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Material Development (MatDev™) Module for Use with SPIRITECH's Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)

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A Material Development tool (*MatDev*™) has been developed as an add-on module to complement SPIRITECH Advanced Products, Inc's existing Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™). *SRHEAT*™ is a scramjet/ramjet heat exchanger design and optimization tool that performs a thermal analysis of a heat exchanger, assesses its structural integrity, and optimizes the heat exchanger design to minimize the cooling flow requirement and the heat exchanger weight. *SRHEAT*™ can be used to evaluate and design complex thermal cooling systems, like those found in dual-mode scramjets for hypersonic aerospace propulsion, that have high thermal loading with limited availability of heat sink sources. *MatDev*™, in combination with *SRHEAT*™, is a trade study tool that is used to compare and contrast high temperature metal alloys and high temperature composites (i.e. CMC, C/SiC) in fuel cooled, heat exchanger liner panel design applications. *MatDev*™ uses typical engineering stress calculations and formulations to assess non-traditional stresses, such as interlaminar tension, interlaminar shear, in-plane shear, and flexure. These non-traditional calculations allow *MatDev*™ to accurately evaluate laminated, directional materials, such as high temperature composites. *MatDev*™ provides detailed outputs summarizing the resulting stress, weight, optimum heat exchanger design, and cooling flow requirements to provide the user with critical insight into the key drivers of the heat exchanger system of interest.

I. Nomenclature

C	Carbon
SiC	Silicon-Carbide
HEX	heat exchanger
SRHEAT™	Scramjet/Ramjet Heat Exchanger Analysis Tool
MatDev™	Material Development Trade Study Tool
CMC	Ceramic Matrix Composite
GUI	Graphical User Interface
σ_x	stress in x-direction
σ_y	stress in y-direction
σ_z	stress in z-direction
τ_{xy}	in-plane shear stress in xy-plane
τ_{yz}	interlaminar shear stress in yz-plane
τ_{xz}	interlaminar shear stress in xz-plane
ε	material strain
E_x	elastic modulus in x-direction
E_y	elastic modulus in y-direction
E_z	elastic modulus in z-direction
Nu_{xy}	Poisson's ratio in xy-plane
Nu_{yz}	Poisson's ratio in yz-plane
Nu_{xz}	Poisson's ratio in xz-plane
k_{xx}	thermal conductivity in x-direction
k_{yy}	thermal conductivity in y-direction
k_{zz}	thermal conductivity in z-direction
V	shear load
A	area
W	width
H	plate thickness
B	fuel port depth
ΔP	delta pressure load
b	I-beam flange width
h	I-beam height
t	I-beam shear web thickness
h_1	I-beam inner height
τ_{min}	minimum shear stress in I-beam bending
τ_{max}	maximum shear stress in I-beam bending
y_1	distance from centroid of I-beam
f	distance from I-beam flange edge to shear web
Q	first moment of an area
Kt	stress concentration

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II. Introduction

THE Air Force Propulsion Directorate continues to aggressively pursue innovative ideas offering major performance advances in all areas of air-breathing propulsion, including turbine engines, advanced and combined cycle engines, fuels, and electrical power. Payoffs include increased aircraft and weapon system effectiveness, survivability, reliability, and affordability. If the United States Air Force wishes to continue to advance its capabilities in the realm of hypersonic flight (Mach > 5), improved understanding of the hypersonic flight regime and development of improved technologies to withstand and/or take advantage of this environment are required.

A critical element to achieving hypersonic flight is the use of hydrogen- or hydrocarbon-fueled hypersonic vehicles. One of the significant challenges in designing and operating these types of vehicles is managing the heat load to critical engine components. In particular, thermal management is critical to the development of dual-mode scramjets for hypersonic aerospace propulsion because they have high thermal loading with limited availability of heat sink sources. To effectively remove these generated heat loads, both passive and active methods can be used. One active cooling method is to flow fuel through critical areas of the engine structure using the fuel's heat sink capacity to provide the necessary cooling. In principle, the fuel can be used over a wide range of flight conditions if it has sufficient cooling properties (presumably this will require an endothermic fuel like JP-7). Once the fuel is heated by the engine structure, it is then burned in the combustor to produce propulsive thrust. For an efficient closed-loop system, the flow rate of fuel required for cooling should not exceed the flow rate necessary for propulsion. In practice, this becomes more difficult as the flight Mach number increases. It is possible that cooling of certain critical areas in the engine may elevate the flow rate requirement above that of the propulsion system, thereby resulting in the need to dump fuel overboard during certain parts of the mission, which dramatically reduces the efficiency of this type of air-breathing propulsion system. *SPIRITECH*'s Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™)[1, 2, 3] provides the heat exchanger (HEX) designer with a user-friendly tool for optimizing the cooling system while considering flight point, engine geometry, material selection, fuel/coolant selection, cooling circuit routing, and heat exchanger geometry. With the addition of *MatDev*™, *SRHEAT*™ may be used to perform material trade studies to thermally and structurally evaluate high temperature metal alloys and composite materials (i.e. C/SiC). In addition to evaluating existing materials, *MatDev*™ can be used to evaluate the thermal system sensitivities to individual material properties, providing materials engineers with insight into which material characteristic modifications provide the greatest impact on thermal system performance. This insight can be very useful for developing high temperature alloys and composites. Lastly, *MatDev*™ generates useful output, summarizing stress, weight, optimum heat exchanger design parameters, and cooling flow requirements that provide insight into the critical liner system factors that impact the design system.

III. Technical Discussion

MatDev™ Summary

The *MatDev*™ module is an add-on to the existing Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™). The *SRHEAT*™ software is comprised of the following modules with the following functions:

- *Engine Performance Module* calculates hot gas boundary conditions for heat exchanger panels and property distribution throughout the engine.
- *Flow Module* calculates fluid boundary conditions within heat exchanger panels and fluid property distribution through a cooling circuit, including frictional losses and heating effects.
- *Thermal Module* calculates heat flux and temperature distribution within the heat exchanger panels.
- *Structural Module* calculates the stresses in the heat exchanger panels.
- *Optimizer Module* optimizes the coolant circuit order and the heat exchanger channel geometry.
- *Properties Module* provides a stored library of material and fuel properties for use within the thermal and flow modules, respectively.

These modules within *SRHEAT*™ evaluate the design of the user-defined heat exchangers. When directed by the user, the tool analyzes the heat exchanger performance over a range of design parameters and selects an optimum design. The addition of *MatDev*™ provides the *SRHEAT*™ user with a tool to experiment with material databases and to perform various trade studies and "what if" scenarios. The user can use *MatDev*™ to compare and contrast high temperature metal alloys and to perform trade studies with high temperature composites (i.e. CMC, C/SiC) relative to fuel-cooled heat exchanger liner panel designs. The user is able to study existing material databases stored within

the *SRHEAT*™ program, modify the existing material databases by adjusting individual material properties, or create totally new material databases to analyze. The simple logic architecture diagram, depicted in Figure 1, shows that *MatDev*™ is a separate module that links to *SRHEAT*™ to use its internal coded modules. By integrating *MatDev*™ into *SRHEAT*™, *MatDev*™ takes full advantage of the thermal and structural optimization algorithms found within *SRHEAT*™ and makes possible the efficient development of advanced high temperature materials.

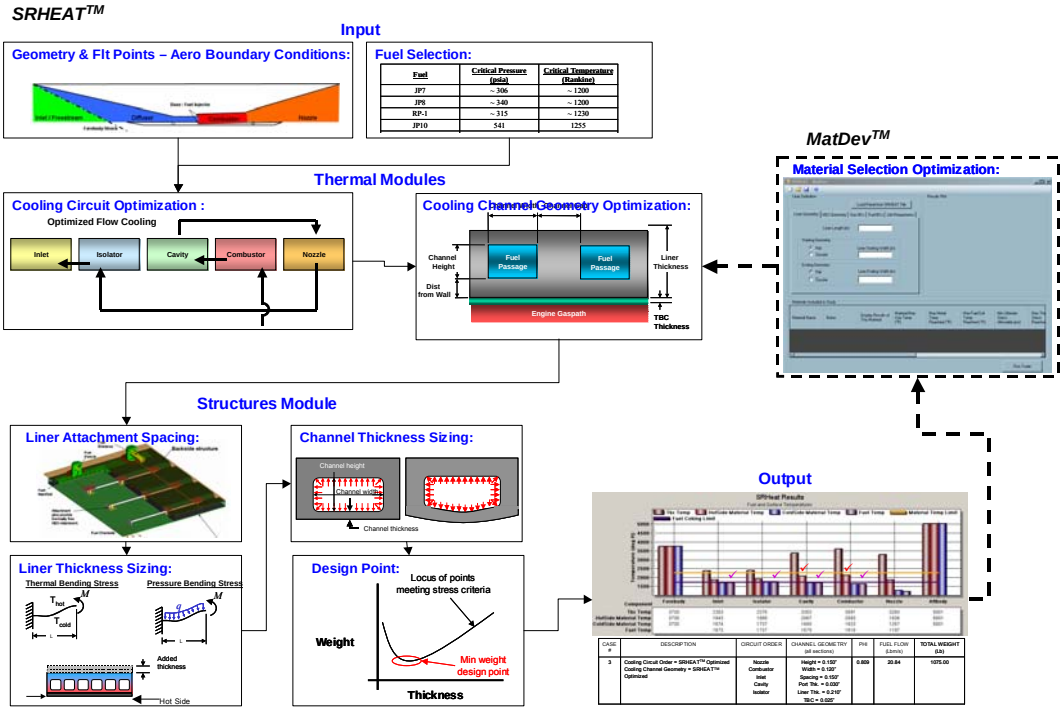


Figure 1. Architecture Diagram of the Integration of MatDev™ into SRHEAT™

A list of benefits and features of integrating *MatDev*™ into *SRHEAT*™ include:

1. Enable side-by-side material evaluations for specified liner panel geometry
    a. Enable user to load existing boundary conditions, thermal loading, and liner geometry into *MatDev*™ from previously run *SRHEAT*™ analyses
    b. Enable user to input new boundary conditions, thermal loading, and liner geometry directly into *MatDev*™
2. Allow the user to make additions and/or modifications to the *SRHEAT*™ materials library
    a. Add new materials and save them to the *SRHEAT*™ materials library
    b. Add new material properties by inputting data manually or by offsetting existing material data curves by a user-defined factor
    c. Adjust existing material properties and add/save modified materials to the materials library
3. Provide the capability for *MatDev*™ / *SRHEAT*™ to structurally evaluate CMC materials in propulsion system trade studies and assess the impacts of the material properties
4. Provide detailed output summarizing the resulting stress, weight, optimum heat exchanger design, and cooling flow requirements to provide the user with additional insight into the driving factors of the liner system of interest

As a trade study tool, *MatDev*™ can be used to analyze a HEX panel located anywhere in the engine, as defined by the user. The purpose is to allow the user to quickly assess any material choice for any particular engine region of interest. This allows the user to get instant feedback from material trade studies for a single panel prior to running the entire *SRHEAT*™ program. For a single liner panel geometry and set of boundary conditions, the user can compare an infinite number of material options in order to determine the best material for the configuration analyzed. Once a desirable material solution for the area of interest is determined, the material can be saved to the *SRHEAT*™ material database to be applied later when using the full capabilities of the *SRHEAT*™ code.

SRHEAT™/MatDev™ GUI Improvements/Additions

The interface to access *MatDev*™ through *SRHEAT*™ consists of a single window that can be accessed through the "Advanced Options" form. *MatDev*™ is available at any time from this menu while using *SRHEAT*™. The user can define the liner geometry, HEX geometry, gas path boundary conditions, fuel boundary conditions, life requirements, and material properties through this single window. Examples of the five information "tabs" that define the liner are shown in Figure 2. In addition, the code is set up so that the user can also read panel geometry and conditions from a previous *SRHEAT*™ analysis. This enhancement greatly increases the "user friendliness" of the *SRHEAT*™ program. When the trade studies are completed, the user can compare results for different material systems "side-by-side" in graphical format, as shown in Figure 3. The results for each parameter (i.e. minimum weight, max fuel temp) are output vs. fuel flow rate to provide the user with insight into the sensitivity of these parameters to assist in making further adjustments to the design parameters for further study.

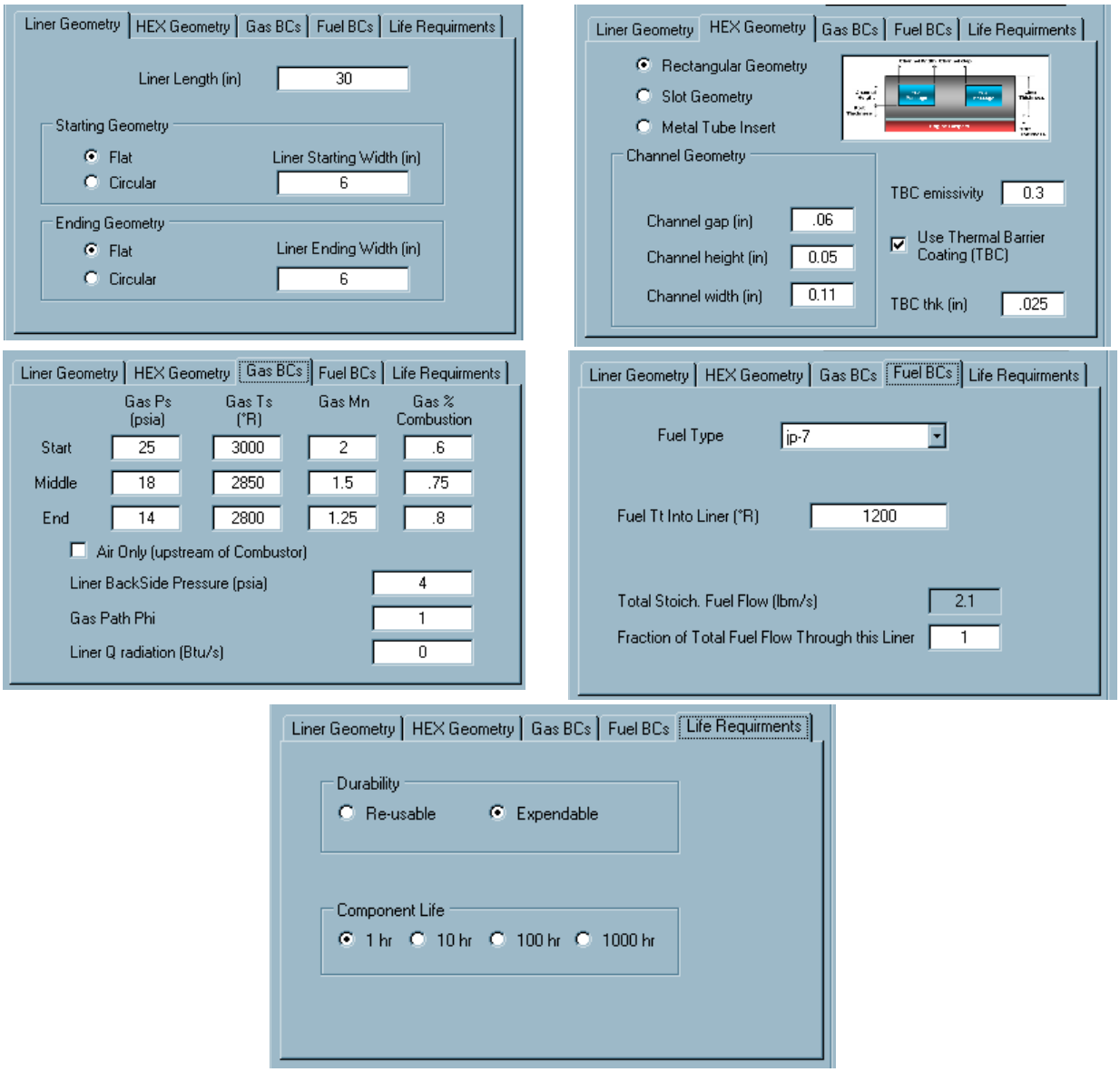


Figure 2. Example of Tabs Used for Liner Geometry Definition

Figure 3. Example of Side-By-Side Comparison of *MatDev*™ Results for Different Materials

While integrating *MatDev*™, enhancements were made to *SRHEAT*™ for saving and editing material properties. These enhancements allow the user to add, save, edit, duplicate, or remove materials from the material library in an easy-to-use GUI format, as shown in Figure 4. For modifying material properties, a graphical feature has been included to illustrate adjustments to the material curve based on user inputs. Again, this provides the user with a graphical output for additional insight when performing trade studies.

A detailed output summary, known as the Structural Audit Sheet, is included in the baseline *SRHEAT*™ code to provide the user insight into the structural stress results. While integrating *MatDev*™, the output summary was updated to include critical composite liner stress results, such as interlaminar shear and in-plane shear. Also, a progress bar was added to be displayed during execution to provide the user with an estimated status of the time remaining. In addition, a feature to run *SRHEAT*™ in batch mode was incorporated. This allows the user to run a series of analyses with a single push of a button. These analyses can be run in the "background" or overnight, which will significantly improve the code's productivity.

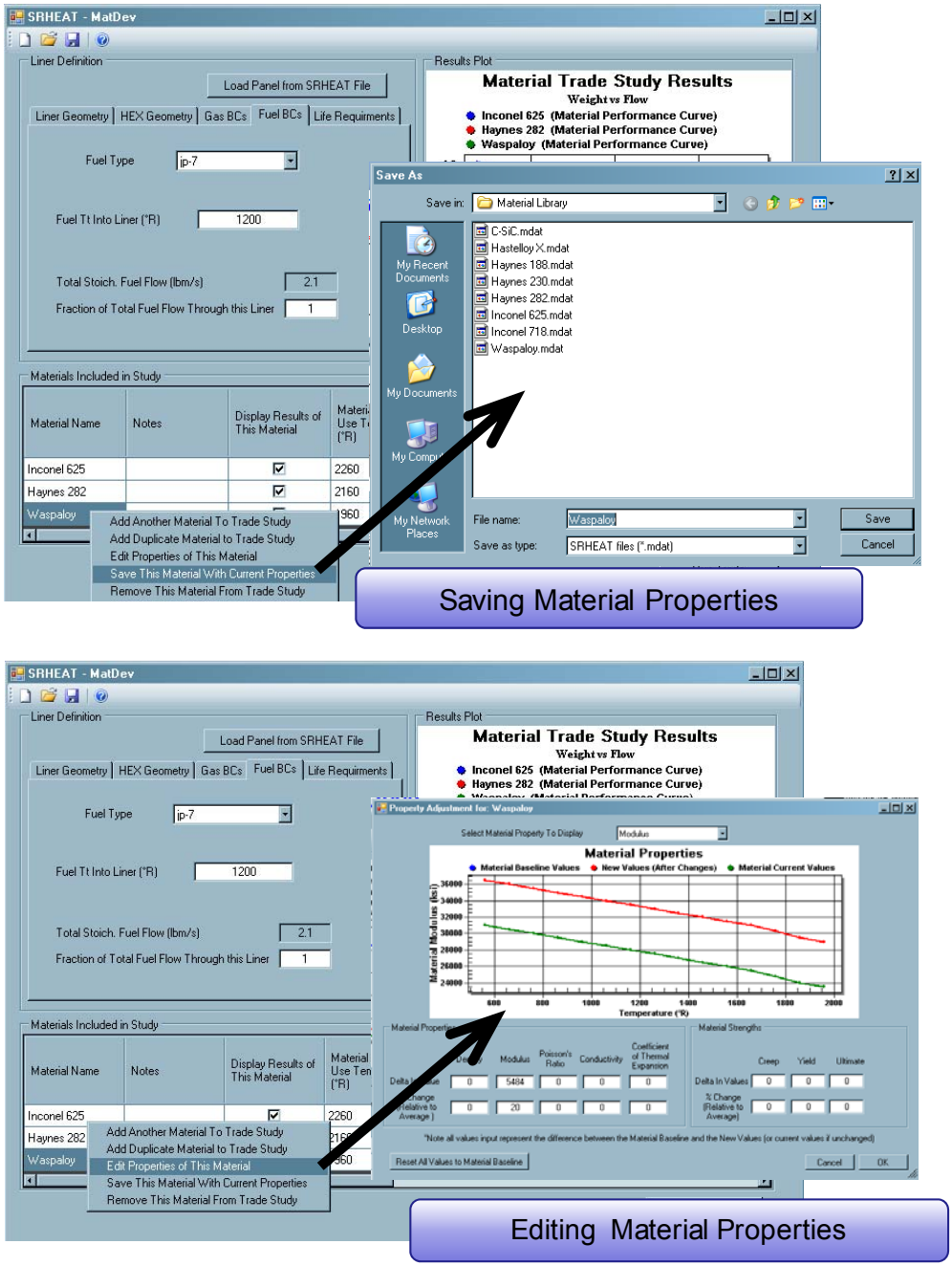


Figure 4. Examples of GUI for Saving and Editing Material Properties

Material's Library User Modifications

When incorporating the *MatDev*™ module, the functionality of the material libraries in *SRHEAT*™ was improved to allow the user to:

- add new materials and save them in the material database
- adjust properties using delta values (offsets) or percent changes to increase/decrease the selected properties
- reset all adjusted material properties to their initial, default values

The latest version of *MatDev*™/*SRHEAT*™ contains a newly defined materials class. Adjustments have been made to accommodate new architecture as well as orthotropic material properties. This text file formatting will allow the user two options for inputting or modifying material properties. First, the user can modify existing

materials or create "new" materials through the *MatDev*™ GUI. Second, the user can manipulate the existing text files to modify existing materials or create new ones. By adding materials and saving them in the database, the user is provided with the ability to accumulate a large library of materials. These materials can include both commercially available materials and new materials in development. This feature allows the database to be updated easily as new material property data is collected.

Input boxes have been incorporated to allow the user to adjust existing material properties as shown in Figure 4. The user can adjust the entire material property curve either by a delta value (offset) or a percentage change. In addition, the property curve is displayed as the changes are being made, enabling the user to see the impacts in graphical format. The adjusted property can be saved over the "old" database or saved as a "new" material database. The "new" material can be instantly added to the "Material Trade Study Results" window to allow the materials developer to instantly see the effect of changes to the material properties.

If so desired, *MatDev*™ will also allow the user to reset all adjusted material properties to their initial, default values. This allows the user to easily undo all of the "what-if" calculations and material adjustments being performed, if so desired.

CMC Materials Capability

Orthotropic Material Database Properties

One of the major benefits of integrating *MatDev*™ into *SRHEAT*™ is the added material capability that allows the incorporation of Ceramic Matrix Composite (CMC) materials. The following is a list of unique composite stress calculations that are evaluated in *MatDev*™/*SRHEAT*™:

- Yield Strengths (σ_x & σ_y)
  - Tensile
  - Compressive
  - Flexure
- Ultimate Strengths (σ_x & σ_y)
  - Tensile
  - Compressive
  - Flexure
- 1% Creep Strengths (σ_x & σ_y)
  - 1-10-100-1000 hr
- Creep Rupture Strengths (σ_x & σ_y)
  - 1-10-100-1000 hr
- In-Plane Ultimate Shear Strengths (τ_{xy})
- Interlaminar Ultimate Shear Strengths (τ_{xz} & τ_{yz})
- Interlaminar Ultimate Tension Strengths (σ_z)

The strengths listed assume the x- and y-directions are in the plane of the hot composite surface and the z-direction is perpendicular to this surface. To properly evaluate a material, *MatDev*™ requires a minimum amount of material data to be input in order for a material to be available within the *MatDev*™ material database. The required list of material properties is shown in Figure 5. Consideration was given to material properties, static material strengths, and life properties required to adequately compare materials to other material systems already in *SRHEAT*™. SPIRITECH's philosophy is that the material databases included as part of the baseline software package must be defined with sufficient characterization (i.e. life properties defined) so that material trade studies are conducted and compared on an equivalent basis. For a material data set to be complete, both room temperature and high temperature properties are needed; however, if high temperature data is not available, the material is considered to be temperature independent (Ceramic Matrix Composites only). *MatDev*™ does allow the user to modify material properties to execute trade studies; however, the baseline code must have well-defined material databases to start with. *MatDev*™ also gives the user an option to "create" or save a "new" material into the database for material study purposes. If the material properties shown in Figure 5 are not all available, then the user must use his/her discretion when interpreting the results.

Composite Material Properties Required for MatDev™/SRHEAT™

Composite Properties & Strengths	Required	Optional
Maximum Use Temperature		
Temperature	✓	
Density		
Density	✓	
Elastic Modulus		
Ex, Tensile Modulus (Msi)	✓	
Ex, Compressive Modulus (Msi)	✓	
Ey, Tensile Modulus (Msi)	✓	
Ey, Compressive Modulus (Msi)	✓	
Ez, Tensile Modulus (Msi)		✓
Ez, Compressive Modulus (Msi)		✓
Poisson's Ratio		
Poisson's Ratio (Nuxy)	✓	
Poisson's Ratio (Nuyz)	✓	
Poisson's Ratio (Nuxz)		✓
Coefficient of Thermal Expansion		
In-Plane CTEx (in/in/F)	✓	
In-Plane CTEy (in/in/F)	✓	
Through-Thickness CTEz (in/in/F)		✓
Conductivity		
Kxx (Btu-in/ft^2*hr)	✓	
Kyy (Btu-in/ft^2*hr)		✓
Kzz (Btu-in/ft^2*hr)	✓	

Composite Properties & Strengths	Required	Optional
Yield Strength		
σx, Tensile Yield (ksi)	✓	
σx, Flexure Yield (ksi)	✓	
σx, Compressive Yield (ksi)	✓	
σy, Tensile Yield (ksi)	✓	
σy, Flexure Yield (ksi)	✓	
σy, Compressive Yield (ksi)	✓	
Interlaminar Shear		
τxz, Shear Ultimate (ksi)	✓	
τyz, Shear Ultimate (ksi)	✓	
Interlaminar Tension		
σz, Tensile Ultimate (ksi)		✓
in-Plane Shear		
σxy, Shear Ultimate (ksi)	✓	
Ultimate Strength		
σx, Tensile Ultimate (ksi)	✓	
σx, Flexure Ultimate (ksi)	✓	
σx, Compressive Ultimate (ksi)	✓	
σy, Tensile Ultimate (ksi)	✓	
σy, Flexure Ultimate (ksi)	✓	
σy, Compressive Ultimate (ksi)	✓	
1-10-100-1000hr, 1% Creep Strength		
σx, Tensile (ksi)	✓	
σy, Tensile (ksi)	✓	
1-10-100-1000hr,, Creep Rupture Strength		
σx, Tensile (ksi)	✓	
σy, Tensile (ksi)	✓	

Figure 5. Composite Material Properties and Strengths Required to Incorporate into *MatDev*™

A set of guidelines for using orthotropic materials within *MatDev*™ / *SRHEAT*™ has been established for the code developers and structural engineers. These "ground rules" allow orthotropic materials to be used with the existing structural calculations and assumptions that are used for the metal liner sizing calculations. The orthotropic "ground rules" are as follows:

- CMC material baseline thicknesses are based on their defined laminate schedule (i.e. 8 ply thickness for a [0/+45/-45/90]s layup, 1 ply thickness for a [0/90] fabric)
- CMC material thickness increases are limited to increments of the baseline laminate schedule (i.e. a 4 ply layup such as [0/90/0/90] is limited to liner thickness increments of 4 plies instead of the metal liner thickness increments of 0.005")
- CMC material properties and strengths are temperature independent
- Assume CMC material laminates are balanced, symmetric layups with uniform, in-plane properties and strengths except for thermal conductivity, unless otherwise specified
- Differentiate between through-thickness and in-plane thermal conductivity properties for CMC materials

Currently, there are two composite material databases stored in the baseline *SRHEAT*™ code – Carbon/Carbon (C/C) and Carbon/Silicon-Carbide (C/SiC). Other various composite material databases were considered for inclusion but none of the provided materials had sufficient characterization at the time of code release to be included in the baseline *MatDev*™/*SRHEAT*™ code.

Composite Material Liner Design Configurations

When designing composite components, a significant consideration must be given to the fabrication process – in particular, the laminate directions and the layup process of forming unique features. The *MatDev*™/*SRHEAT*™ code accounts for two known composite manufacturing methods, both of which are shown in Figure 6. The first composite liner fabrication configuration used by *SRHEAT*™ consists of metal tubes sandwiched between two composite panels. This was chosen because many of the HEX applications for ceramics being investigated today include high conductivity metal tubes used as a sub-layer in the ceramic construction. In this design, the pressurized fuel is contained inside the metal tubes. This eliminates the need for the composite laminate to sustain the high fuel pressure loads. Therefore, this composite liner carries only the liner gas path pressure loads and the thermal stresses.

The second composite fabrication method consists of composite face sheets with integral composite ribs (Figure 6). In this design, the fuel travels through a completely composite channel. Therefore, in this configuration the upper and lower face sheets have to carry channel/port stresses due to fuel pressure in addition to the liner pressure loads and thermal stresses. The *MatDev*™ / *SRHEAT*™ code adjusts the stress calculations for each of these configurations.

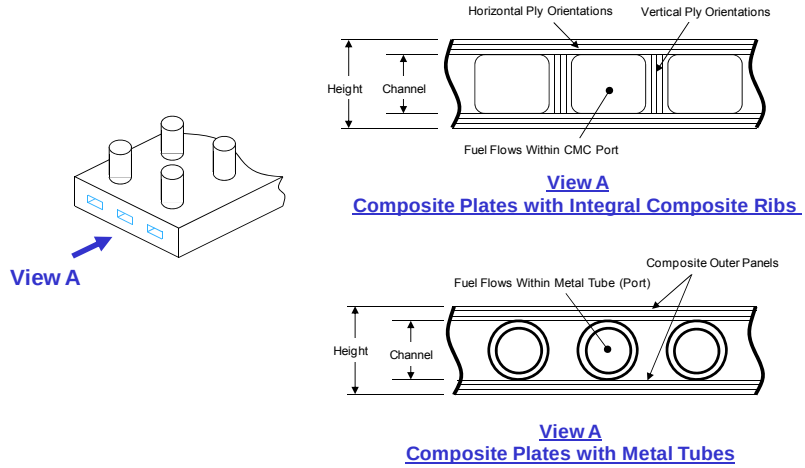


Figure 6. Two Options for Modeling Composite Liner Panels in *MatDev*™ / *SRHEAT*™

Shear Stresses in Composite Materials

In composite designs, interlaminar shear stresses are a major concern. Typically, in metal designs shear stresses are considered a secondary effect and, therefore, do not drive design configurations. However, the shear stresses must be accounted for in each composite material design. The primary reason is that the ratio of interlaminar shear stress to tensile yield strength can be 10% or lower whereas metals typically have a ratio of about 57%. When designing liners, *MatDev*™ accounts for various sources of shear stress, such as shear due to bending in the liner flat plates (channel/port bending) and I-Beam sections (liner panel bending). The results of a sample problem using hand calculations, plotted in Figure 7, show the relationship between bending tensile, bending compression, and interlaminar shear stress for a plate in bending. The results represent the stresses in a fixed-fixed beam of varying lengths with a uniform, distributed load. For a constant load (lb_f/linear inch), the graph in Figure 7 shows the variation in the bending stresses and shear stresses (interlaminar) as the length of the beam increases. Also plotted are the tensile, compressive, flexure, and interlaminar strengths horizontally on the graph. At a channel length of 8 inches in this example, the "maximum shear stress due to bending and edge effects" exceeds the interlaminar shear strength of this material even though there is still plenty of margin in the tensile, compression, and flexure stresses. This result is just one example why the shear stresses must be calculated when designing a composite HEX liner panel.

In the *MatDev*™/*SRHEAT*™ code, shear calculations account for composite directional properties and strengths in both the liner ports (internal fuel passages) and the liner surfaces due to pressure bending. In the port, it has been defined that the "x-direction" (or 1-direction) of the liner will be oriented along the width of the channel/port (W, inner) as shown in Figure 8. Therefore, the interlaminar shear stress due to bending is defined as τ_{xz}. For a typical beam in bending similar to liner port in bending, the average shear stress is V/A (V= shear load, A = area of beam cross section), and the maximum shear stress at the neutral axis is 3V/2A. This assumption is limited to tall, narrow beam cross-sections[4]. As the width increases up to 2X the thickness of the beam, the maximum shear stress increases from 3V/2A up to 2V/A (two times the average stress)[5]. Although shear stress due to bending is usually very small and is typically neglected when designing with metals, it is obviously important to check in high temperature composites because of their typically poor interlaminar shear strengths.

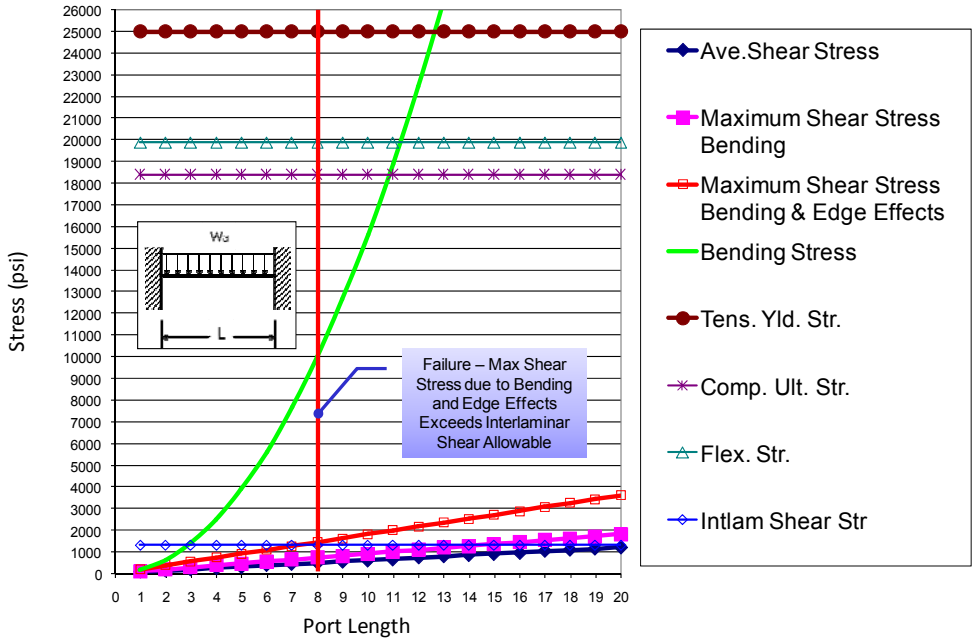


Figure 7. Comparison of Stresses Generated in a Flat Plate in Bending

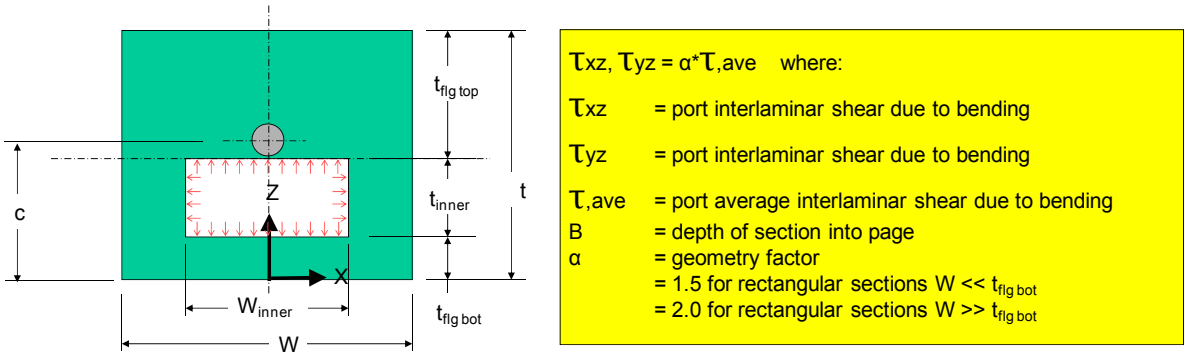


Figure 8. Channel/Port Stress Calculations for Shear

To verify the assumptions used to generate the maximum shear stress values in port bending, a parametric finite element model was created to check the shear stresses generated due to the fuel pressure in the channel. The first model created was a flat plate that had various ratios of thickness (H) over depth of fuel port channel (B). This plate was simply supported on two edges with the other two edges free. It was loaded with a uniform pressure load across the entire surface. The results showed that, as the B/H ratio increased to values of B >> H, the peak interlaminar shear stress increased to values as high as 3V/A, as shown in Figure 9. This is important for the HEX liner panel designs because the depth of the channel/port (B) can be much greater than the channel/port thickness (H) due to the fact that the channels can run axially along the engine length.

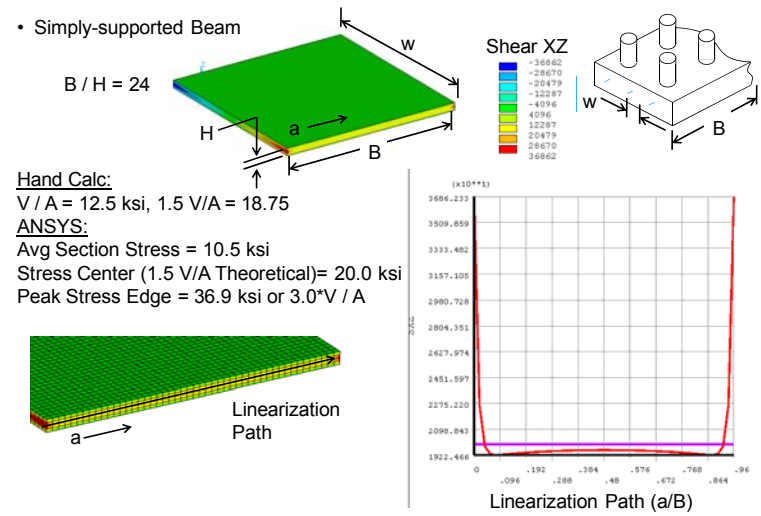


Figure 9. ANSYS Shear Stress Results for Thin, Wide Plate

In addition to the simply supported plate model (Figure 9), a submodel of a single cooling channel was created and analyzed as shown in Figure 10. Although this model had the same B/H ratio as the plate model in Figure 9, the channel/port plate edge constraints more closely represented a plate fixed on two sides and free on the other two sides. Interestingly, the maximum shear stress due to bending was 1.4V/A. This is significantly different than the 2V/A as predicted by Roark [6]. After running other cases and thoroughly reviewing the trends, it was concluded that the geometry of the channel and the fact that the two edges are closer to fixed-fixed boundary conditions than simply supported edges causes the shear stress to only maximize to approximately 1.5V/A. Therefore, the *MatDev*™/*SRHEAT*™ code has been modified to capture these effects in its structural calculations.

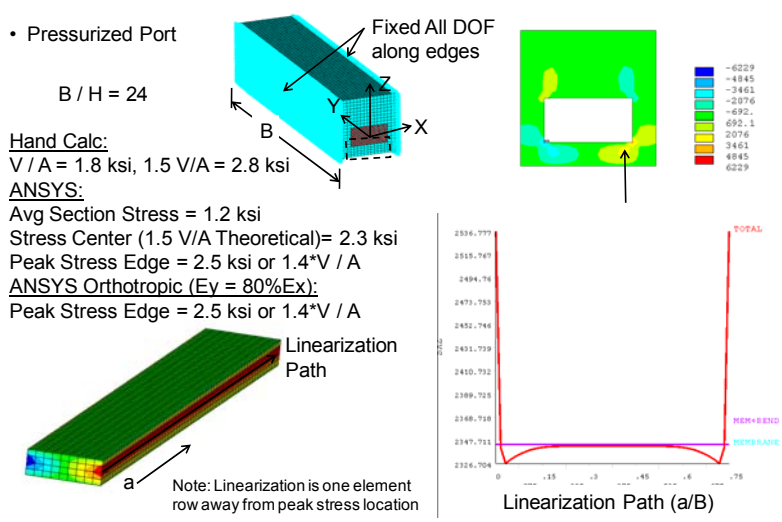


Figure 10. Submodel of Pressurized Channel Representing a Thin, Wide Plate (Port)

In addition to shear calculations in the liner ports, *MatDev*™/*SRHEAT*™ code also calculates in-plane and interlaminar stresses in the liner panel due to the overall panel bending. As shown in Figure 11, when a pressure load (ΔP) is applied across a liner, bending between fasteners occurs and induces a bending stress across the I-beam section height of the liner panel. In metal I-beam structures, only the typical shear stresses ($\tau_{,min}$, $\tau_{,max}$) in the shear web are calculated, as shown in Figure 12a. However, when an I-beam is in bending, the actual shear stresses occur not only in the web but also in the flanges, as shown in Figure 12b. Although the flange stresses are typically small, they must be calculated and compared to the composite material's shear strengths for the reasons stated previously. Therefore, these additional shear stress calculations have been added to the *SRHEAT*™ structural module to evaluate interlaminar and in-plane shear stresses developed in the CMC liner webs and flanges. It is important to note that

shear due to bending in this situation produces two different areas of shear stress for composite beams. The first is the "maximum" shear stress (τ_{max}) that is developed at the neutral axis of the I-beam that is contained within the shear web. This stress calculation needs to be compared to the in-plane allowable stress because of the vertical orientation of the plies as shown in Figure 11. The second is a "minimum" shear stress (τ_{min}) that is developed in the junction between the web and flange (Figure 12). It is referred to as the "minimum" shear stress because it is the minimum shear stress in the web that should be compared to the in-plane strength material allowable. However, when designing with composites, this shear stress is the "maximum" interlaminar shear stress in the I-beam flange. Therefore, this shear stress must also be compared to the interlaminar allowable stress in the flange layup because of the horizontal orientation of the plies in the upper and lower flanges (Figure 11).

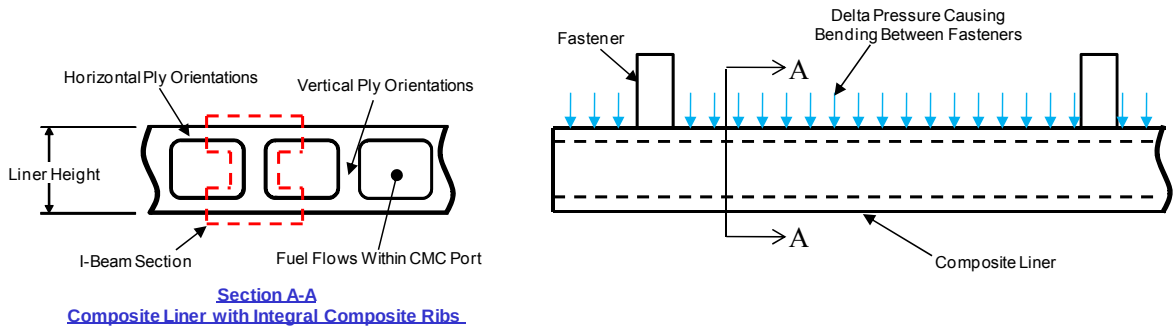


Figure 11. Ply Orientations for an Integral Composite Laminated Structure

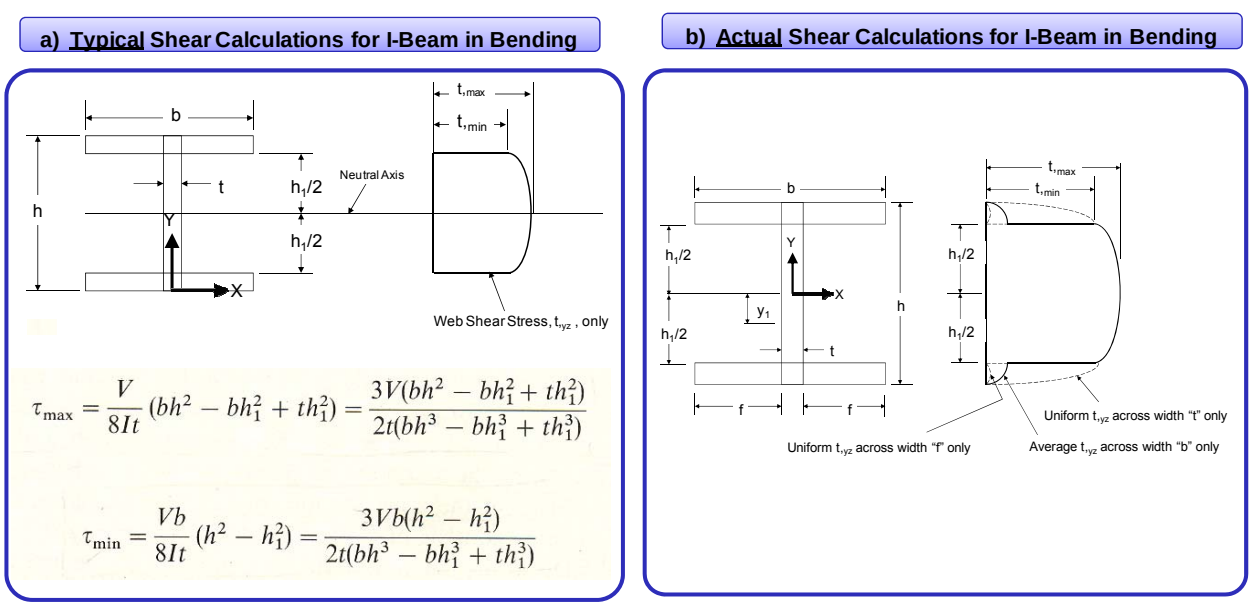


Figure 12. Typical Shear Stress[7] vs. Actual Shear Stress[8] in I-Beam Bending

In order to verify that these shear stresses are actually generated in HEX liner panels due to bending, a submodel of an I-beam section representative of the liner panel geometry was created. The results of the I-beam section in bending are shown in Figure 13. It is shown that the maximum in-plane shear stress in the shear web occurs at the neutral axis and that a smaller horizontal shear stress does occur in the flanges. A more detailed assessment of the shear stress results for the flanges is also shown in Figure 13. The stress distribution reveals that the peak interlaminar shear stress in the flange does occur right at the junction of the shear web and tapers off to the sides of the flanges. Therefore, these peak interlaminar shear stresses in the flange and web are calculated in the *MatDev*™/*SRHEAT*™ code. The τ_{max} shear stress is compared to the in-plane strength of the composite in the shear web while the τ_{min}, shear stress is compared to the interlaminar strength of the composite.

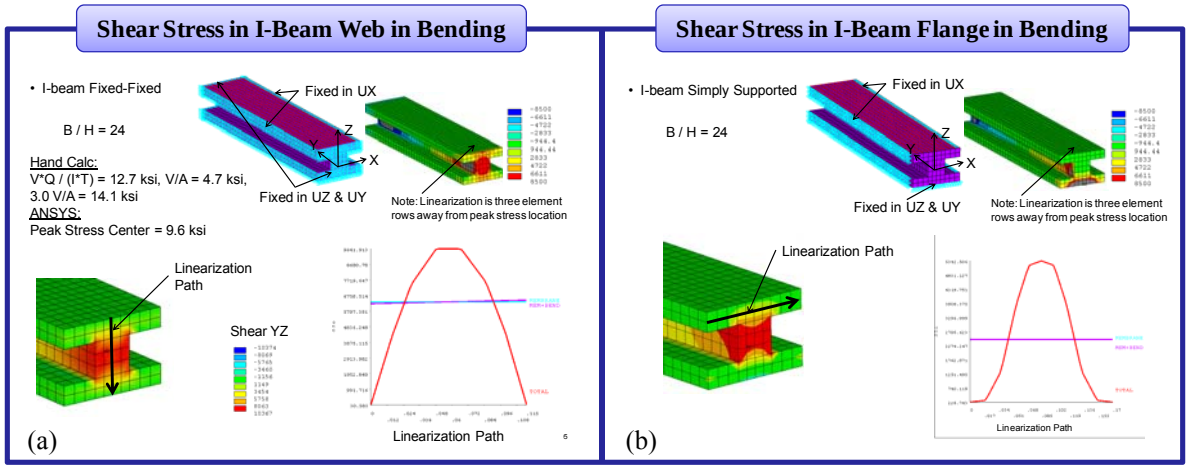


Figure 13. ANSYS Results for In-Plane and Interlaminar Shear Stress Distribution Through the Height and Across the Width of an I-Beam in Bending

SRHEAT™/*MatDev*™ Structural & Thermal Predictions

While *MatDev*™ was being developed and integrated into *SRHEAT*™, SPIRITECH continued to improve the fidelity of the thermal and structural analysis capabilities of the *SRHEAT*™ modules. To validate the *SRHEAT*™ code, a side-by-side comparison using ANSYS was performed for both the thermal and structural results. For liner thermal contour plots, *SRHEAT*™ uses a series of coupled heat transfer equations to predict the heat exchange (Q) between the hot gas path and the liner coolant (fuel). These equations include convection, conduction, and radiation, as summarized in Figure 14. As shown in Figure 15, the thermal nodal results are within 50°F of a similar ANSYS thermal analysis. After the thermal map of the liner is created, the thermal stresses are generated. The improved *SRHEAT*™ code predicts thermal stresses using a differential analysis between nodes with a force balance. This provides a more accurate thermal stresses results across the width (x-direction), along the liner length (y-direction) and through the liner thickness (z-direction) than in previous versions of *SRHEAT*™. Figure 15 shows *SRHEAT*™*'s* accuracy is within 2-10% for both metals and composites for multiple material directions.

"Cold Side" Convection

$$\mathrm{Re} = \frac{\rho V L}{\mu} \qquad \mathrm{Pr} = \frac{\upsilon}{\alpha} = \frac{C_p \mu}{k}$$

$$Nu = 0.0264\, Re^{.764}\, Pr^{.320} \left(\frac{\mu_b}{\mu_w}\right)^{.165} AR^{-.0615} \left(1 + \frac{10}{x / D_h}\right)^{.748}$$

"Hot Side" Convection

$$St = \frac{C_f}{2} = \frac{h_c}{\rho V C_p} = \frac{q_c}{\rho V C_p (T_{aw} - T_w)} = \frac{q_c}{\rho V (h_{aw} - h_w)}$$

$$q_c = \frac{C_f \rho V (h_{aw} - h_w)}{2}$$

Liner Conduction

$$q_{Cond} = k_{Material}\left(T_{Hotsurf} - T_{Fuelsurf}\right)$$

Surface-to-Surface Radiation

$$q_{Rad,Surf} = F_{1-2} \cdot \varepsilon \cdot \sigma\left(T_{Surf1}^4 - T_{Surf2}^4\right)$$

Gas-to-Surface Radiation

$$q_{Rad,Gas} = \sigma\left(\frac{1 + \varepsilon_{wall}}{2}\right)\left(\varepsilon_{gas} T_{gas}^4 - \alpha_{gas} T_{wall}^4\right)$$

Figure 14: Convection, Conduction, and Radiation Scaling Equations

The *SRHEAT*™ code solves for three different mechanical stresses in addition to the thermal stress calculations. These include fuel channel bending (pressure across channel from fuel to gas path), liner bending (between

fasteners), and shear. The fuel channel and liner bending stresses are predicted using typical engineering calculations for panel bending and plate bending between a square pattern of fastener locations. These stresses are distributed through the thickness of the liner based on each node's distance from the centroid. For the fuel channel bending, a stress concentration (Kt) is added based on the channel geometry and applied only in the internal corners of the fuel channel. The shear stresses are predicted as previously discussed. It is shown in Figure 15 that the bending stresses are calculated within 3 ksi and the shear stresses within 0.5 ksi. Each of these thermal and mechanical stresses are calculated separately for increased fidelity for the user and then added together mathematically using the correct sign conventions.

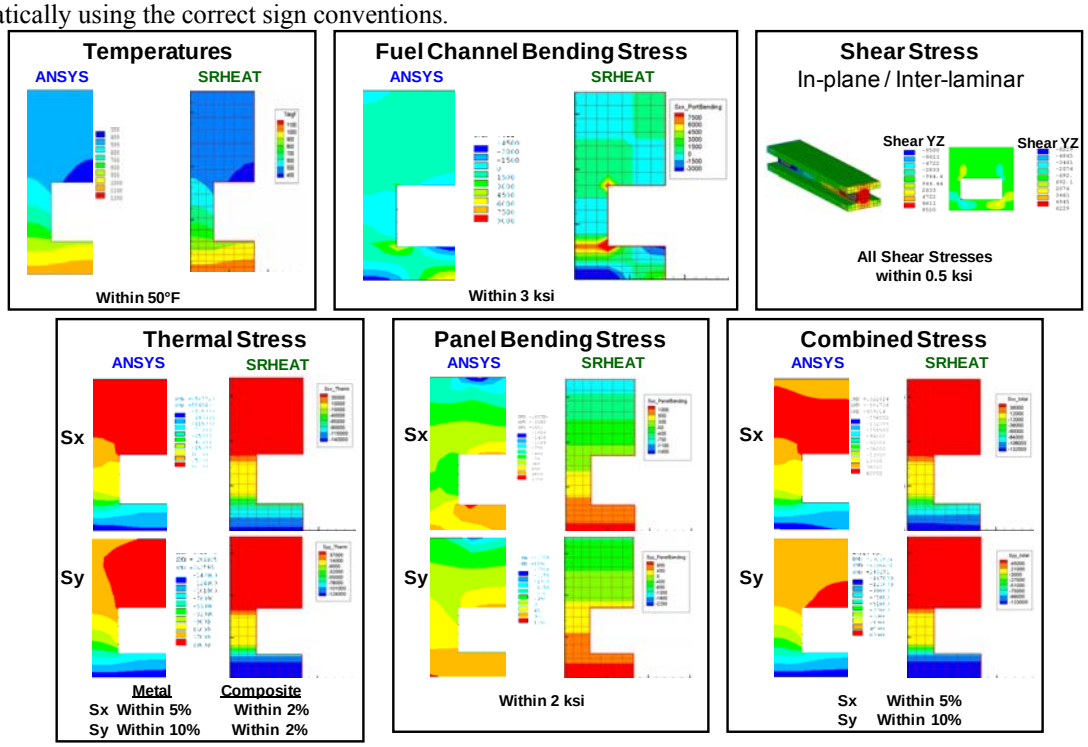


Figure 15: SRHEAT™/MatDev™ Validated Thermal and Structural Results

MatDev™ Trade Study Example

The following is an example of a trade study that was performed using *MatDev*™. The purpose of this trade study is to show how *MatDev*™ might be used by an engineer to develop a new composite material for use in the Combustor Body HEX liner system of a hypersonic vehicle. This process shows how sensitivities in material property changes can be modified and evaluated, how the results from *MatDev*™ can be used in developing HEX liners, and how *MatDev*™ can provide tremendous insight during the design and development of HEX liner systems. To perform the trade study, a set of boundary conditions representing an aircraft speed of Mach 7.0 at an altitude of 85,000 ft were input from RJPA (Ramjet Performance Analysis) into *SRHEAT*™. The analysis was run in *SRHEAT*™ to generate inlet conditions for all of the propulsion system liners (heat exchangers). After the system analysis was completed, the inlet conditions were loaded into *MatDev*™ from *SRHEAT*™ by choosing the "CombustorBody" with a "combustion phi" as the individual component for the trade study to be performed (see Figure 16).

After all of the inputs were loaded, three materials were chosen for study. Two of the materials, C/SiC and Inconel 625, were chosen from *MatDev*™'s material database. A third material was created based on the C/SiC material. Using *MatDev*™'s editing tool (see Figure 17), the baseline C/SiC material was added to the materials list and renamed to "C/SiC RevA". To simulate the process a materials engineer might go through when developing a new version of a material, four properties (elastic modulus, thermal conductivity, yield strength, and shear strength) were chosen to be changed from the original C/SiC that is found in *MatDev*™'s material database. As shown in Figure 17, the elastic modulus was increased by 25%, thermal conductivity was decreased by 35%, yield strength was increased by 20% and shear strength was increased by 15%. These changes represent what might happen to a material's properties if, for example, its constituents are adjusted either by chemistry or by fabrication technique in an attempt to increase the material's strength. In this case, the yield strength was increased by 20%, but other

properties (elastic modulus, thermal conductivity, and shear strength) were also affected, which typically happens during the material development process. In order to make these material property adjustments, *MatDev*™ offers a very simple and intuitive method for changing material properties. The user can "right click" inside the material properties box, as shown in Figure 17, to pull up a list of menu items which includes "Edit Properties of This Material". Once this option is chosen, a new "property adjustment" window opens. This window contains two sections: display option and material properties. Starting with the "Material Properties" section, the user can either input a "delta" value or a percentage change. For example, in Figure 17 inputting a 20% increase in yield strength results in a delta increase of 1.45 ksi, relative to the baseline material.

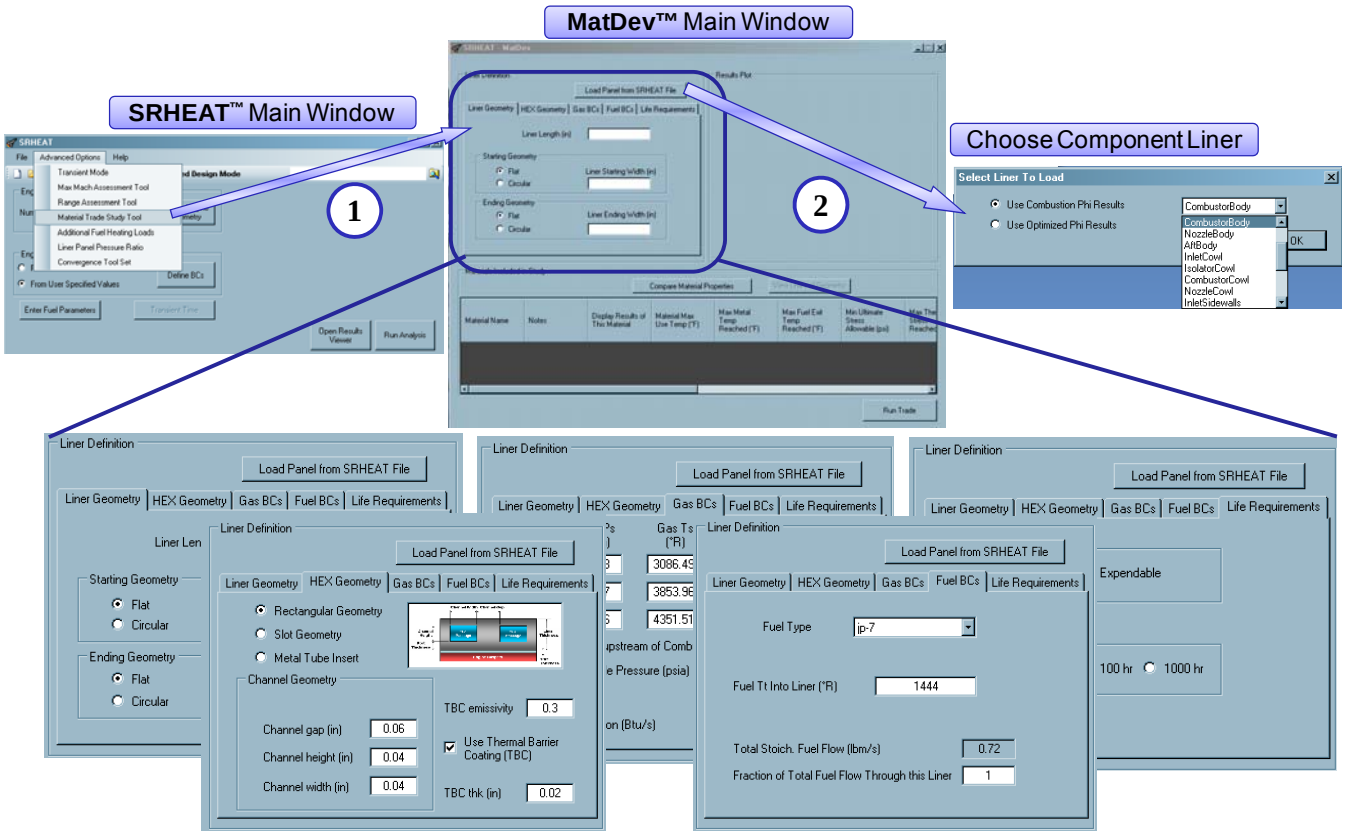


Figure 16: Input Conditions for MatDevTM Trade Study

At this point in the material development cycle, the materials engineer has changed the material properties but is uncertain if these changes will improve the material's performance or be a detriment. This is where *MatDev*™ can really pay off. By changing the properties as shown in Figure 17, the engineer can quickly find out if these changes are favorable or unfavorable for the engine design conditions for this liner system. Once these inputs were completed, *MatDev*™ was run and a solution was generated within seconds. Shown in Figure 18, Figure 19, and Figure 20 are the results of a trade study performed using *MatDev*™. These figures give an example of the output displays and the types of data that are generated.

The left side of Figure 18 shows the complete results output window generated for the inputs specified in Figure 16 and Figure 17. The lower section of the window (enlarged for clarity) shows the results summary for the three materials specified previously. In the upper right corner of the display, the results are shown in graphical form. As shown in Figure 18, there are several "material comparison" charts to choose from and four different graphical displays are enlarged for demonstration purposes. Each time a display is chosen, the materials are graphed in the upper right corner of the display in different colors so the user can compare each material. If so desired, the user can view all the materials at once or toggle any of the materials on or off by simply selecting the "display results" button.

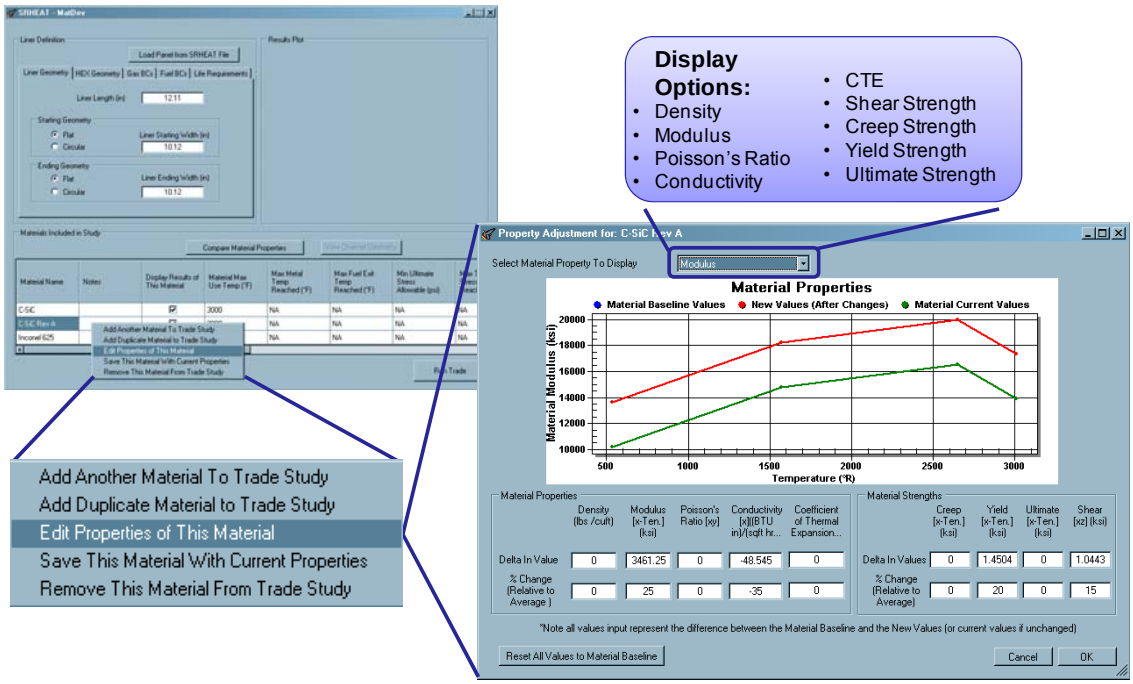
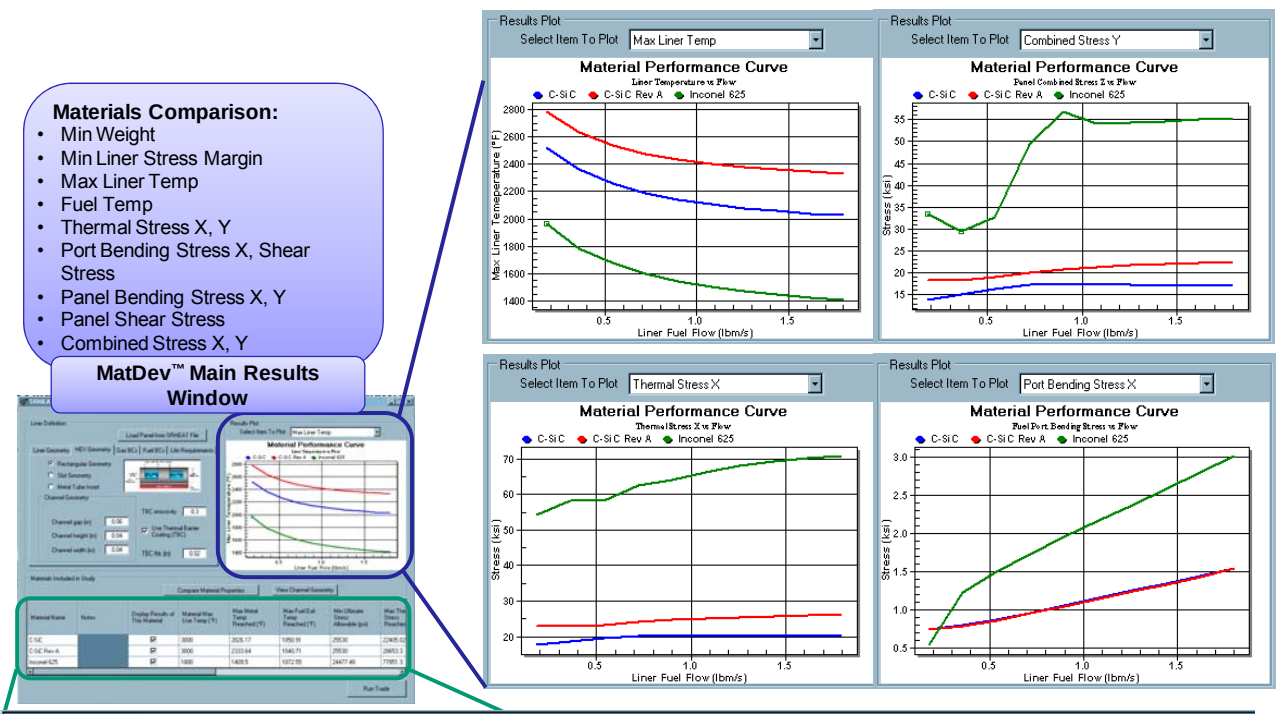


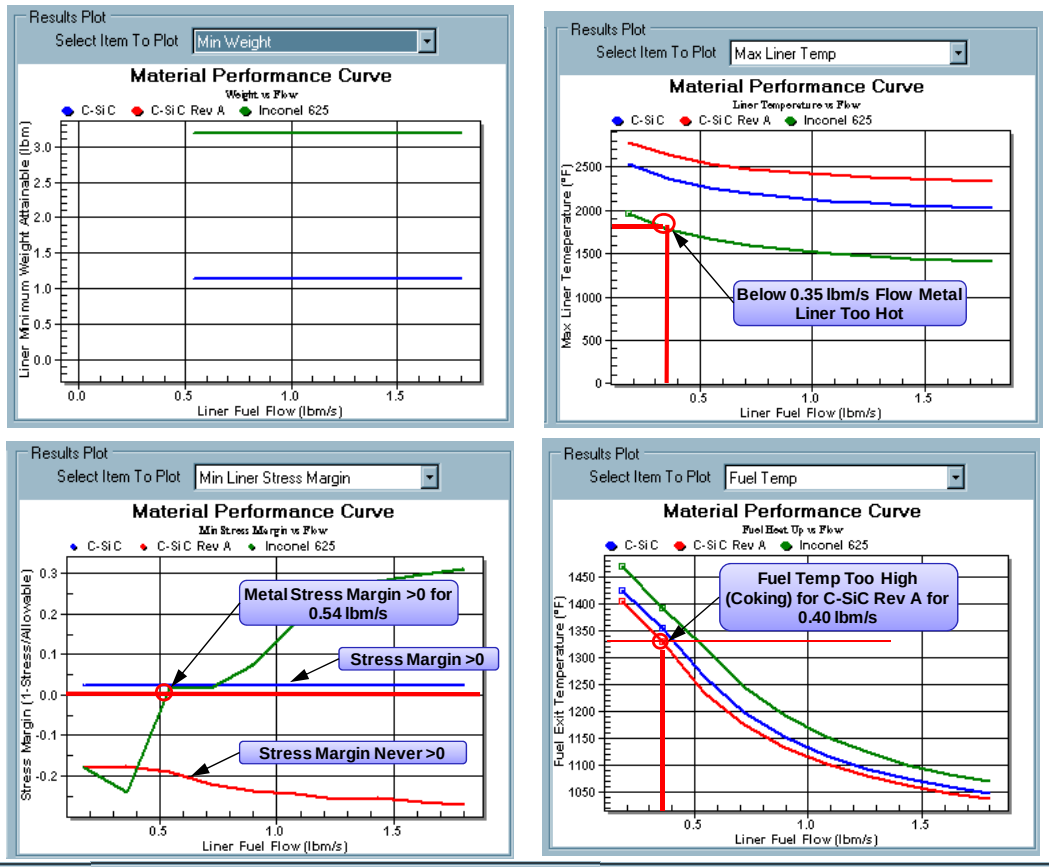
Figure 17: MatDevTM's Material Editor



Material Name	Material Max Use Temp (°F)	Max Metal Temp Reached (°F)	Max Fuel Exit Temp Reached (°F)	Min Ultimate Stress Allowable (psi)	Max Thermal Stress Reached (psi)	Max Mech Stress Reached (psi)	Max Combined Stress Reached (psi)	Max Liner Mass Flow (Acceptable Relative to Limits)	Min Mass Flow (Acceptable Relative to Limits)
C-SiC	3000	2024.84	1046.97	25530	22457.11	7983.4	17368.45	1.8	0.54
C-SiC Rev A	3000	2332.97	1036.73	25530	37599.29	10584.64	32417.59	NA	NA
Inconel 625	1800	1407	1068.68	24514.92	78141.64	83584.31	70841	1.8	0.54

Figure 18: Trade Study Results and MatDev™ Display

Not only will *MatDev*™ determine which materials successfully work for an input set of design constraints, it will also allow the user to investigate each design constraint, or requirement, in order to get a complete understanding of which material properties have the most/least margin and which ones are the most/least sensitive to adjustments in their values. Figure 18 and Figure 19 show an example of the post-processing that can be done using the results of a *MatDev*™ analysis. First, shown in Figure 19 is the *Results Summary* table which, for this example, indicates that two of the three materials provided successful liner designs for the "CombustorBody" over a range of fuel flow rates from 0.54 lbm/sec to 1.8 lbm/sec. The optimized liner geometry that corresponds to each material is also shown in this figure. The only material that did not produce an acceptable design was the "C/SiC RevA" that had the yield strength, shear strength, modulus, and conductivity changed relative to the baseline C/SiC material. At this point, it is important to understand why these changes in material properties did not produce a better design. Upon further review using a variety of *MatDev*™ tools, one can perform a thorough investigation into the results. As shown in Figure 19, one can determine that the Inconel 625 material produced a 3.2 lbm/ft^2 liner weight where the C/SiC produced a liner that weighed 1.2 lbm/ft^2 for the flow rates specified previously. By reviewing the "Min Liner Stress Margin" graph, the results show the "C/SiC RevA" never achieves a positive stress margin for the fuel flow range between 0.2-1.8 lbm/sec. Also shown in this chart is that Inconel 625 fails (stress margin < 0) below a fuel flow rate of 0.54 lbm/sec. However, the C/SiC material has a positive stress margin over the entire range of fuel flow rates. By reviewing the "Max Liner Temp" output graph, it can be concluded that the metal liner exceeds its temperature limit of 1800°F for flow rates below 0.35 lbm/sec whereas the composite materials stay within an acceptable temperature range for the entire range of fuel flow rates between 0.2-1.8 lbm/sec. The "Fuel Temp" chart shows that each liner material requires a different minimum fuel flow rate in order to keep the fuel from coking. For the composite materials, the minimum fuel flow rate is approximately 0.40 lbm/sec and for the metal it is approximately 0.50 lbm/sec. For the C/SiC this is important to know because even if the material strengths were improved or the stresses lowered, it is not a feasible design below 0.40 lbm/sec fuel flow rate because the fuel starts to "coke". For the metal design this is important to know because, even if Inconel 625 were to improve its stress margin for fuel flow rates below 0.54 lbm/sec, it could not produce a successful liner design below 0.50 lbm/sec because the fuel will also start coking due to the amount a heat being transferred through the metal liner into the fuel. This is vital to the material developer because *MatDev*™ provides insights into these various critical bounding constraints and notifies the developer that improving material properties further for this design will not help. The true limiting constraint at these low flow rates is fuel coking rather than material strengths.



Material Name	Material Max Use Temp (°F)	Max Metal Temp Reached (°F)	Max Fuel Exit Temp Reached (°F)	Min Ultimate Stress Allowable (psi)	Max Thermal Stress Reached (psi)	Max Mech Stress Reached (psi)	Max Combined Stress Reached (psi)	Max Liner Mass Flow (Acceptable Relative to Limits)	Min Mass Flow (Acceptable Relative to Limits)
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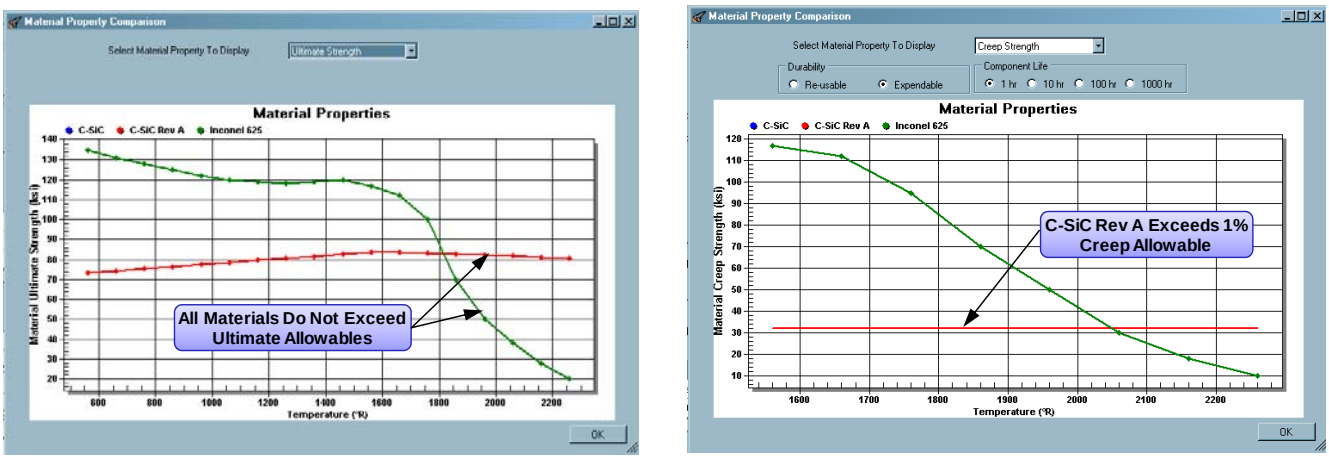
C-SiC Rev A	3000	2332.97	1036.73	25530	37599.29	10584.64	32417.59	NA	NA
Inconel 625	1800	1407	1068.68	24514.92	78141.64	83584.31	70841	1.8	0.54

Figure 19: Trade Study Results for Weight, Stress Margin and Temperature

However, to understand why the "C/SiC Rev A" material has failed due to stress margin, the material strength comparison charts must be reviewed (Figure 20). When comparing materials based on Creep Strength and Ultimate Strength, it can be seen that both versions of the composite materials have the exact same temperature dependent properties because these were not altered during the material development. Therefore, both material property curves are laying on top of each other in the graphs shown in Figure 20. When comparing the "Max Thermal Stress Reached" value to the Ultimate Strength material curves, one can determine that all three materials do not exceed their material allowables up to their "Max Metal Temperature Reached". However, when reviewing the Creep Strength comparison graph, the analysis shows that the "C/SiC RevA" failure occurs due to creep. By reviewing the results summary, it is shown that "Max Combined Stress Reached" for the C/SiC is 17,368 psi and for the "C/SiC RevA" is 32,418 psi. When compared to the Creep Strength of 32,000 psi for both of these composite materials, it shows that the "C/SiC RevA" fails due to creep whereas the C/SiC meets its margin. This is a very important discovery for the material developer because even though there has been an increase in yield strength in the "C/SiC RevA" composite over the baseline C/SiC it does not produce a better, lighter liner design. This is counter intuitive. This is a unique case where increasing a material's strength in one area indirectly produced a less structurally capable design.



Material Name	Material Max Use Temp (°F)	Max Metal Temp Reached (°F)	Max Fuel Exit Temp Reached (°F)	Min Ultimate Stress Allowable (psi)	Max Thermal Stress Reached (psi)	Max Mech Stress Reached (psi)	Max Combined Stress Reached (psi)	Max Liner Mass Flow (Acceptable Relative to Limits)	Min Mass Flow (Acceptable Relative to Limits)
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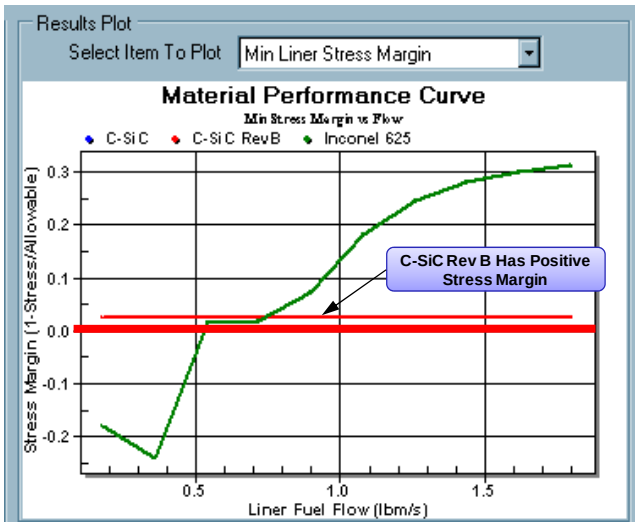
C-SiC Rev A	3000	2332.97	1036.73	25530	37599.29	10584.64	32417.59	NA	NA
Inconel 625	1800	1407	1068.68	24514.92	78141.64	83584.31	70841	1.8	0.54

Figure 20: Trade Study Results for Strength

For these types of cases, the insight provided by *MatDev*™'s material comparison charts is extremely useful for the user. Since the elastic modulus did increase due to the composite material changes, one might conclude that the increase in creep stress is due to the increase in elastic modulus of "C/SiC RevA". However, the increase in creep stress could also be due to the decreased thermal conductivity of the material. With so many possible material properties interactions, the "root cause" cannot always be achieved through engineering judgment alone. Again, this is where *MatDev*™ provides tremendous benefit. To further understand the material property interactions, another *MatDev*™ analysis was performed using the same three materials. However, this time the analysis was performed using "C/SiC RevA" with the same material modifications as used by the previous analysis except without decreasing the thermal conductivity. The trade study analysis was performed and the results are shown in Figure 21. This time the updated "C/SiC RevA" without a decrease in thermal conductivity produced an acceptable design throughout the same fuel flow range as used for the other two materials. Upon further inspection of Figure 21, it is shown that the "Max Combined Stress Reached" is equal to 20,820 psi compared to the previous stress of 32,418 psi. This new actual stress is below the Creep Strength limit of 32,000 psi, which now shows the "C/SiC RevA" as having a positive margin for stress. This positive stress margin is a direct result of the difference in thermal conductivities that translates into a decrease in "Max Thermal Stress Reached". Without the quick analysis and trade study capabilities of *SRHEAT*™/*MatDev*™, this conclusion might not have been determined until a much more costly and time consuming FEA analysis was completed. With *MatDev*™, the materials engineer has practically instantaneous feedback on the effects of the material properties modifications that have been made. This type of instantaneous feedback is invaluable for developing new or existing materials.

It is important to note that *MatDev*™ not only tells the user what changes affected the final design configurations but also what changes did not. For example, increasing the yield strength alone did not provide a decrease in stress margin or a decrease in weight of the final design. Even more interesting is the fact that increasing the shear strength also did not decrease the final design weight. Again, these types of answers provide the materials engineer with invaluable insights into what properties and characteristics are the most important for each application. These types of material property relationships could easily have been missed without the availability and use of *SRHEAT*™ and *MatDev*™. This is the type of discovery that could prevent significant amounts of research time and money from being wasted by focusing on solving the wrong problems. These tools provide tremendous value for guiding materials engineers in the development and customization of materials for hypersonic propulsion systems.



Material Name	Material Max Use Temp (°F)	Max Metal Temp Reached (°F)	Max Fuel Exit Temp Reached (°F)	Min Ultimate Stress Allowable (psi)	Max Thermal Stress Reached (psi)	Max Mech Stress Reached (psi)	Max Combined Stress Reached (psi)	Max Liner Mass Flow (Acceptable Relative to Limits)	Min Mass Flow (Acceptable Relative to Limits)
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Inconel 625	1800	1407	1068.68	24514.92	78141.64	83584.31	70841	1.8	0.54

Figure 21: Additional Trade Study to Assess Sensitivity to Thermal Conductivity

IV. Conclusion

A module has been developed as an add-on for *SPIRITECH*'s Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) code that enables a user to perform material trade studies for high temperature heat exchangers. This module, *MatDev*™, is capable of comparing different types of materials, including high temperature metal alloys and high temperature orthotropic materials. Because *MatDev*™ brings composite material analysis capabilities to *SRHEAT*™, it enables the code to evaluate critical laminate stresses like interlaminar and biaxial stresses in addition to time dependent stresses like 1% creep and creep rupture. This combined analytical model provides a multidisciplinary system level thermal analysis tool that balances the heat load from the gas path, through the liners, and into the fuel.

MatDev™ is user-friendly, trade study design tool that continues the "ease-of-use" focus that is indicative of the main *SRHEAT*™ software. Its architecture is designed with the flexibility to run single component or large system trade studies quickly and efficiently. More importantly, *MatDev*™'s trade study capabilities provide tremendous insight into liner designs for hypersonic flight. It is also an invaluable tool for someone designing and developing new, advanced, high temperature materials. *MatDev*™ easily performs sensitivity trade studies so adjustments in material properties can be evaluated in terms of their system level impacts. *MatDev*™'s multidisciplinary approach allows an engineer to simultaneously assess the impacts on critical system level parameters (fuel flow rates, liner temperatures, fuel coking limits, stress limits, etc) due to a variety of loading conditions (thermal, mechanical, aerodynamic). *MatDev*™'s post-processing capabilities offer tremendous insights into each design parameter (stress, temperature, etc) so that an analyst can determine the margin each parameter has in order to understand which design and/or material parameters are limiting the design configuration. By strategically using *MatDev*™'s features and capabilities, one can determine the true "root cause" of a design or material failure which, in turn, provides timely, essential information and direction for further design and material development. This translates into tremendous time and cost savings.

V. Acknowledgment

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