Actively Cooled Ceramic Matrix Composite Concepts for High Heat Flux Applications

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ABSTRACT

High temperature composite heat exchangers are an enabling technology for a number of aeropropulsion applications. They offer the potential for mass reductions of greater than fifty percent over traditional metallics designs and enable vehicle and engine designs. Since they offer the ability to operate at significantly higher operating temperatures, they facilitate operation at reduced coolant flows and make possible temporary uncooled operation in temperature regimes, such as experienced during vehicle reentry, where traditional heat exchangers require coolant flow. This reduction in coolant requirements can translate into enhanced range or system payload. A brief review of the approaches, challenges and test results are presented, along with a status of recent government-funded projects.

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Actively Cooled Composites

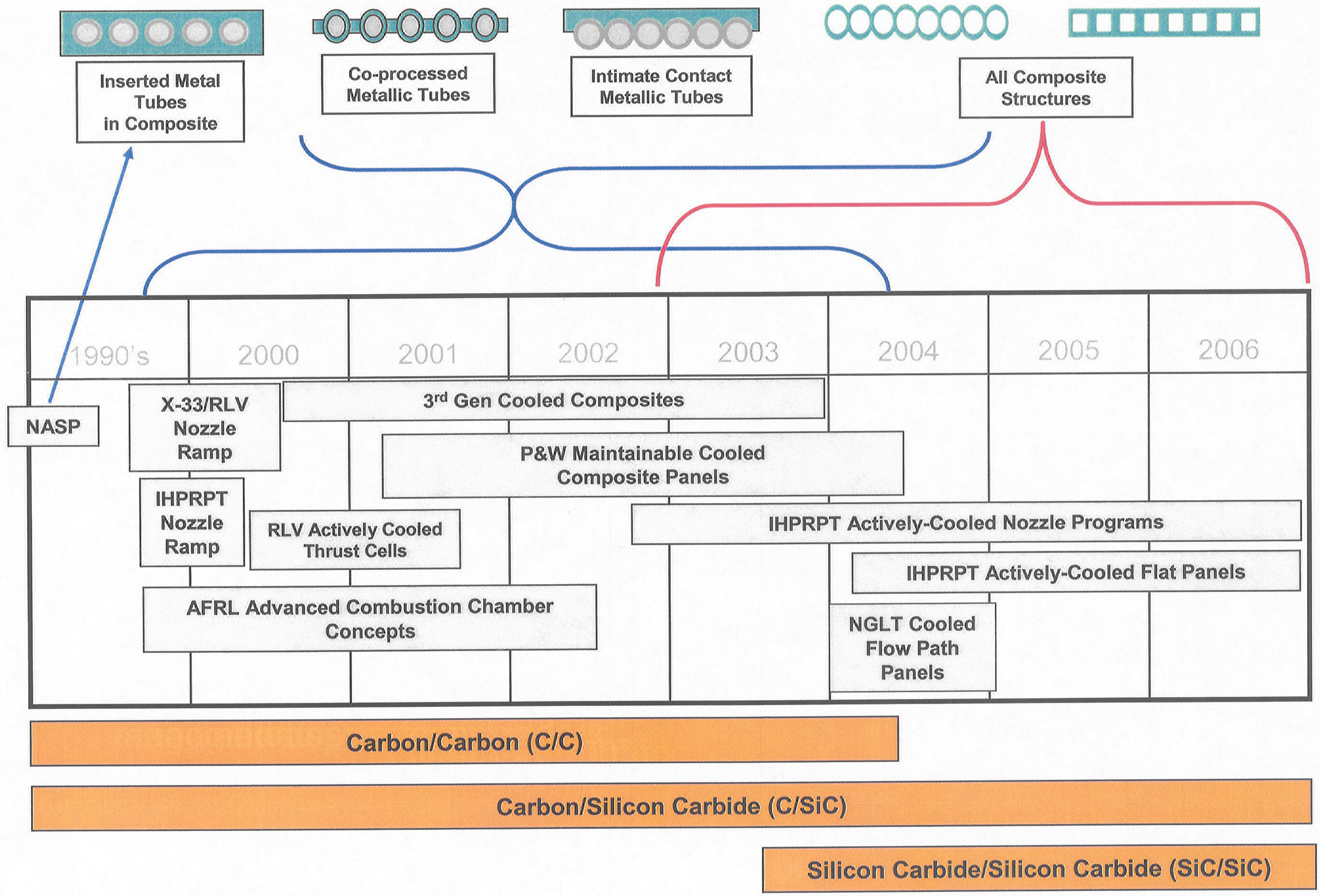
What are actively cooled ceramic matrix composites?

- Heat exchanger with coolant contained within structure.
- Distinctly different than back-side cooled, film cooled, or transpiration cooled structures

Why Actively Cooled Ceramic Matrix Composites?

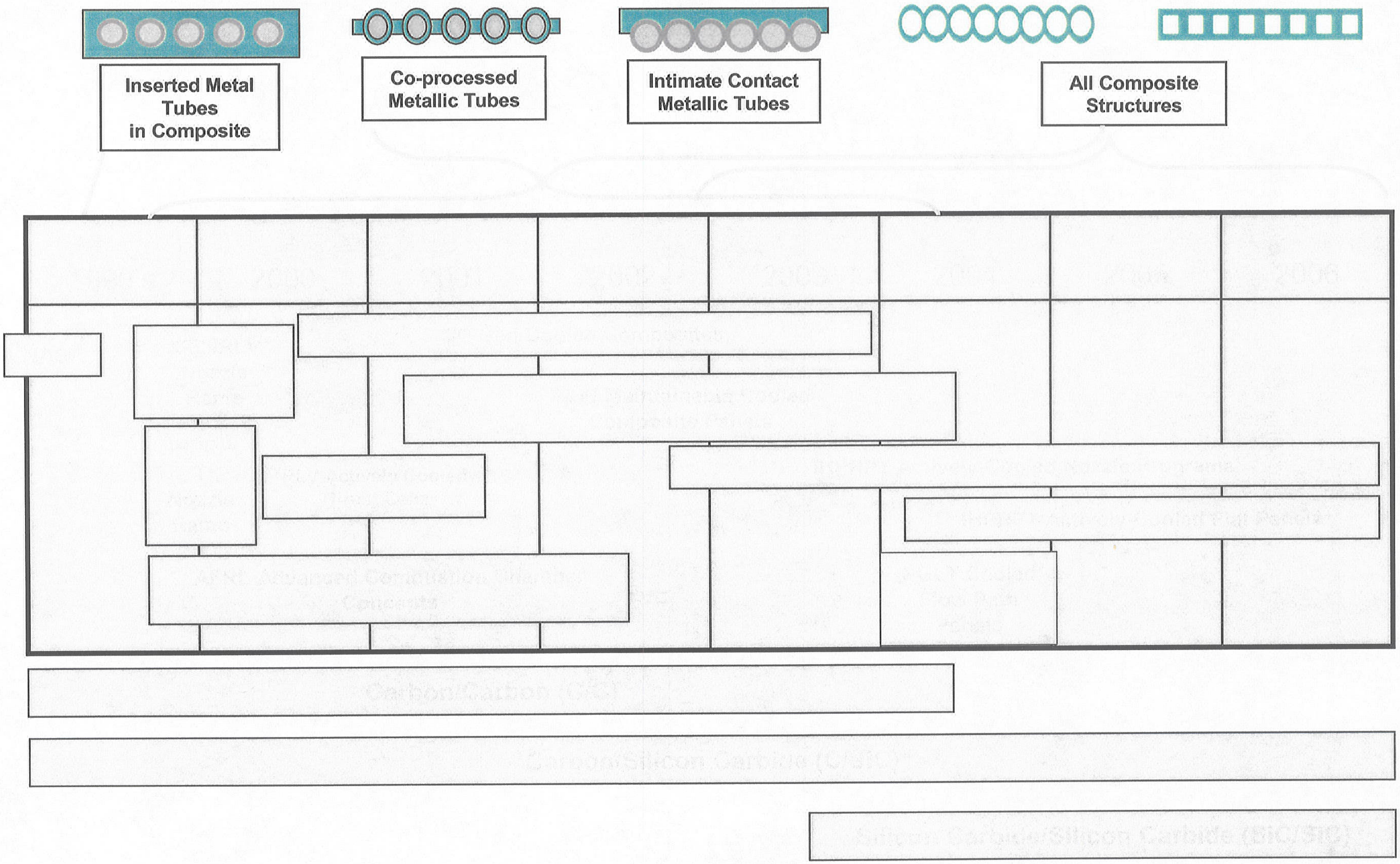
- Lighter weight than metallic designs
  – up to 50% weight reductions calculated
- Lower coolant flow requirements
- May eliminate re-entry cooling requirements
- Can provide higher fuel injection temperatures
- Enables vehicle and engine designs/cycles and missions
- Increased operational margin -- translates to enhanced range and/or system payload

Actively-Cooled Ceramic Composites

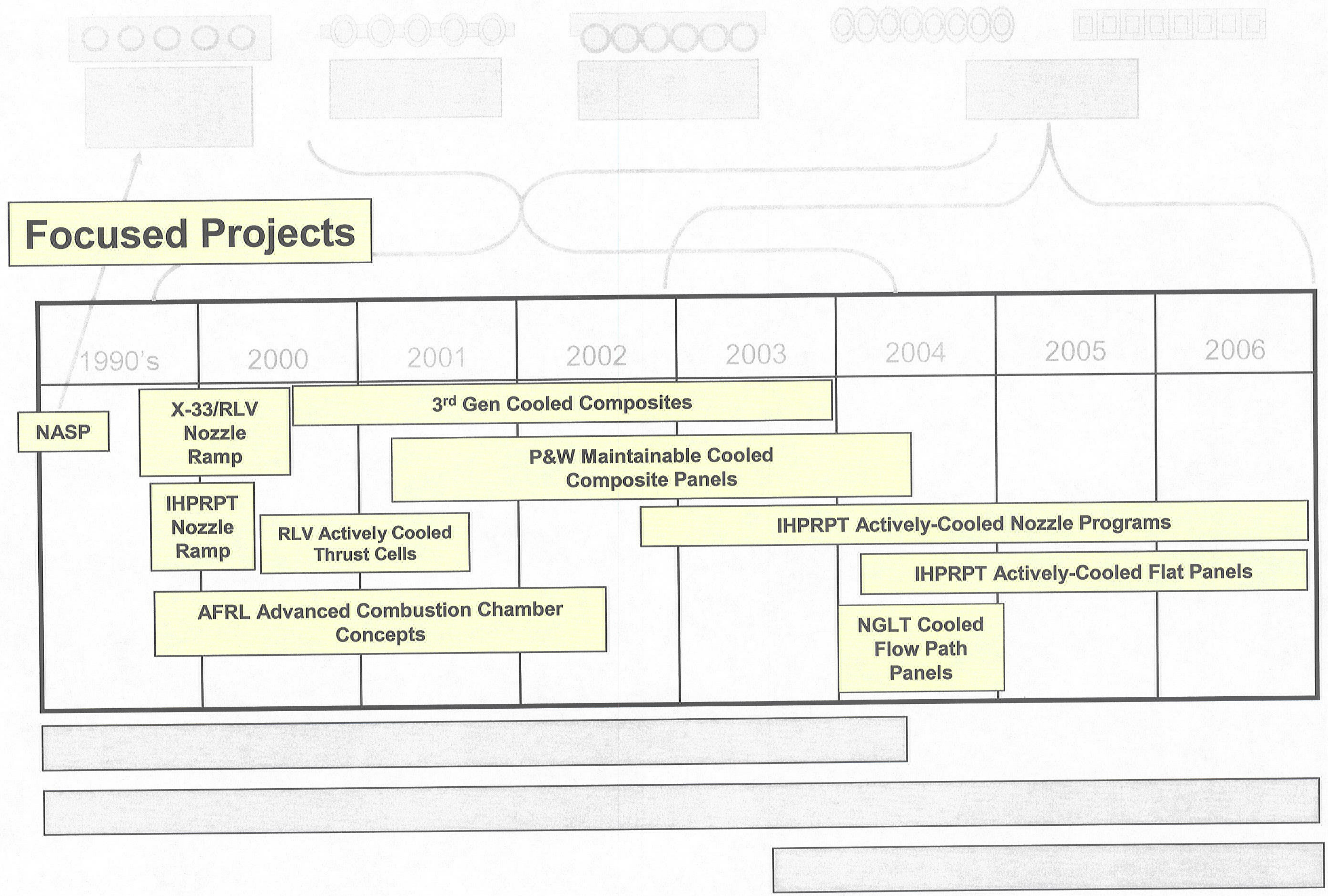


Actively-Cooled Ceramic Composites

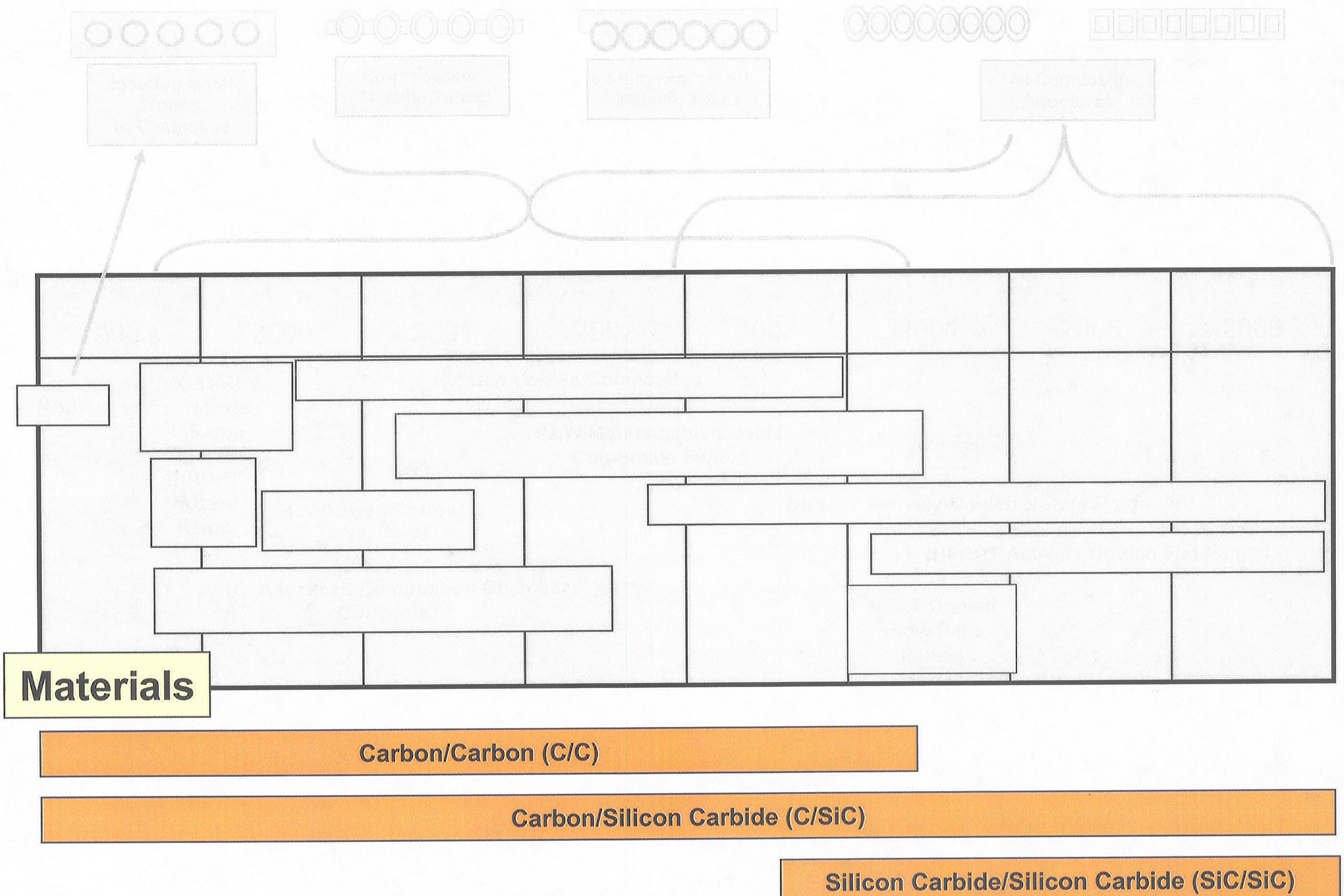
Structural Concepts



Actively-Cooled Ceramic Composites



Actively-Cooled Ceramic Composites

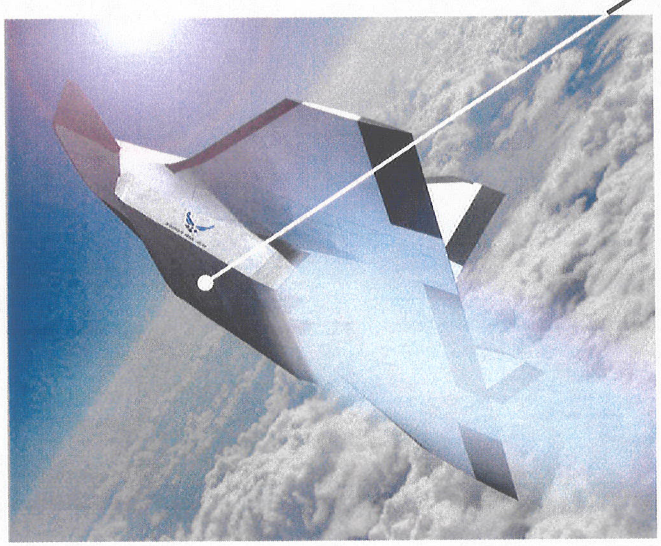


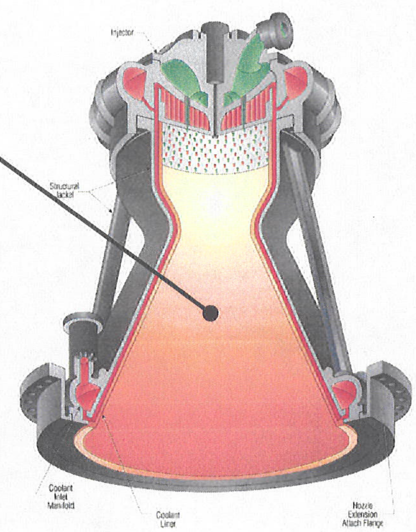
Actively-Cooled Composite Focused Projects

Objectives

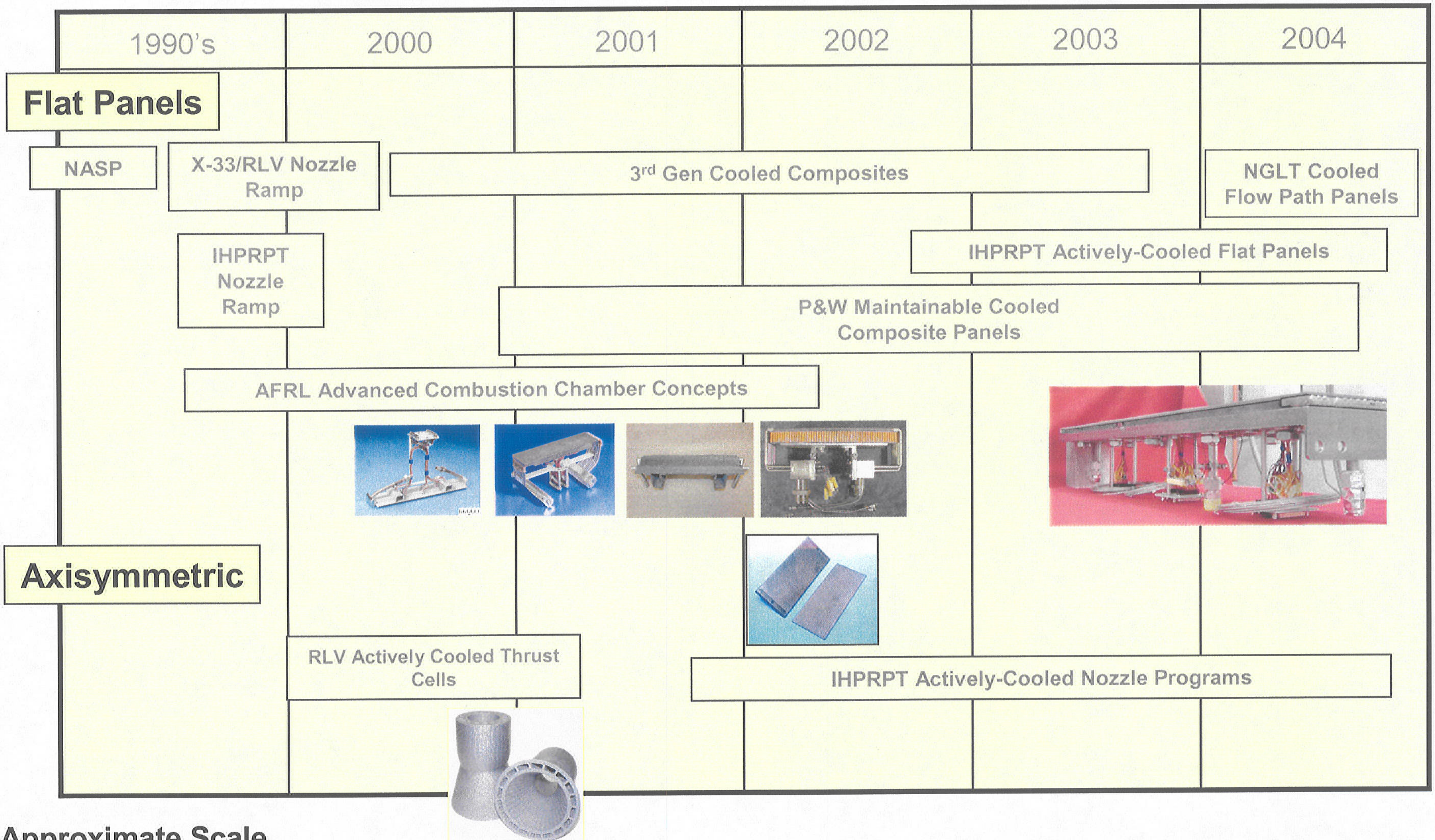
- Each project has focused on specific goals, though system weight is a common driver
  Preliminary designs result in ~ 50% weight savings projections, for most projects.
- Applications generally target hot-flow path propulsion components for either rocket or scramjet vehicles
- Many projects have been terminated prematurely, for programmatic reasons, but collectively, have:
  Developed and demonstrated actively-cooled ceramic matrix composites heat exchanger designs that meet a range of thermal and structural requirements, for future vehicles.

Potential Cooled Composite Components





Demonstrated Geometry and Scale



Approximate Scale

Flat Panels	1"x4" →	3"x10" →	6"x30"
Axisymmetric		3" dia x 8" →	18"dia x 30"

Key Parameters Driving Structural Concept and Materials Selection

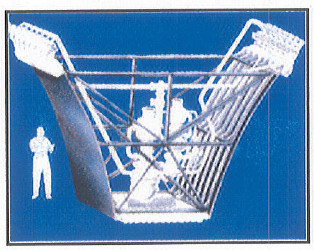
- **Heat Flux**
  Range from 10's of kW/m^2 to 10's of MW/m^2

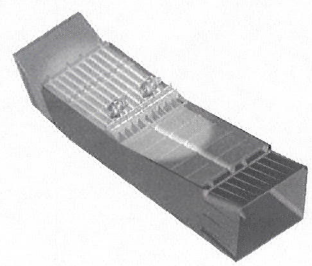
- **Coolant Properties**
  Coolant: hydrogen, hydrocarbon, water
  Pressure: 10's to 10,000's of kPa

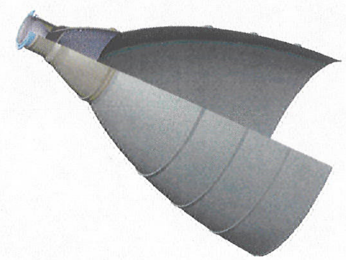
- **Mission requirements**
  Single Use or Multiple Cycles (reusable?)

- **Geometry**
  Axisymmetric or "flat"

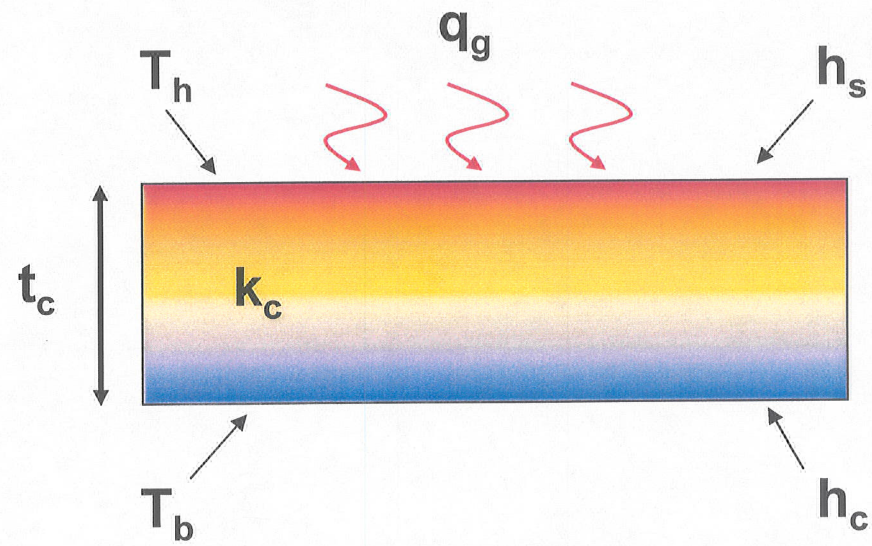
Chart of SSME heat flux (to be inserted)



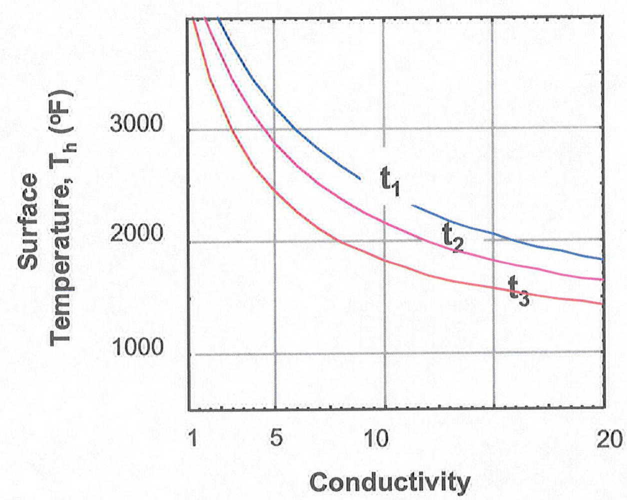




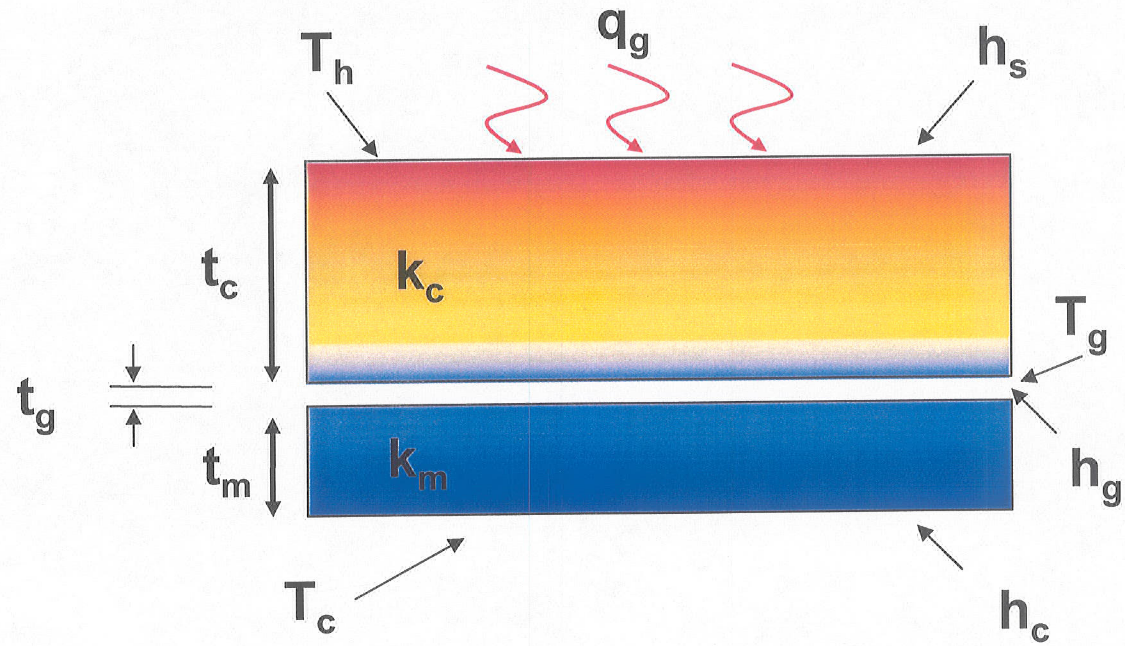
Structural Concepts
Simplified 1-D Thermal Analysis



Q_g = heat flux
T_h = hot surface temperature
T_b = backside surface temperature
h_s = hot side heat transfer coefficient
h_c = backside heat transfer coefficient
t_c = composite wall thickness

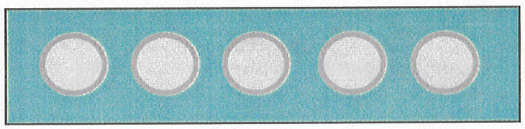
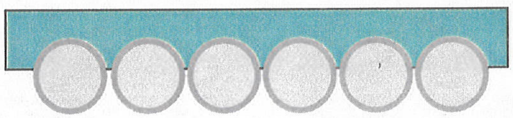
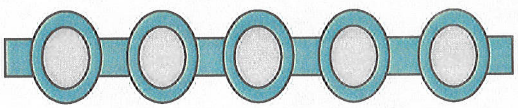
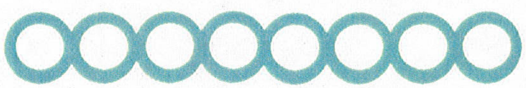


Structural Concepts
Composite with Metal Tube



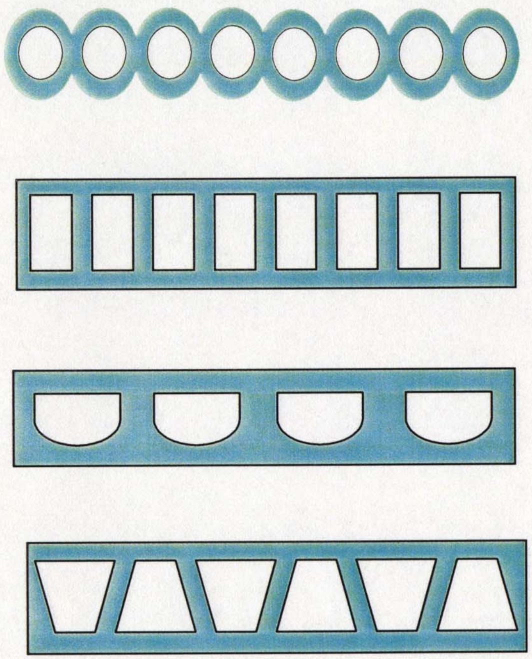
T_c = cool metallic surface temperature
T_g = gap metallic surface temperature
h_g = gap heat transfer coefficient
h_c = backside heat transfer coefficient
t_g = gap thickness
t_m = metal tube thickness

Cooled Composite Structural Concepts

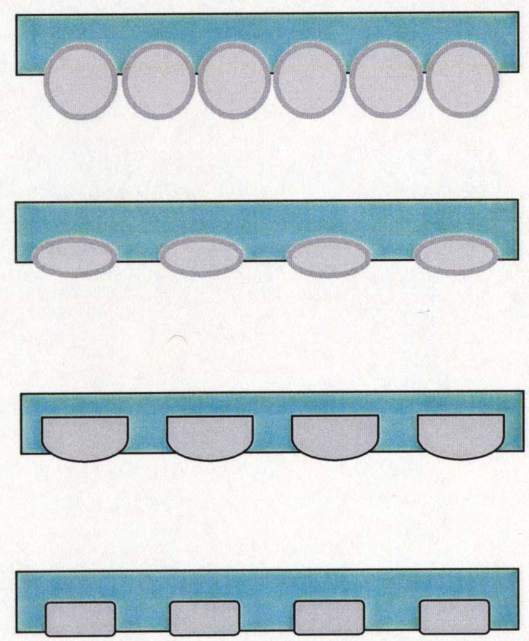
	"Interference fit" metallic tubes
	metallic tubes adhered (e.g.,brazed) to composite
	metallic tubes co-processed with composite
	Composite "tubed" structure

Other Examples of Cooled Composite Structural Concepts

All Composite



Metallic Tube



Materials Selection

Properties for Cooled Composite Materials

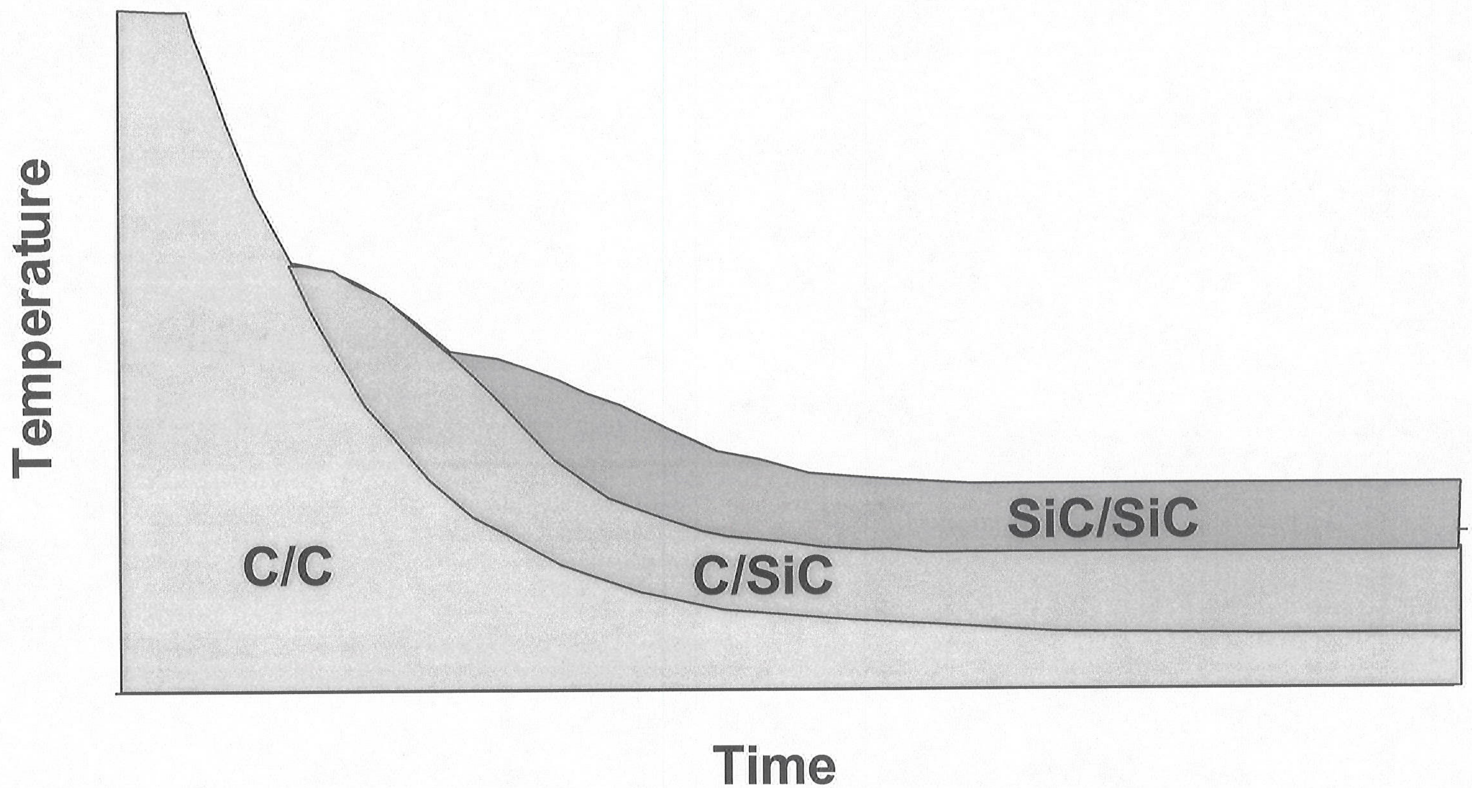
- High Thermal Conductivity
- Hermiticity
- Oxidation Resistance
- High Temperature Strength
- High Specific Strength
- Compatibility with Coolant
- Thermal Expansion Coefficient Compatible with Interfacing Materials

Materials Selection Prioritization

	Metal	C/C	C/SiC	SiC/SiC
High Thermal Conductivity	1	2	4	3
Hermiticity	1	3	4	2
Oxidation Resistance	2	4	3	1
High Temperature Strength	4	1	2	3
High Specific Strength	4	1	2	3
Compatibility with Coolant	2	4	3	1
Thermal Expansion Match	1	4	3	2

Materials – and Structural Concept -- Selection Dependent Upon Application

Oxidation Resistance of Composites

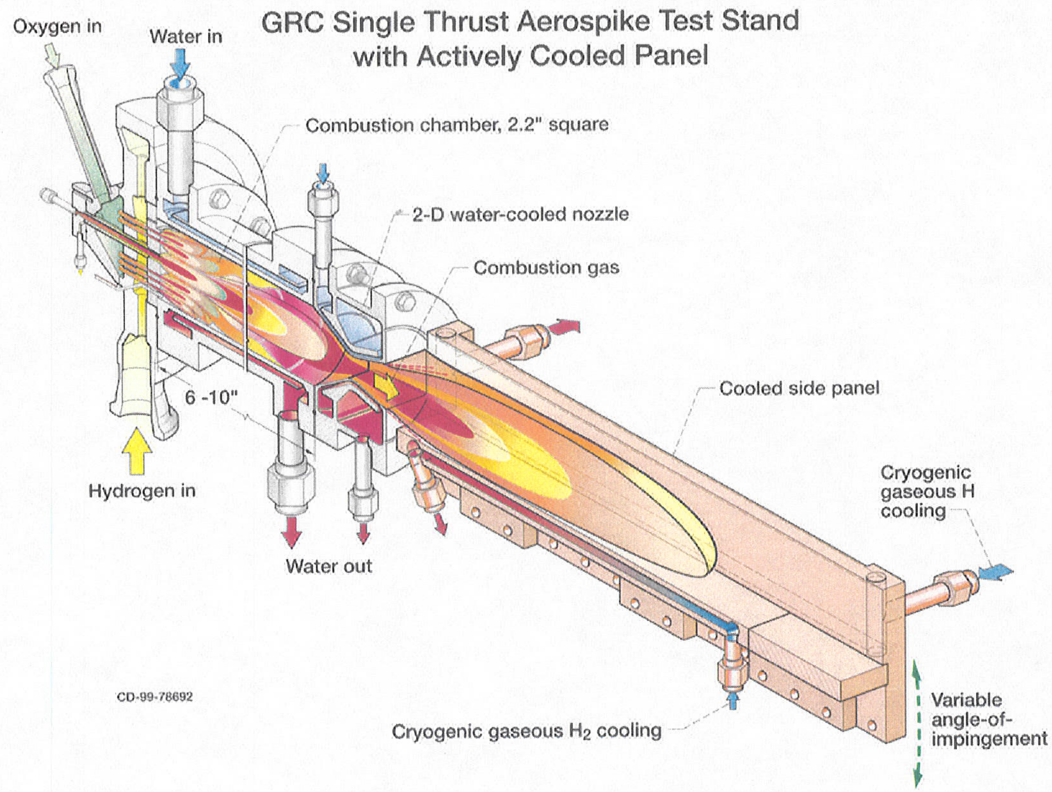


Concept Screening and Validation

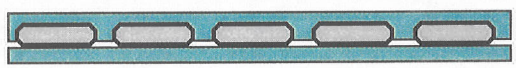
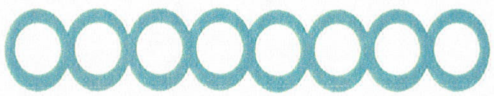
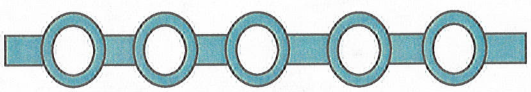
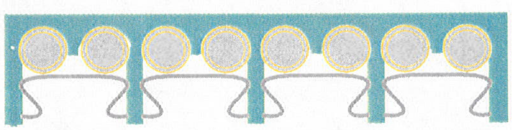
Four concepts evaluated at 3” x 10” scale in rocket engine exhaust

- Propellants- Gaseous O_2/H_2
- Coolant – H_2O,
- Coolant pressure, 1200psi
- Coolant flow, 300gpm
- Run Durations –
- Cycles –

GRC Single Thrust Aerospike Test Stand with Actively Cooled Panel

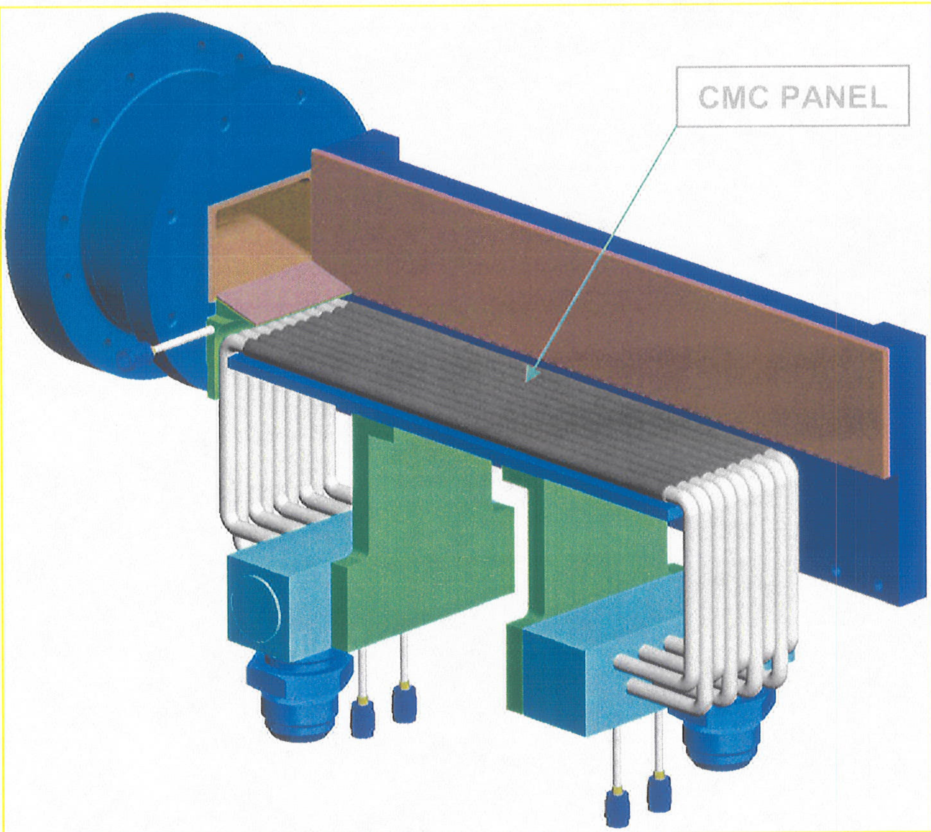


Cooled Panel Concepts Evaluated in Cell22

	***P&W***, Non-bonded, rolled Inco 625 tubes, Maintainable design	C/C-P25, ICC-P30X SiC surface coating
	***RSC***, Woven CMC tube design, No metallic tubes	PIP C/SiC, T300 fibers
	***GEPS***, ***RCI***, MoRe tubes co-processed with composite	CVI C/SiC, K321, T300, PyC interface
	***Snecma***, Non-bonded C263 tubes w/superalloy spring clips	C/SiC, Novoltex

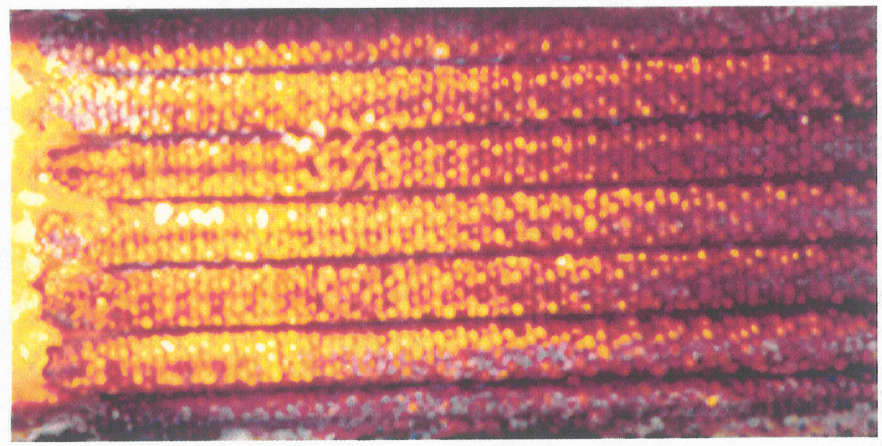
Cooled Composite Subelement Test at NASA GRC

Panel Arrangement at Thrust Cell Exit



LEFT FENCE & ABLATIVE
SHIELDING NOT SHOWN

Top View During Test



- Heat fluxes to 14 MW/m^2
- Outer surface temperatures to 2800 F

3” x 10” Test Panel Results

- Four different structural concepts tested - all of the panels completed the test matrix which was tailored to their design requirements

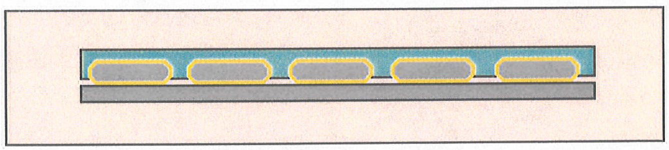
- Issues identified with each panel - all panels tested would require modification before further scale up

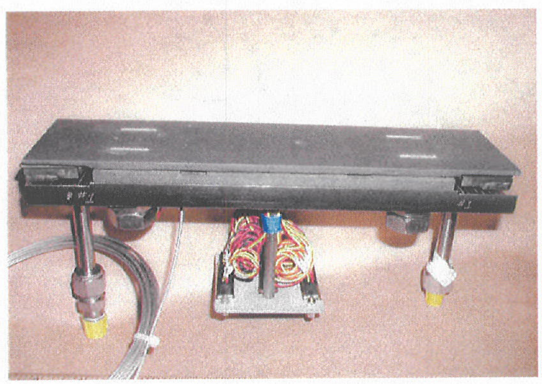
- Primary issues identified for panels
  - permeability through panel of either coolant or combustion gases, need to either eliminate or seal microcracking of current C/SiC or concentrate on other systems
  - low thermal conductivity due to processing flaws, need more uniform densification
  - low thermal conductivity due to increased thermal contact resistance, need better contact between tubes and hot face sheet
  - lack of high temperature durability for extended times

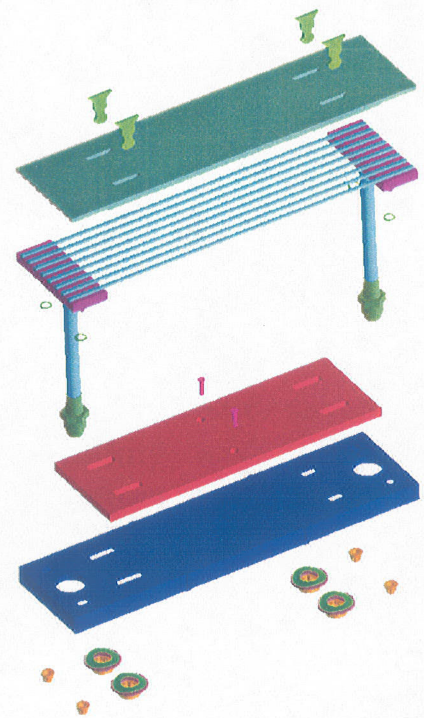
- Lessons learned in testing
  - seals pose considerable challenge to long duration runs,
  - need to strategically instrument panel and backside air to determine when data may reflect erroneous heat loads / heat fluxes due to backside heating
  - streaking issues caused early retirement of 1st two panels, need to remedy this situation earlier in the future if same situation occurs

6” x 30” Panel Test

- To address the needs of a scramjet engine, a 6” x 30” panel was fabricated of a ~~a~~ “maintainable panel” design.
- Inco 625 tubes press-fit on backside of silicon carbide coated carbon/carbon composite.
- Tests conducted in United Technologies Research Center scramjet facility.
  - hydrocarbon coolant

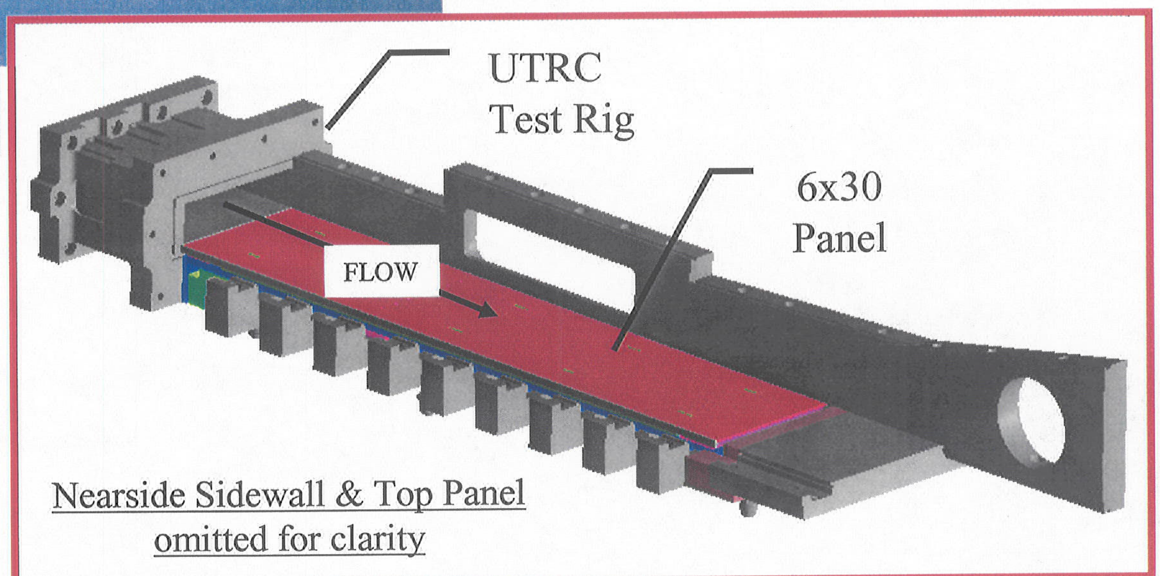






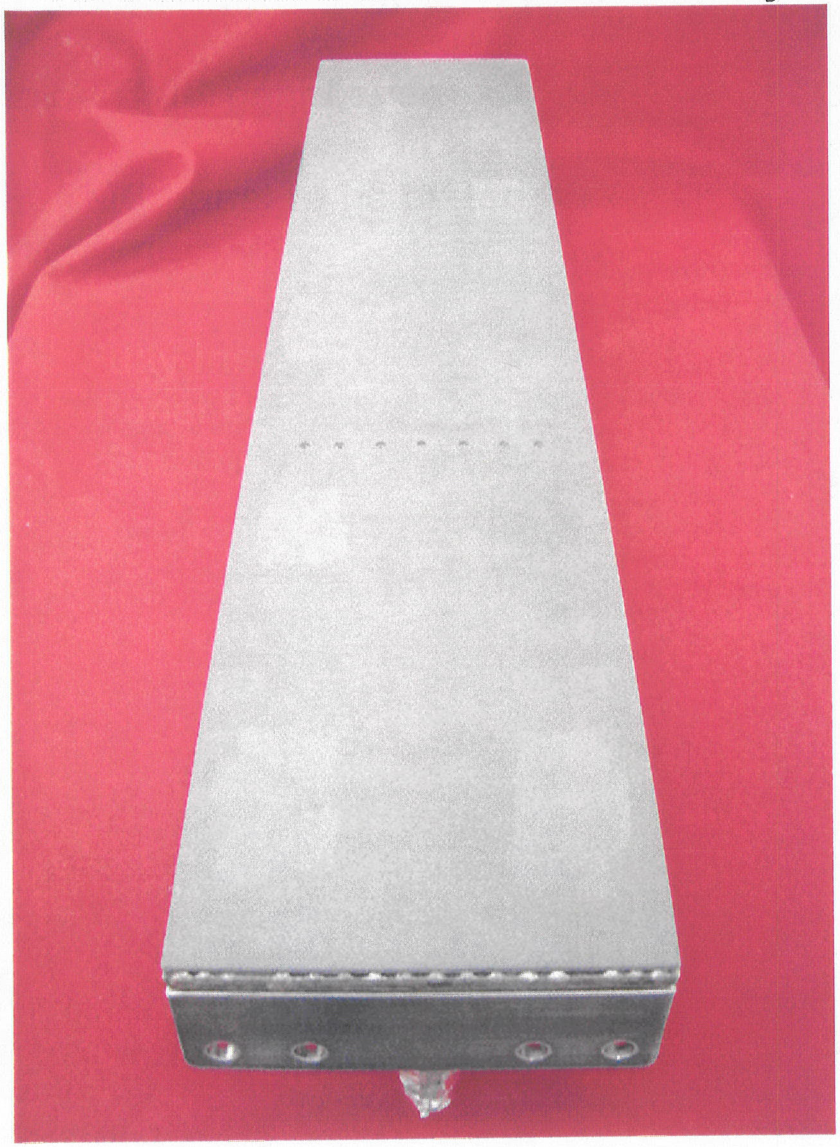
3” x 10” panel

UTRC Scramjet Facility

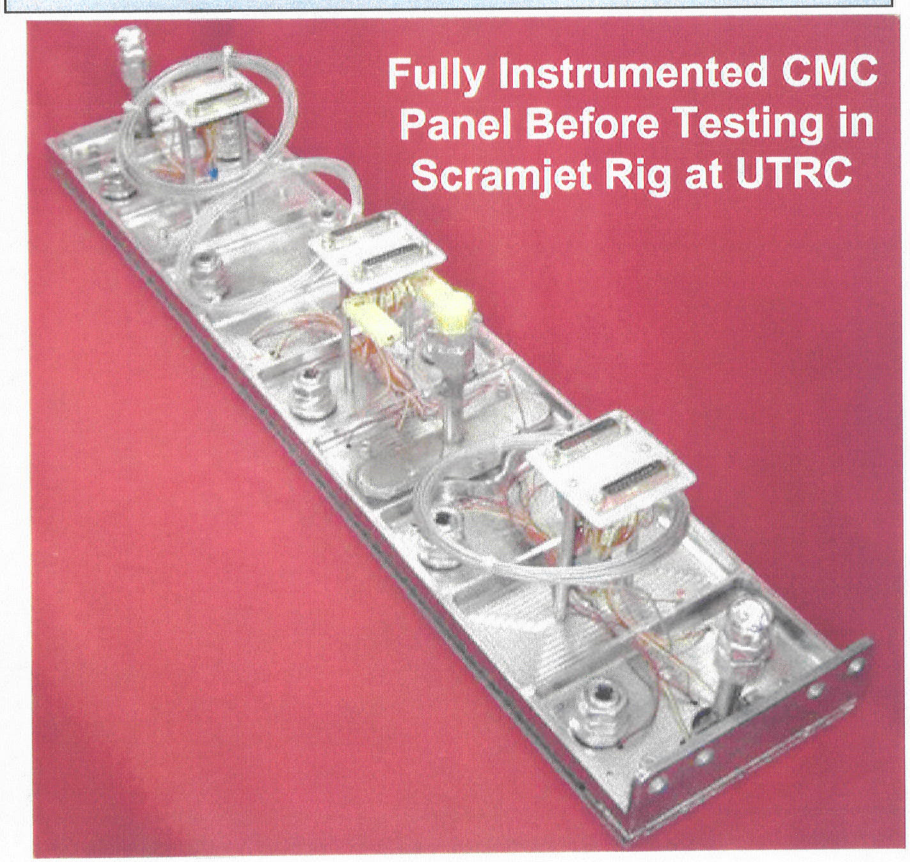


6"x30" Cooled Ceramic Matrix Composite Panel

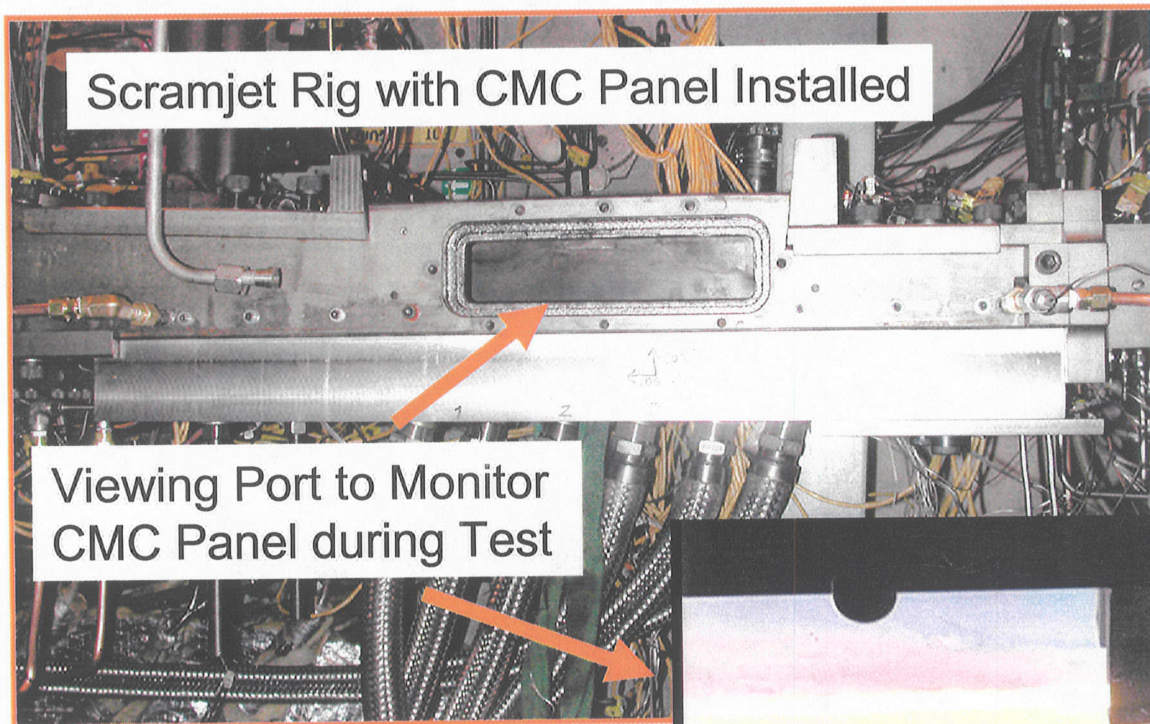
As-Fabricated CMC Panel Assembly



Represents:
- Largest cooled CMC panel ever fabricated
- First cooled CMC panel to be tested in scramjet engine



Testing of Cooled CMC Panel in UTRC Scramjet Rig



- Panel successfully tested at Mach 6.5 flight conditions with hydrocarbon coolant
- CMC exposed to 4000°F combustion gases
- No structural damage to the panel

Summary of Scramjet Panel Testing

- Panel tested in the UTRC direct connect scramjet combustor facility using JP-7 fuel as the coolant.
- Overall objectives of the test were to provide data to evaluate heat exchanger performance and validate analytical tools used to predict heat exchanger behavior under simulated engine conditions.
- Cooled composite panel survived M6.5, Q 750 psf scramjet conditions for a maximum possible run duration of 30 seconds with no damage to the C/C substrate.
- Degradation of surface coating which was evident near injector ports did not cause any detectable structural damage to the C/C substrate.
- Maximum temperature of C/C panel, measured with TC embedded below the panel surface was 2533°F with the surface temperature estimated at ~ 2800°F (within the predicted range of 3000°F.

Summary

- Actively cooled non-metallic composites are a key technology for hypersonic and rocket propulsion systems.
- While individual programs/tasks are focused on specific technical challenges, they all contribute synergistically to advancing the technology base for actively cooled composites.