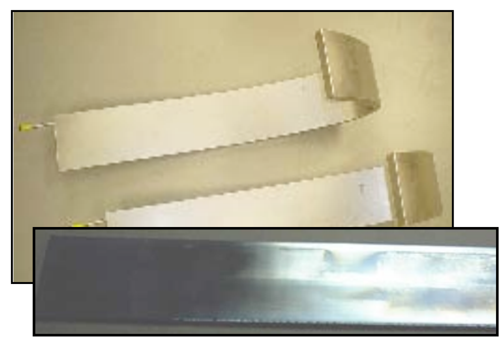
- **Design, Fabrication and Testing of Prototype Articles**
  - 4” x 36” Superalloy/Li Heat Pipes
  - Passed Functional Tests, Operational Performance Test (in Progress)

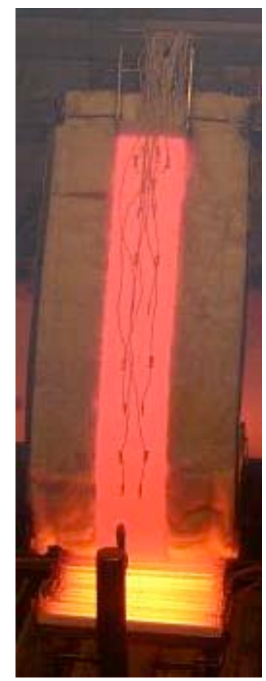
- **HPCLE Design Development for Hypersonic Cruise Vehicles (Ongoing)**











Additional Air Force-Funded Activities

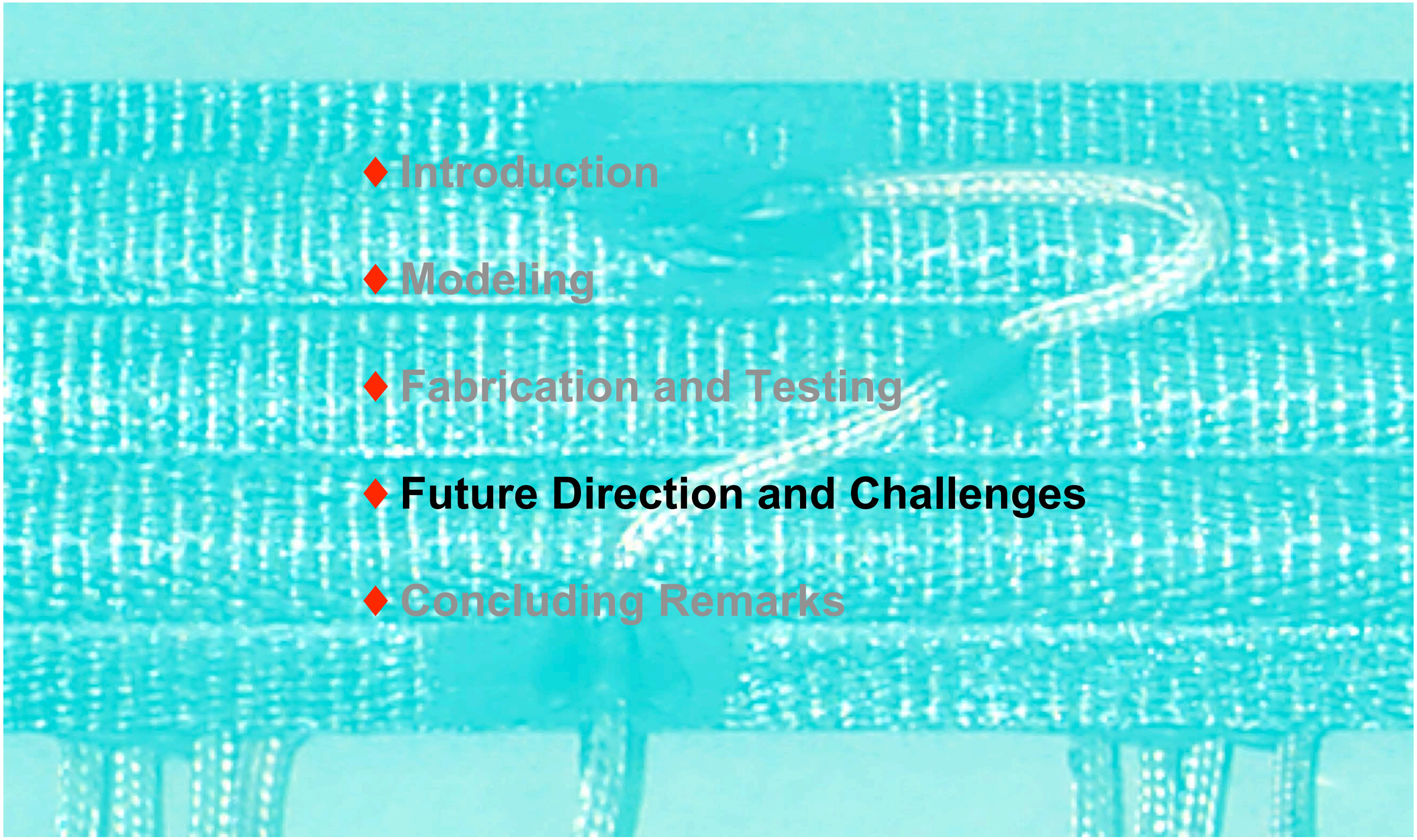
- **Refrac Systems - Norm Hubele (480) 940-0068**
  - Wick/artery fabrication utilizing Mo-5Re alloy
  - Wick/artery insertion technique
  - Heat pipe container welding technique
  - Diffusion bonding methods
  - Modular heat pipe fabrication
  - Novel lithium fill method development
  - Alternate screen material evaluation

- **MR&D – Brian Sullivan (610) 964-6131**
  - Design and analysis of heat pipe cooled refractory composite leading edges

- **Ultramet – Art Fortini (810) 899-0236 x118**
  - Low cost CVD heat pipe fabrication

- **Lockheed – Suraj Rawal (303) 971-9378**
  - Small radius heat pipe cooled leading edge designs for hypersonic cruise vehicles

Agenda



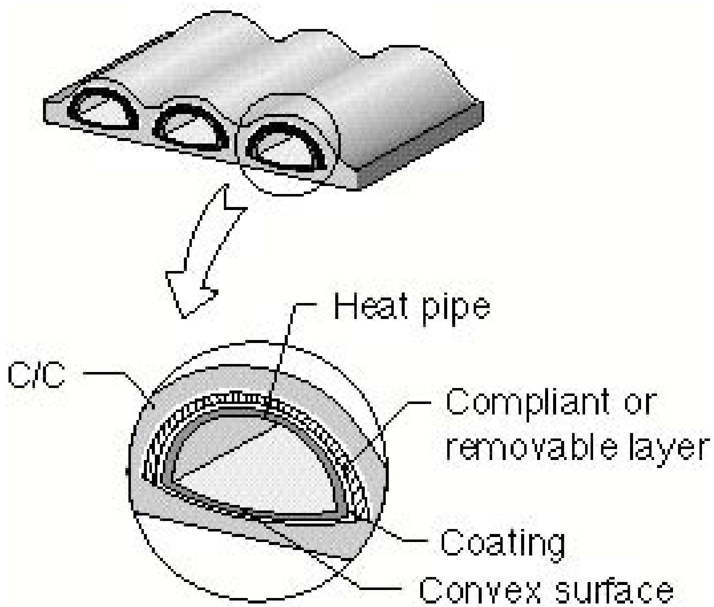
- ♦ Introduction
- ♦ Modeling
- ♦ Fabrication and Testing
- ♦ **Future Direction and Challenges**
- ♦ Concluding Remarks

Path Forward

- **For heat pipes to be utilized on the leading edges of flight vehicles**
  - Designers must be willing to insert the technology
  - The payoff must be significant and the technical evolution not
- **High temperature heat pipe options**
  - Superalloy or refractory metal
  - Embedded or not embedded
- **Superalloy heat pipes offer increased heat flux capability to the designer using "conventional" materials**
- **Refractory metal heat pipes embedded in a refractory composite offer a significant increase in heat flux capability**

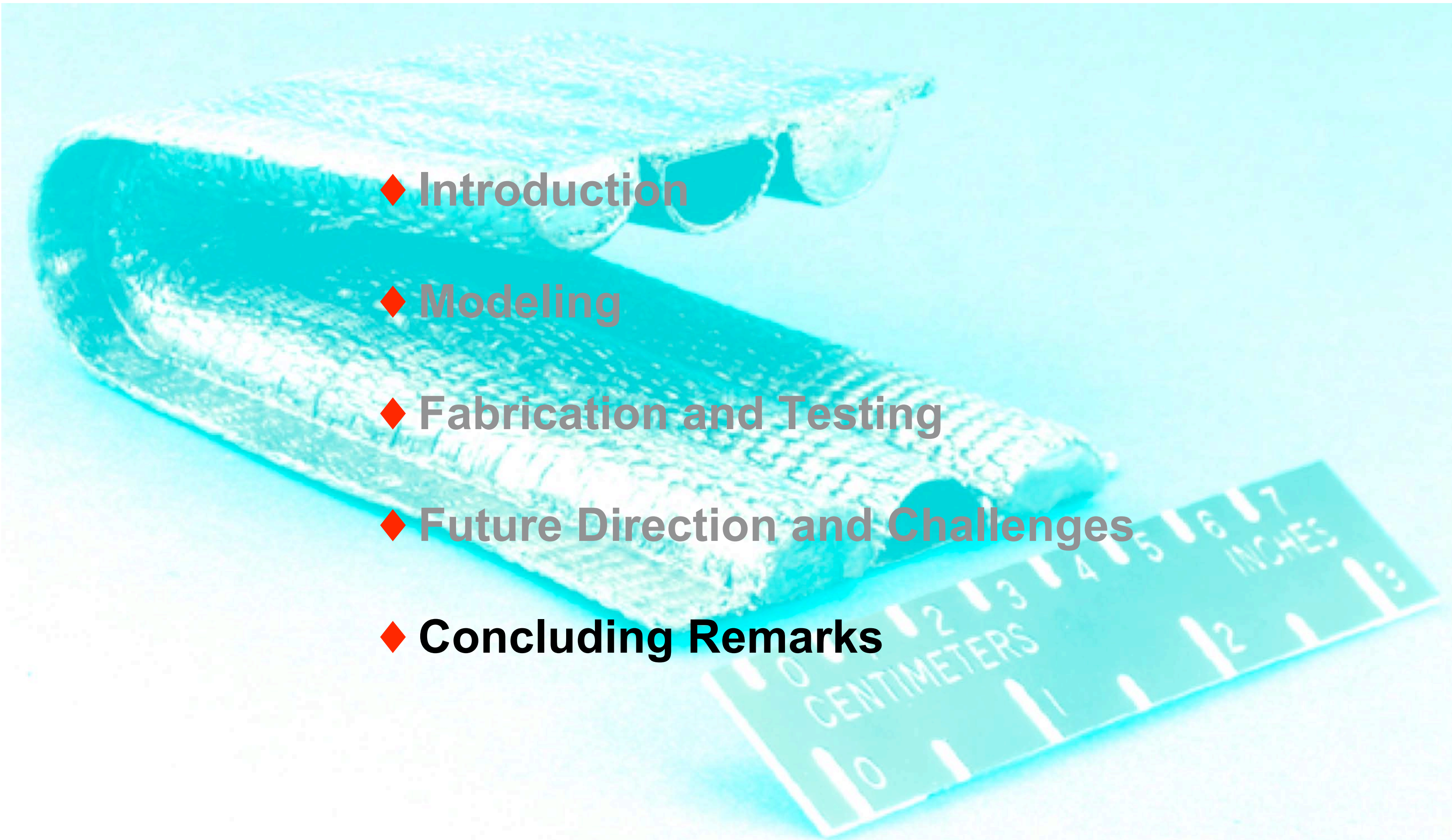
Different Materials At Elevated Temperatures Are Problematic

- Material compatibility, f(t,T)
  - Problem: Brittle carbides,
    Carbon in heat pipe
  - Solution: Coating on Mo-Re



- Coefficient of thermal expansion mismatch (loose for stress, tight for thermal)
  - Problem: Buckling of flat surface,
    Increased contact resistance
  - Solution: Convex surface,
    Compliant or removable layer

Agenda



- Introduction
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- **Concluding Remarks**

Concluding Remarks

- **Heat pipes can be used to effectively cool wing leading edges of hypersonic vehicles**

- **Heat-pipe leading edge development**
  - Design validation heat pipe testing confirmed design
    - Three heat pipes embedded and tested in C/C
  - Single J-tube heat pipe fabricated and testing initiated

- HPCLE work is currently underway at several locations