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Development of a Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*^{TM})

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A Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*^{TM}) has been developed for rapid analyses of complex thermal cooling systems. Thermal management is critical to the development of dual-mode scramjets for hypersonic aerospace propulsion, which have high thermal loading with limited availability of heat sink sources. It is necessary that rapid trade studies of the thermal management system be accomplished to optimize the system for weight and cooling efficiency. To meet this need, *SPIRITECH* has developed a scramjet/ramjet heat exchanger design and optimization tool that performs a thermal analysis of the heat exchanger, assesses its structural strength, and optimizes the heat exchanger design to minimize the cooling flow requirement and the heat exchanger weight. Radiation, conduction, and convection are all included to accurately model this complex aero/thermal system. The user can select the coolant/fuel from various jet fuels (with endothermic properties) or common combustible fluids (H_2 & CH_4). In addition, the option for several high temperature materials are included. The code is packaged with a user-friendly interface to simplify its use within large trade studies. The detailed heat exchanger design features included in the code (i.e. geometry, material properties, fuel/coolant properties, etc.) make *SRHEAT*^{TM} a valuable tool in scramjet and hypersonic vehicle development, providing the low cost analytical capabilities that make possible the efficient development of aerospace components.

Introduction

Managing the heat load to critical engine components remains a significant challenge in the design and operation of a hydrogen or hydrocarbon-fueled hypersonic vehicle. Passive and active methods can be used for heat-load management. One method for active cooling is to flow fuel through critical areas of the engine structure using its 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*^{TM})[1] provides the heat exchanger 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.

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The Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) is comprised of several modules

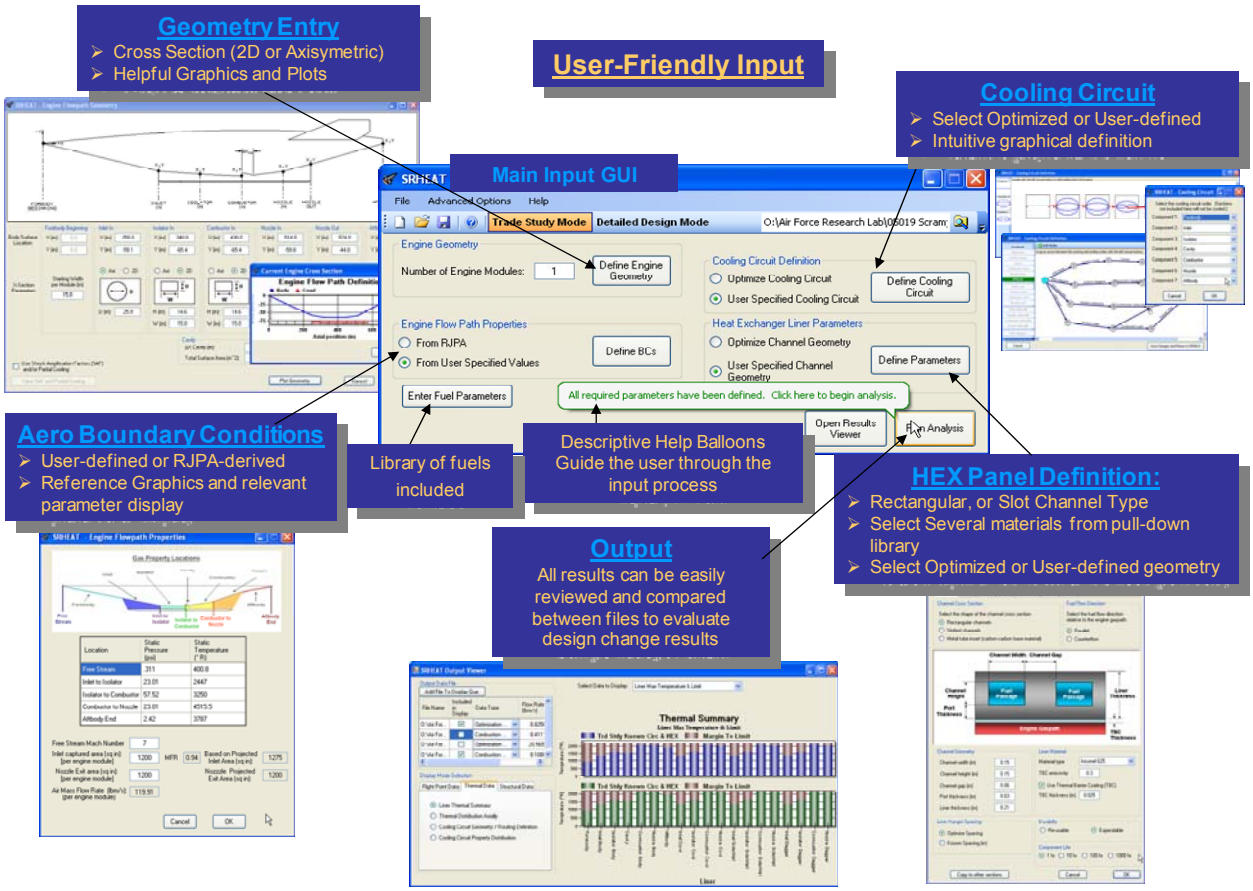
- **Thermal Module** calculates heat flux and temperature distribution within the heat exchanger panels.
- **Flow Module** calculates fluid boundary conditions within heat exchanger panels, and fluid property distribution through a cooling circuit, including frictional losses and heating effects.
- **Engine Performance Module** calculates hot gas boundary conditions for heat exchanger panels and property distribution throughout the engine.
- **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 employ the input from a user friendly interface to evaluate the design of the user-defined heat exchanger. Also, when directed by the user, the tool analyzes the heat exchanger performance over a range of design parameters and selects an optimum design.

The significant advantages of this model are:

1. User-friendly interface
2. Modeling technique yields fast and accurate results
3. Automatic system optimization

The user-friendly interface includes a series of input forms containing information which allows the user to identify engine geometry, flight point, fuel type, material selection, cooling circuit routing, and heat exchanger panel geometry.



Technical Discussion

SRHEAT™ is a user-friendly design tool developed with ease-of-use as a primary focus. A series of input forms provide easy entry of all of the parameters needed for analysis. Using advanced optimization techniques developed within *SPIRITECH*, the code can identify both the optimum channel geometry and cooling circuit, or the user may select to run a specific configuration at off-design conditions. The analytical approach utilized in *SRHEAT*™ is summarized below.

Code Architecture

Definition of the basic logic architecture, which satisfies system energy balance during convergence within an iterative approach, is shown in Figure 1. The solution provides distributions for material temperature, fuel coolant properties, and hot gas path property throughout the system. Note that the main logic structure calls upon several sub models which perform specific analyses on a particular aspect of the full system.

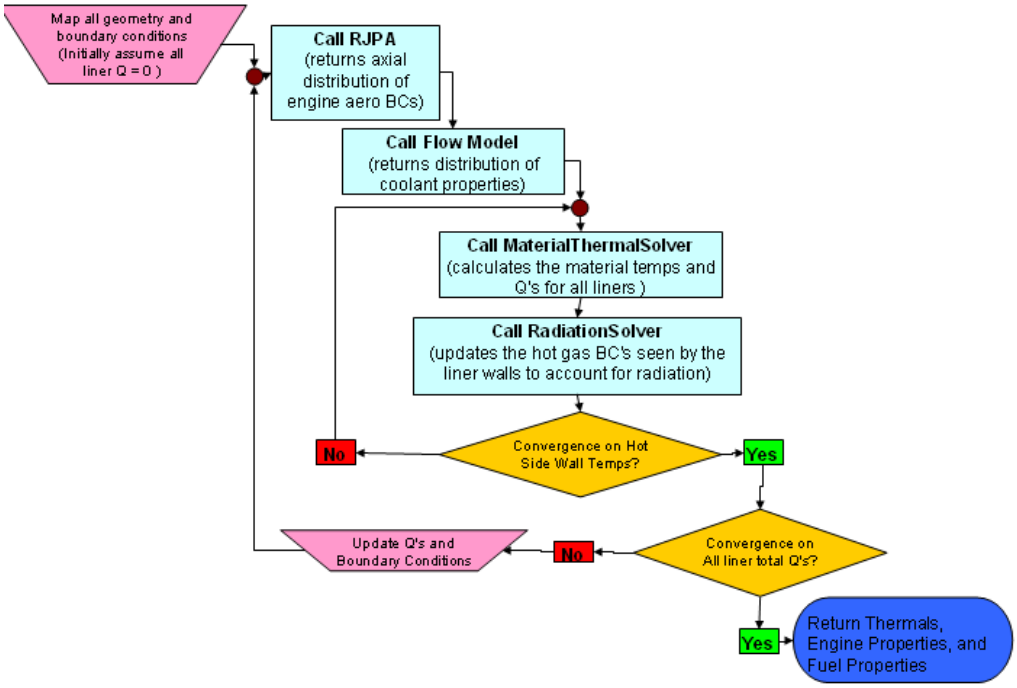


Figure 1 - *SRHEAT*™ Logic Diagram

RJPA Interface

The calculation of the scramjet/ramjet propulsion system boundary conditions within *SRHEAT*™ has been automated through the incorporation of the Ramjet Performance Analysis (RJPA) code, a one-dimensional integral simulation code for determining ramjet performance. Keeping with the user friendly principle, the text input file normally required to run RJPA is automatically generated by *SRHEAT*™ based on the user entry within the GUI. During analysis, *SRHEAT*™ runs RJPA with this text input file and automatically sorts through the resulting RJPA text output file to map relevant information into the analysis. An important note is that the user is not constrained to the use of RJPA. The results of any external analysis on the flow path can be easily incorporated using the option for *User-Specified Boundary Conditions* and its associated user-friendly form.

The user input for RJPA is a single form with input separated into groupings (see Figure 2). These groupings contain the required flight point and performance inputs for each engine section. An important note is that the RJPA executable is not included with *SRHEAT*™. To use RJPA within *SRHEAT*™, the user must locate the local directory which contains the user's installed copy of RJPA and the corresponding JANNAF chemical database file.

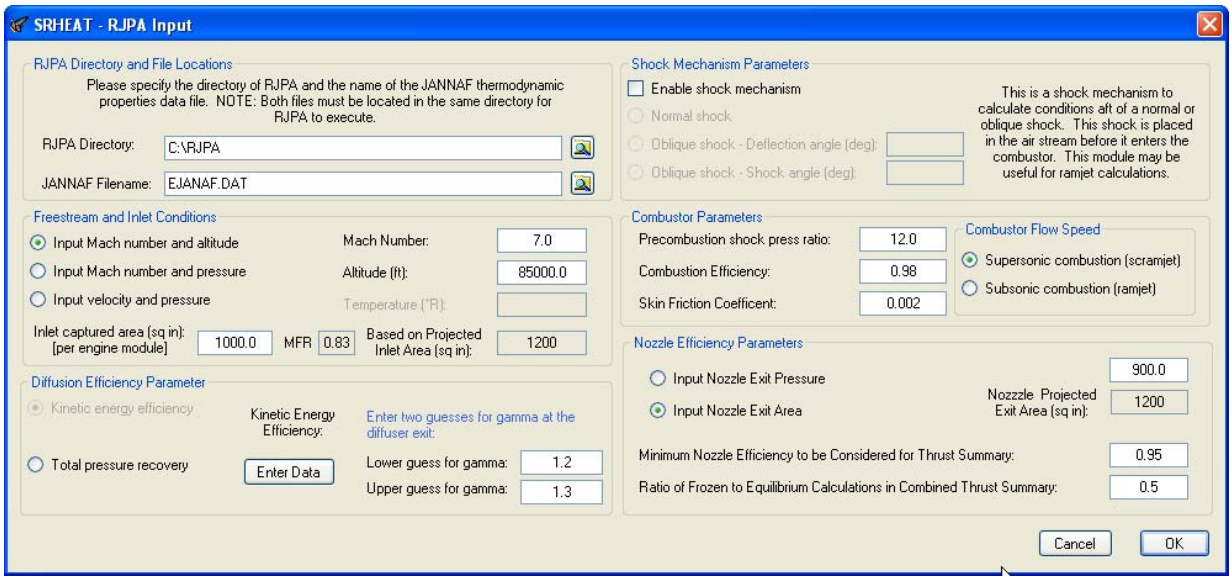


Figure 2 – RJPA Input Form.

Input to the RJPA form has been kept to a minimum to facilitate ease of use. Also, to simplify user entry, all data fields are labeled with descriptive terminology and arranged using an intuitive format. The engine geometry relevant to inlet captured area and nozzle exit area specified within the *SRHEAT*™ geometry form is displayed on the RJPA input form for user reference. Note that the required RJPA input of engine geometry is defined within the *SRHEAT*™ geometry form and is not repeated here to eliminate redundancy. The RJPA input is automatically generated for the diffuser, combustor, and nozzle based on *SRHEAT*™'s geometry input.

Calling RJPA within *SRHEAT*™ provides the capability of performing a complete thermal balance. RJPA accounts for the effect of heat leaving the propulsion system as well as the increased temperature of the incoming fuel. *SRHEAT*™ accounts for the heat absorbed by the fuel in the heat exchanger panels, thereby balancing the heat flow at the system level. It is important to note that analyses performed using the optional *User-Specified Boundary Conditions* will not model these affects.

Thermal Module

SRHEAT™ provides a system-level analysis of the thermal management system for scramjet/ramjet propulsion systems. The thermal analysis accounts for a complete thermal balance, including the heat loss from the propulsion system hot gas to the fuel, the temperature rise of the fuel, and the effects of fuel injection temperature on combustion gas properties. As mentioned, the propulsion system engine gas path conditions are calculated using RJPA. The fuel circuit is modeled using a 1D compressible flow model. The thermal circuit is modeled using advanced algorithms for radiation and convection from which boundary conditions are mapped to a two-dimensional finite-difference conduction model. Material options permit the use of a different material for each heat exchanger liner component, including the option for a thermal barrier coating (TBC) on the hot surface of the liner. Built-in temperature dependent properties libraries are automatically linked to the material selection.

Coolant Flow Model

A detailed 1D compressible flow model is included in *SRHEAT*™ for modeling the fuel cooling circuit. This detailed flow model calculates the pressure drop and temperature rise throughout the fuel cooling system due to frictional losses and heating boundary conditions, respectively. This information provides pump sizing criteria, pressure loading for the structural analysis, and fuel side thermal boundary conditions. The use of a detailed flow model enables high fidelity heat transfer calculation and facilitates the construction/modeling of any generic cooling circuit, which allows fine-tuning of the cooling circuit to reduce cooling requirements. To simplify the user interface, the user is given the option to define the cooling circuit with predefined circuit templates. In the *Trade Study* mode of operation, the circuit definition is further simplified by combining the sidewalls, body, and cowl

panels for each engine section into a single component. However, in the *Detail Design* mode of operation, the user is permitted complete freedom in defining the desired flow circuit.

SPIRITECH's incompressible flow model was developed using an electrical circuit analogy. When using an electric analogy for flow analysis, the resistance is defined as:

$$R_f = \frac{\Delta P}{\dot{m}}$$

The flow network is defined with nodes which link circuit elements. Each circuit element then has an associated resistance to flow, so the magnitude of flow through a path within the circuit is based on its resistance relative to the resistance of the rest of the circuit. Solving the set of simultaneous equations linking all resistances between nodes allows calculation of flow, pressure, and temperature throughout the flow circuit.

The graphical flow circuit input form allows the user to design and review the flow network at a glance. A screenshot of the flow model GUI is shown in Figure 3.

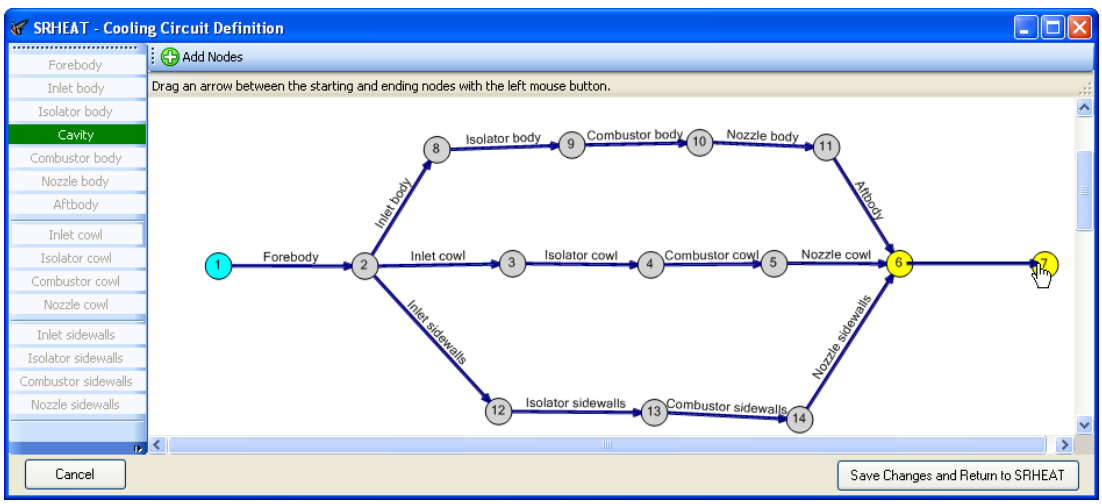


Figure 3 - Graphical User Interface for Flow Model with Known Circuit Order

A separate graphical user interface is included to handle cases where the flow model circuit order is to be optimized. This user interface is based on a "building block" approach wherein the user arranges sub-circuits composed of pre-defined templates. Each template contains paths which may include several elements in series. The building block model GUI, shown in Figure 4, allows the user to construct the cooling circuit in a methodical manner so that the code may automatically make ordering changes to minimize cooling flow requirements.

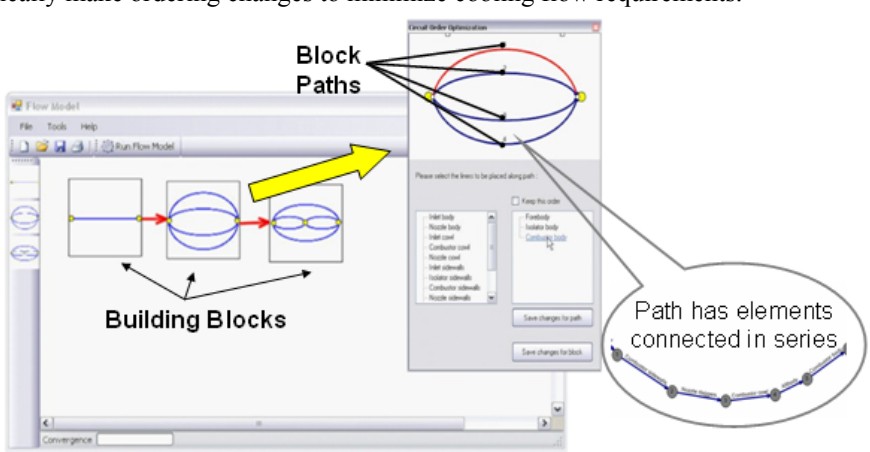


Figure 4 - Graphical User Interface for Flow Model with Optimized Circuit Order ("Building Blocks")

The flow model determines the fluid phase throughout the network based on the nodal temperatures and pressures. At temperatures below the fuel's critical (two phase dome) temperature, the fuel is assumed to behave as an incompressible liquid. At temperatures above the critical temperature, the fuel is assumed to be a quasi-ideal gas; i.e. local variations in fluid properties such as specific heat ratio and density are taken in account, but the ratio of total-to-static conditions is assumed to follow ideal gas behavior. It is assumed that the pressure is always above the critical pressure and that two-phase flow is not present.

Conduction Model

The temperature distribution through the liner is calculated by applying the relationship

$$q = \frac{k}{L}(\Delta T)$$

for a set of simultaneous equations representing the nodal temperatures of a 2-D grid. A finite-difference solver is used for solving the matrix of simultaneous equations governing heat flow. The grid is shown in Figure 5 for a slotted channel liner. In addition to handling rectangular and slotted channel geometries, the 2-D heat conduction model also allows the use of metal tube sleeves within the base liner material, providing the ability to analyze non-metallic liners which incorporate metallic sleeves around the flow channels (Figure 6).

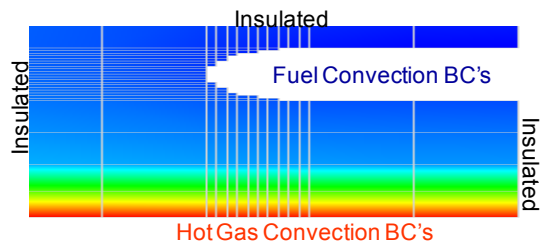


Figure 5 - Grid Definition for Slotted Channel Geometry

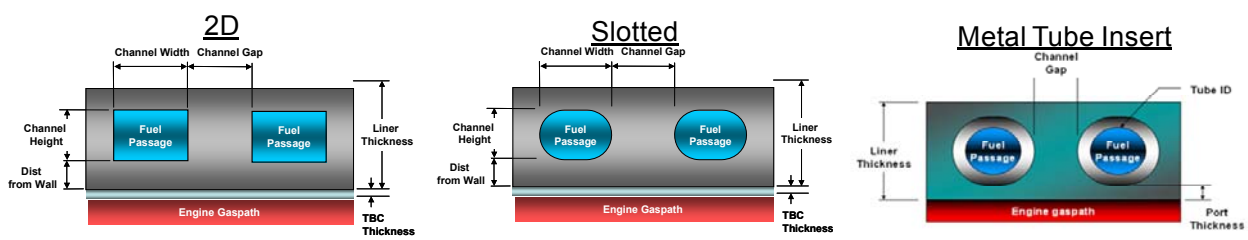


Figure 6 - HEX Liner Cross Sections

Convection Model

Within the fuel passage of the heat exchanger liner, *SRHEAT*™ calculates the heat transfer coefficient based on thermal data for small scale heat exchanger channels as documented by Natman and Sturgis[2]. The objective of this research, conducted at Edwards AFB, was to develop heat transfer correlations for use in high aspect ratio coolant channels having conducting sidewalls and subjected to asymmetric heating. The test panel incorporated milled-slot liner channels similar to those incorporated within *SRHEAT*™. Correlations for Nusselt number were developed as functions of Reynolds number, Prandtl number, ratio of viscosities, channel aspect ratio, and axial location based on experimental data acquired in a straight channel with a turbulent flow of water. The data analysis examined different characteristic lengths, temperatures for property evaluation, axial locations, and functional forms. The Nusselt number correlation developed from this test data accurately predicted 95% of the data to within ±10%.

The documented correlation, omitted from this paper due to ITAR restrictions, was developed for fluid properties evaluated at the bulk temperature and for channel geometry defined by hydraulic diameter. The aspect ratio, AR, is defined as:

$$AR = \frac{H_{channel}}{W_{channel}}$$

For the hot side of the heat exchanger liner, the heat flux is calculated based on the local skin friction coefficient. The derivation of this approach is summarized. The Stanton number, which normalizes the convective wall heat transfer to the external flow enthalpy flux based on the wall conditions, is given by

$$St = \frac{q_{c,w}}{\rho_e u_e (h_w - h_{aw})}$$

Where $q_{c,w}$ is the convective heat flux at the wall, ρ_e is the density at the edge of the boundary layer, u_e is the velocity at the edge of the boundary layer, h_w is the hot gas enthalpy at the wall, and h_{aw} is the hot gas enthalpy at an adiabatic wall.

Using the modified Reynolds analogy, the Stanton number is related to the skin friction according to

$$St = \frac{C_f}{2Pr^{2/3}} \qquad \text{which is valid for } 0.6 < Pr < 60$$

Combining these relationships results in the following equation for heat flux:

$$q_{c,w} = \frac{C_f \rho_e u_e}{2Pr^{2/3}} (h_w - h_{aw})$$

SRHEAT™ accounts for increases in the convection coefficient due to the local shock structure. This "*shock amplification factor*" (SAF) has been incorporated in a manner that provides the user with the capability to specify the shock amplification factor along with a distinct "affected area". Two options for expressing SAFs have been included:

- Option #1 specifies a percentage of affected area within a component and is valuable for quick evaluations when specific locations are not known
- Option #2 specifies the affected region as range of axial locations and is used if specific SAF locations are available

The shock amplification factor is applied as a multiplier to the heat flux according to

$$q_{c,w} = (SAF) \frac{C_f \rho_e u_e}{2Pr^{2/3}} (h_w - h_{aw})$$

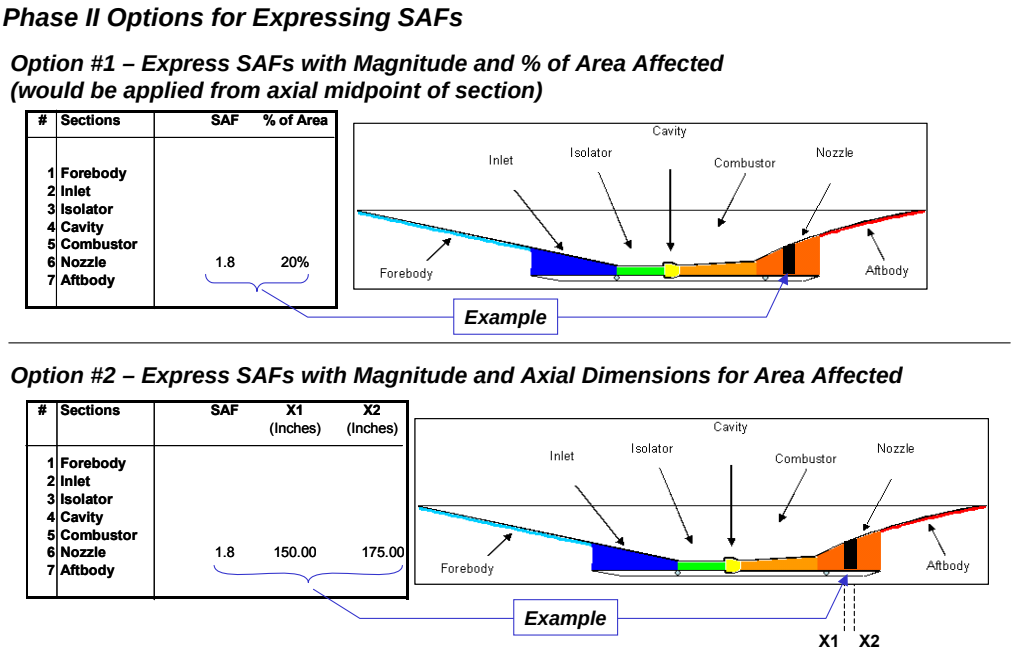


Figure 7 - SRHEAT™ Phase II Code SAF Application Options

Radiation Model

The effects of thermal radiation include the net heat transfer to a liner from two sources. The first of these is the high intensity emission from the hot combustion gasses to a liner (gas-to-wall radiation) and is given by the relationship:

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

The second is the coupled interdependent network of emission and absorption between all of the liner surfaces (wall-to-wall radiation) and is given by:

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

The hot combustion gasses contribute a sizable quantity of thermal radiation to all of the liner surfaces for which it is visible. Gas radiation modeling is performed using the method of Leckner[3]. This model incorporates a polynomial curve fit of the emittance curves for carbon dioxide and water vapor (major radiatively participating constituents). The surface-to-surface radiation model incorporates a geometric analysis to determine the view factor for each surface. The view factor is a geometric quantity that is used to determine the radiant exchange of energy between multiple surfaces. View factor equations have been developed for 2D propulsion system geometries from basic view factor equations, as shown in Figure 7. The Zonal method of radiation heat exchange is used to calculate the net radiative heating load on each liner using a matrix of simultaneous equations, which includes the effect of the gas on the total emitted and absorbed energy.

$$\sum_{j=1}^{N}\left(\frac{\delta_{kj}}{\varepsilon_j} - F_{k-j}\cdot\frac{1-\varepsilon_j}{\varepsilon_j}\cdot\tau_{gas(k-j)}\right)q_j = \sum_{j=1}^{N}\left(\left(\delta_{kj} - F_{k-j}\cdot\tau_{k-j}\right)\sigma\cdot T_j^4 - F_{k-j}\cdot\alpha_{gas}\cdot\sigma\cdot T_{gas}^4\right)$$

$$\delta_{kj} = \begin{cases} 1 & k=j \\ 0 & k\neq j \end{cases}$$

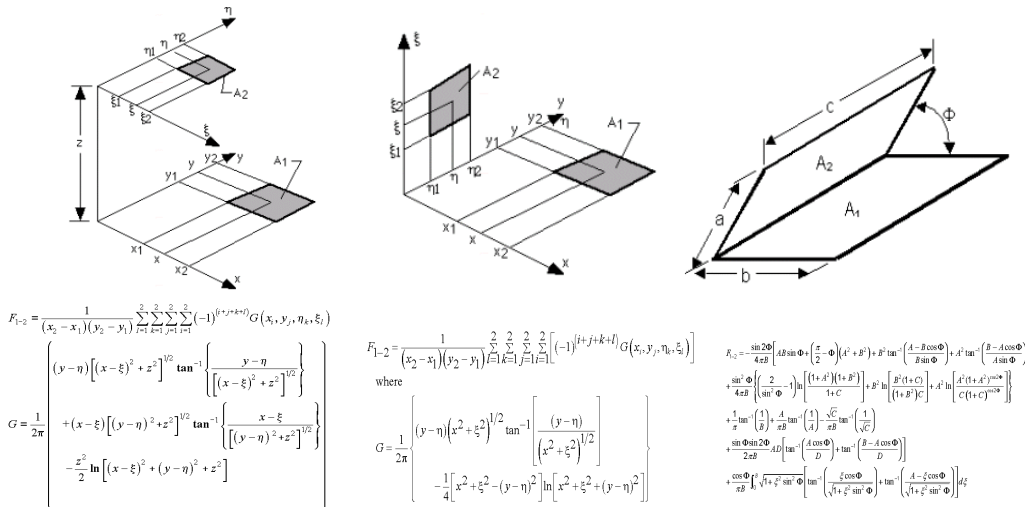


Figure 8: Examples of Generic Geometric Cases Incorporated in the View Factor Library

Structural Module

The structural module incorporated within *SRHEAT*^{TM} was developed to examine heat exchanger panel stresses due to the panel's pressure loading and thermal gradient and to design the liner panel to meet life requirements. The predicted stresses are compared to the applicable material allowables evaluated at the appropriate metal temperatures provided by the thermal module. If the stress is found to be above yield during optimizations, then the structural module iterates to determine the minimum panel thickness at which the yield stress is achieved. This additional thickness is added to the cold side of the panel so as not to affect the heat transfer results. Once the minimum thickness is known, a weight per unit area of liner is calculated and output for evaluation and comparison.

The *SRHEAT*^{TM} structural analysis module analyzes a given geometric HEX liner structure (Flat Plate or Cylindrical), along with the boundary conditions provided by the other *SRHEAT*^{TM} modules, to determine a minimum liner weight that meets structural allowables for a given material system. The HEX liner panel geometry to be analyzed includes liner thickness, attachment spacing, and cooling passage geometry, all of which are input by the user or are optimized based on system parameters. The algorithm for the structures module is illustrated in Figure 9.

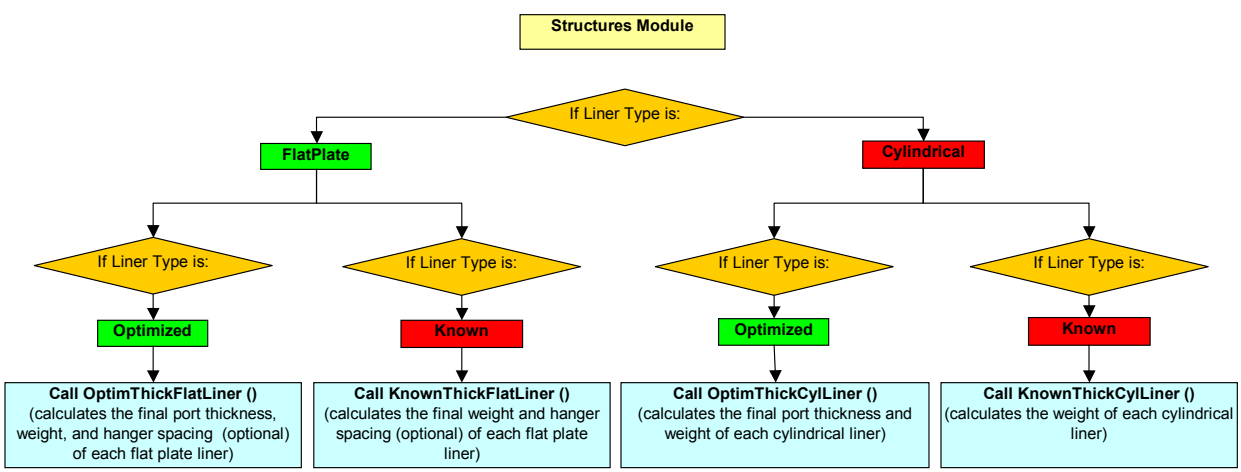
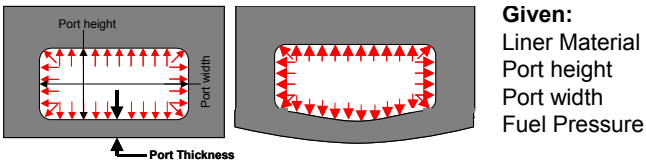


Figure 9 - *SRHEAT*^{TM} Structural Analysis Algorithm

The *SRHEAT*^{TM} structural module evaluates three liner stress "drivers" of typical HEX liner panels and sizes the liner geometry parameters accordingly to meet specified material allowables. The stress drivers include:

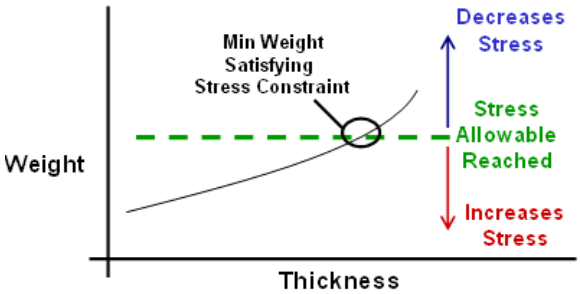
1. **Cooling Channel Static Pressures**
   (Port thickness sizing)
2. **Static ΔP across the HEX Panel**
   (Overall panel thickness sizing and fastener spacing)
3. **HEX Panel Thermal Gradients**
   (Thermal stress effects due to through-thickness gradients)

Cooling Channel Fuel Flow Static Pressure Stress



The structural module incorporated within *SRHEAT*™ examines the bending stresses of the heat exchanger panel that exist in the liner surface (port) as a result of the high pressure in each of the cooling channel slots. Since the stress is a function of fuel pressure and the cooling channel geometry, maps of stress as a function of fuel pressure and cooling channel height, gap, and width were generated and incorporated within *SRHEAT*™. These maps are used during code execution to calculate the stress from the known geometry and fuel pressure. The resulting stress values are then compared to material allowables. As a lower bound on port thickness, a minimum-manufacturing limit is imposed. The port thickness is incrementally increased relative to the minimum thickness until the material stress allowable is achieved.

Hot Gas Flow Static Pressure Stress on Liner Panel



The structural module incorporated within *SRHEAT*™ also predicts the heat exchanger panel stresses that result from the hot gas-side pressure acting on the overall panel. The structural analysis for flat plate liners includes the stress effects of both the liner thickness and attachment spacing. The relationship between liner thickness and attachment spacing is determined from a structural analysis that compares the liner stress to the max allowable stress within the HEX liner panel due to pressure and thermal loads. The structural module iterates on liner thickness and attachment spacing to ensure that none of the allowables are exceeded. Since the weight of the liner increases with increased thickness and the total weight of attachment hardware decreases with increased spacing, there exists an optimum combination for minimum weight. The structural routine determines this optimum combination (minimum weight) as a function of the material properties and boundary conditions.

Liner Panel Thermal Gradients

SRHEAT™ examines the thermal gradient stresses in the HEX liner panel caused by the disparity in temperatures between the hot gas side and coolant passages of the liner. This "through-thickness" gradient causes a large stress due to the in-plane thermal growth differences on the panel. As the code is calculating a system wide solution, the HEX panels are checked for excessive thermal gradient stresses. When an excessive thermal gradient stress is determined, the code has the ability to modify system variables (geometry, fuel flows, material data) to achieve acceptable thermal stresses.

Incorporation of User Specified HEX Panel Application & Life Options

The user is provided the option to select between 1, 10, 100, and 1000 hrs of application life in either an "expendable" or "reusable" design class. The creep evaluation feature provides the user with the ability to set design constraints to prohibit detrimental creep from occurring in a given design configuration.

Carbon-Carbon Material

A single, carbon-carbon (C-C) material option has been included in the materials available in *SRHEAT*™. The selected C-C material is a high-conductivity variant to facilitate its usefulness in a heat-exchanger panel application. In keeping with the durability option scheme adopted for metals, the C-C material is provided both an "expendable" and a "reusable" set of properties varying by usage temperature and strength. Although composite materials are very application-specific regarding weave, fiber volume, lay-up architecture, etc., the C-C materials within *SRHEAT*™

provide the user with a good "first-look" at the design implications of using a C-C material in the heat exchanger application.

Flat Panel Liner Stress Assessment

In order to accurately predict the panel stresses due to static pressure loading, the stress calculation includes the 3D pillowing effects of a liner panel on a "bed" of fastener posts. The analysis approach calculates the high stresses that occur near the edge of the fasteners as the liner panel deflects due to static pressures. These fastener edge stresses are generally higher than the peak stresses that would occur at the center of 4 fasteners in a square pattern. As seen in Figure 10, the code-calculated stresses are in agreement with the ANSYS verification model stresses.

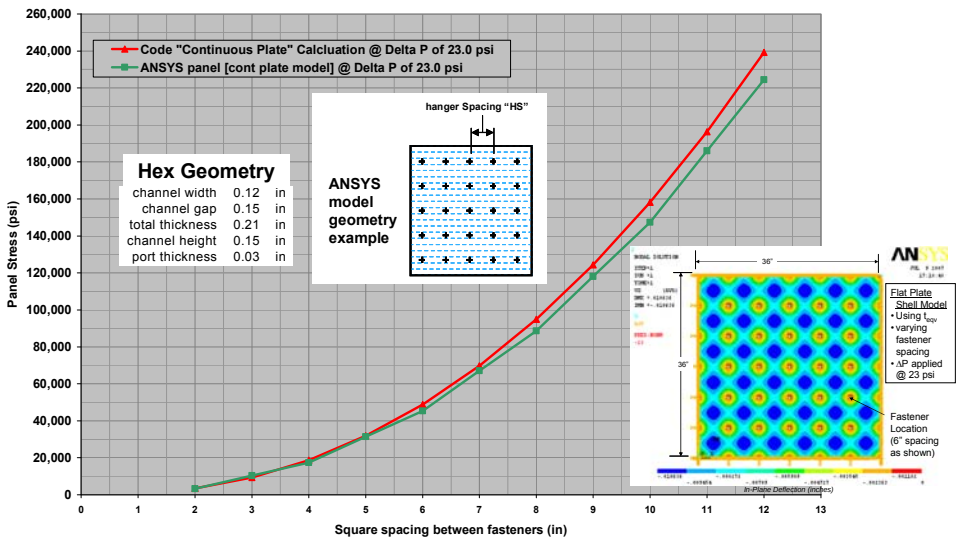


Figure 10 - Comparison of Code-Calculated Stress vs. ANSYS Verification Model

Optimizer Module

A module of the code was developed to optimize the coolant circuit order and heat exchanger coolant passage geometry to minimize cooling flow requirements. The basis for optimizations is the minimization of ϕ, where ϕ is defined as a normalized fuel flow ratio according to:

$$\phi = \frac{\dot{m}_{cooling}}{\dot{m}_{stoichiometric}}$$

The routines to optimize coolant circuit order and channel geometry for minimum cooling flow requirement have been documented in detail by Gamble and Giel[4] and are not included in this paper.

Material and Fuel Libraries

SRHEAT™ employs data libraries specifying material and fuel properties. By including these properties internal to the code the user is never burdened by the input of property data or any unit conversion of that data.

SRHEAT™ Materials Library Includes	Properties Include:
Inconel 625	Modulus of Elasticity
Inconel 718	Density
Hastelloy X	Poissons Ratio
Haynes 188	Conductivity
Haynes 230	Coefficient of Expansion
Haynes 282	Yield Strength
Waspaloy	Ultimate Strength
Carbon-Carbon Composite	1% Creep Deflection Strength
	Creep Rupture Strength

A library of typical fuels utilized in advanced aerospace applications has been incorporated within the *SRHEAT™* code. The appropriate fuels and corresponding properties were compiled under close coordination with AFRL (Dr. Tim Edwards).

SRHEAT™ Fuel Library Includes	Properties Include:
JP7	Density
JP8+100	Thermal Conductivity
JP10	Viscosity
RP-1	Specific Heat
N-Octane	
Liquid H2	
Liquid Methane	

Pressure- and temperature-dependent fuel properties have been generated for use in the coolant flow model. Density, viscosity, thermal conductivity, and specific heat (constant pressure) were among the properties generated for the fuels JP7, JP8, JP10, N-Octane, Hydrogen, Methane, and RP-1. The properties of the cryogenic fuels Hydrogen and Methane, which are pure fluids, were generated using SUPERTRAPP and the web-based program "NIST Chemistry WebBook." The Chemistry WebBook models were used since they are more accurate for these particular fuels. The properties for all the other fuels were generated using SUPERTRAPP. Surrogate mixtures were required when modeling JP7, JP8, and RP-1 since these fuels consist of many constituents. The surrogate mixture for JP7 and JP8 was defined by Huang and Sobel[5] while that for RP-1 is defined by Edwards and Maurice[6]. The mixture for RP-1 was modified relative to that defined by Edwards and Maurice to accommodate limitations within SUPERTRAPP. Dr. Marcia L. Huber of the Physical and Chemical Properties Division at NIST provided guidance in defining the RP-1 surrogate.

SRHEAT™ Validation

Parallel Liner Design

To validate the analytical computations and to ensure the HEX panel design features within *SRHEAT™* appropriately follow traditional design methods, a hypersonic vehicle cooling panel was designed in detail for a specific two-dimensional nozzle sidewall panel configuration (shown in Figure 11). The validation consisted of completing a design of the panel using conventional methods/analysis and comparing the results of these analyses with those obtained using *SRHEAT™*. The objectives of the validation design effort are summarized as follows:

Parallel Design and Code Validation Objectives:

1. Verify assumptions within code and determine impact on final design configuration.
2. Verify code output is comprehensive for providing product definition.
3. Compare code structural output and weight predictions to those predicted in detailed design effort.
4. Assess differences between code output and design results and provide list of recommendations/improvements.

Panel Selection – Nozzle Sidewall

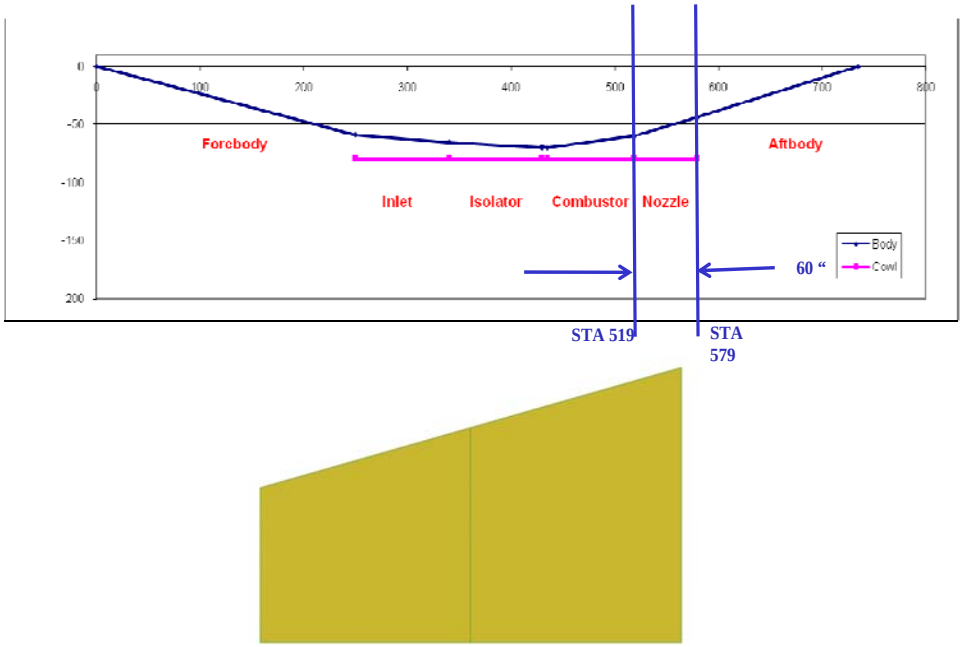


Figure 11: Two-Dimensional Nozzle Sidewall Panel Selected for Parallel Design

A detailed breakdown of the conventional HEX panel design process was compiled (as shown in Figure 12) to serve as the outline for the parallel design and code validation effort. The results of these specific elements provide the basis of the *SRHEAT*™ validation.

Comparison – Typical HEX Panel Design Compared to SRHEAT™

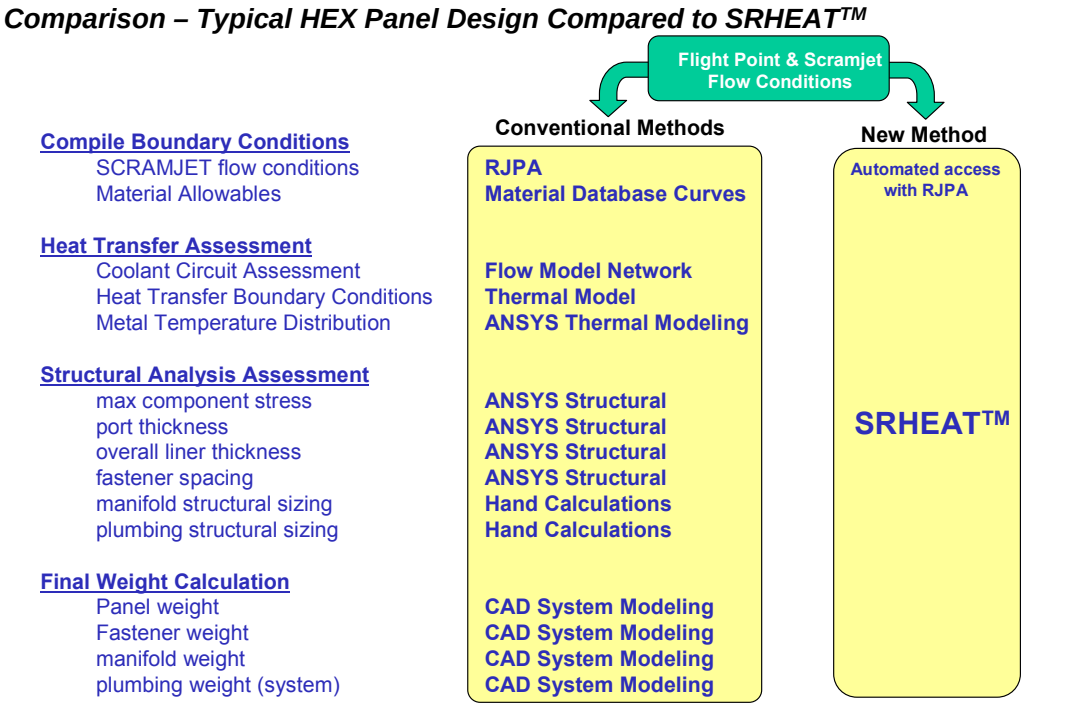


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Figure 12: Elements of Conventional HEX Panel Design Process and Methods

The following are detailed comparisons of each of the four elements of the parallel design and code validation effort outlined above;

1. *Compile Boundary Conditions Comparison*

RJPA - Although RJPA was not developed by *SPIRITECH*, the calculation of the scramjet/ramjet propulsion system boundary conditions within *SRHEAT*™ are provided through RJPA analysis via programmed mapping routines and text file generation. To ensure that RJPA produces the same output when called by *SRHEAT*™ as it would during standard execution, the example input files provided with the distributed copy of RJPA were entered into *SRHEAT*™. Since the fuel used in some of these example input files is different from the fuel used in *SRHEAT*™, the code was temporarily altered for these validation cases and the fuel data from each example file was hard-coded in.

The EXAMPLE3 input file was used for the validation since it was a ramjet example using a hydrocarbon fuel. Validation was made by simply ensuring that the input file created by *SRHEAT*™ contains the correct data in the correct formatting as the input file provided with the distributed copy of RJPA. As shown in Figure 13, the plug-in does generate an input file identical to the EXAMPLE3 input file, confirming that *SRHEAT*™ may be used to call RJPA and accurately calculate scramjet/ramjet propulsion system boundary conditions. A comparison of the resulting output from a stand-alone RJPA run and from RJPA executed through *SRHEAT*™ also shows identical results.

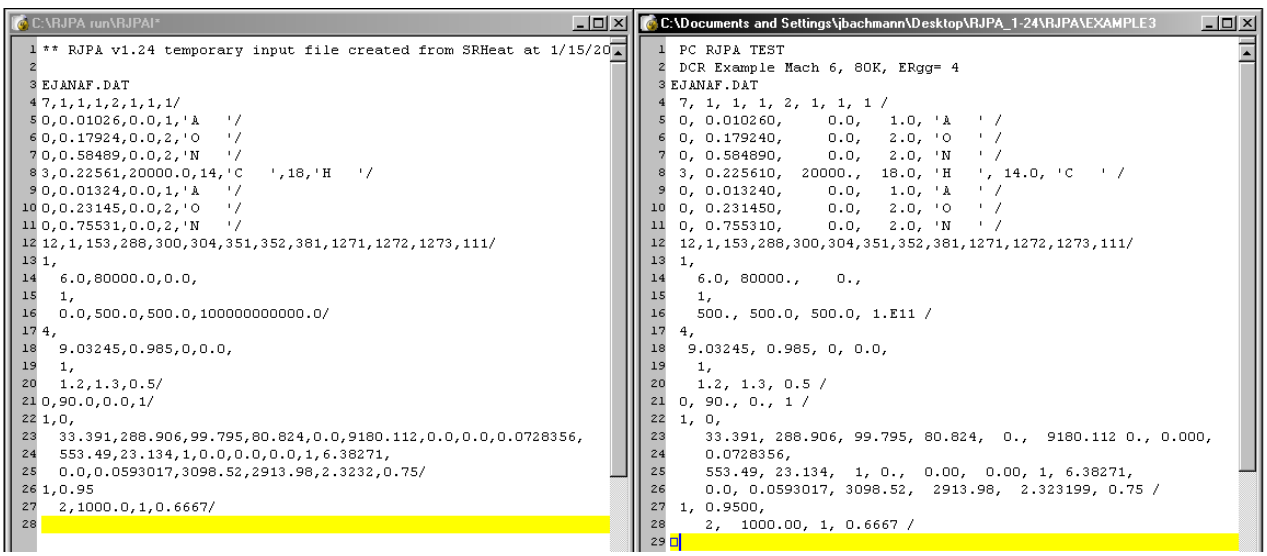
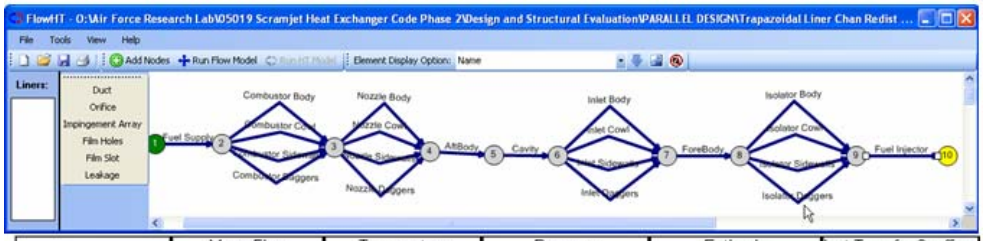


Figure 13: The RJPA Plug-in Input File is Identical to the EXAMPLE 3 Input File.

2. *Heat Transfer Assessment Comparison*

Flow Model – A flow model of the specific overall engine system was modeled utilizing *Flow HT*™, *SPIRITECH*'s in-house flow network code. A comparison of the resulting output from *Flow HT*™ and from *SRHEAT*™ was performed. The comparison (shown in *Figure 14*), shows that results for mass flow, temperature, pressure, enthalpy, and heat transfer coefficient are nearly identical for the two codes.



Element	Mass Flow		Temperature		Pressure		Enthaply		Heat Transfer Coefficer	
	SRHEAT	FLOWHT	SRHEAT	FLOWHT	SRHEAT	FLOWHT	SRHEAT	FLOWHT	SRHEAT	FLOWHT
FuelSupply	8.17	8.17	520.00	520.00	1135.00	1133.95	-884.10	-884.10	NA	65.55
CombustorBody	2.01	2.00	520.00	520.00	1135.00	1133.92	-406.20	-405.86	494.60	494.43
CombustorCowl	1.87	1.87	520.00	520.00	1135.00	1133.92	-357.70	-357.20	499.70	499.53
CombustorSidewalls	2.15	2.15	520.00	520.00	1135.00	1133.92	-348.50	-348.36	502.40	502.15
CombustorDaggers	2.15	2.15	520.00	520.00	1135.00	1133.92	-348.50	-348.36	502.40	502.15
NozzleBody	1.42	1.41	1272.00	1271.91	1133.00	1131.39	31.11	33.22	553.50	552.35
NozzleCowl	1.45	1.44	1272.00	1271.91	1133.00	1131.39	23.99	26.20	560.20	559.05
NozzleSidewalls	2.67	2.66	1272.00	1271.91	1133.00	1131.39	28.66	30.73	560.40	559.22
NozzleDaggers	2.67	2.66	1272.00	1271.91	1133.00	1131.39	28.66	30.73	560.40	559.22
Aftbody	8.20	8.17	1594.00	1594.84	1132.00	1130.10	114.50	114.69	2174.00	2169.63
Cavity	8.19	8.17	1624.00	1624.07	1005.00	1003.57	120.60	119.36	2510.00	2506.26
InletBody	1.88	1.88	1625.00	1625.61	996.90	995.52	342.40	342.44	749.00	747.53
InletCowl	1.89	1.88	1625.00	1625.61	996.90	995.52	342.20	342.17	749.70	748.20
InletSidewalls	2.21	2.21	1625.00	1625.61	996.90	995.52	344.00	343.98	749.80	748.31
InletDaggers	2.21	2.21	1625.00	1625.61	996.90	995.52	344.00	343.98	749.80	748.31
Forebody	8.20	8.17	1697.00	1697.15	992.50	991.07	394.70	393.62	2428.00	2421.89
IsolatorBody	2.08	2.07	1712.00	1712.64	670.30	669.63	567.00	565.80	891.30	888.70
IsolatorCowl	2.08	2.07	1712.00	1712.64	670.30	669.63	567.00	565.80	891.30	888.70
IsolatorSidewalls	2.02	2.01	1712.00	1712.64	670.30	669.63	567.40	566.20	891.30	888.74
IsolatorDaggers	2.02	2.01	1712.00	1712.64	670.30	669.63	567.40	566.20	891.30	888.74
FuelInj	8.21	8.18	1788.00	1789.26	661.10	660.45	568.90	566.02	NA	461.82
Max Error	0.03%		0.01%		0.02%		0.03%		0.01%	

Figure 14: Flow Model Comparison

Heat Transfer Solver Validation – The thermal analysis of the nozzle sidewall panel was performed using ANSYS. Coolant channel boundary conditions were predicted using *Flow HT*^{TM} while hot gas boundary conditions were calculated based on the RJPA output. Since the thermal solution is completely coupled within *SRHEAT*™ (i.e. the hot gas and fuel side boundary conditions are dependent on the surface temperature and total heat load on the panel, respectively), several iterations were completed in order to couple the solution between all three components.

Comparison of the resulting surface temperature distribution was made between the ANSYS and *SRHEAT*™ solutions (Figure 15). The comparison shows maximum disagreement of 3.8% in final metal temperature distributions through the HEX panel.

	SRHEAT	Parallel Design	
	Heat Transfer Boundary Conditions		
Coolant Thermal Conditions	h =614.7BTU/ft²/hr/ F Coolant Temp 816.2 F	h = 604 BTU/ft²/hr/ F Coolant Temp 859 F	
Hot-Side Thermal Conditions	Heat Flux = 0.6776 BTU/sec/in²	h = 177 BTU/ft²/hr/ F Coolant Temp 4796 F	
	Resulting Panel Material Temperatures		Results Comparison
TBC Hot-side Temp	2243 F	2312 F	3.0 %
Metal Hot-side Temp	1384 F	1439 F	3.8 %
Metal Cold-side Temp	906 F	936 F	3.3 %

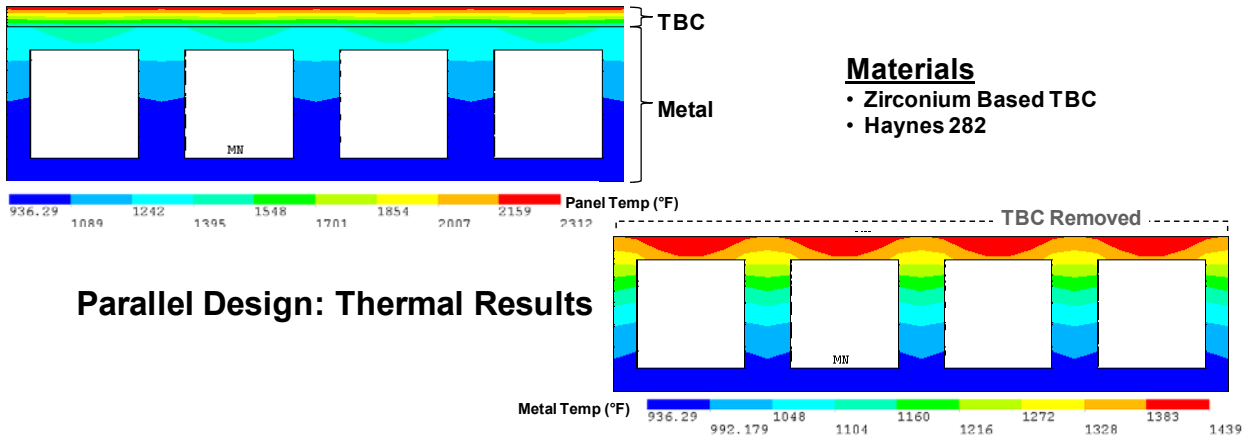


Figure 15: *SRHEAT*™ Temperature Comparison with Parallel Design on Nozzle Sidewall Panel

3. Structural Analysis Assessment Comparison

A structural model was built to assess the strength of the nozzle sidewall HEX panel resulting from the parallel design effort. The panel is examined as a submodel of the larger nozzle sidewall panel component in order to capture the small cooling channel features. The component was analyzed using ANSYS FEA for the worst-case load conditions resulting from the thermal gradient profile and HEX panel pressure load (ΔP). See Figure 16 for loading and constraint details. Temperature dependent data for Haynes 282 was utilized within ANSYS for the analysis.

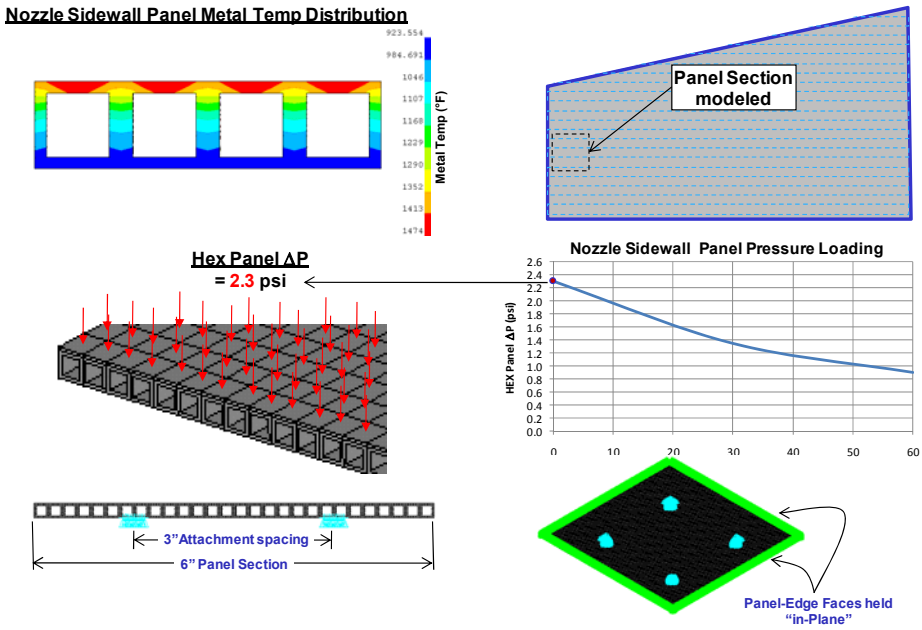


Figure 16: HEX Panel FEA Boundary Conditions and Constraints on Nozzle Sidewall Panel

The structural analysis was conducted utilizing a multiple-load step process to examine the resulting stresses as a function of the load type (thermal or mechanical). As shown in Figure 17, the thermal stresses dominate the HEX panel's stress state. This is typical due to the thermal gradients magnitudes that are experienced with these types of thermal boundary conditions. The stress due to static pressure across the panel is minimal as long as the hanger spacing and overall HEX panel structure are appropriately sized. The overall peak stress in this loading arrangement is the addition of the thermal stress and pressure-driven stress, which occurs on the hot-side of the panel at the fastener attachment. For this particular analysis, the design was assumed to be "expendable". For expendable designs, the safety factors for limit and ultimate load are 1.0 and 1.2, respectively.

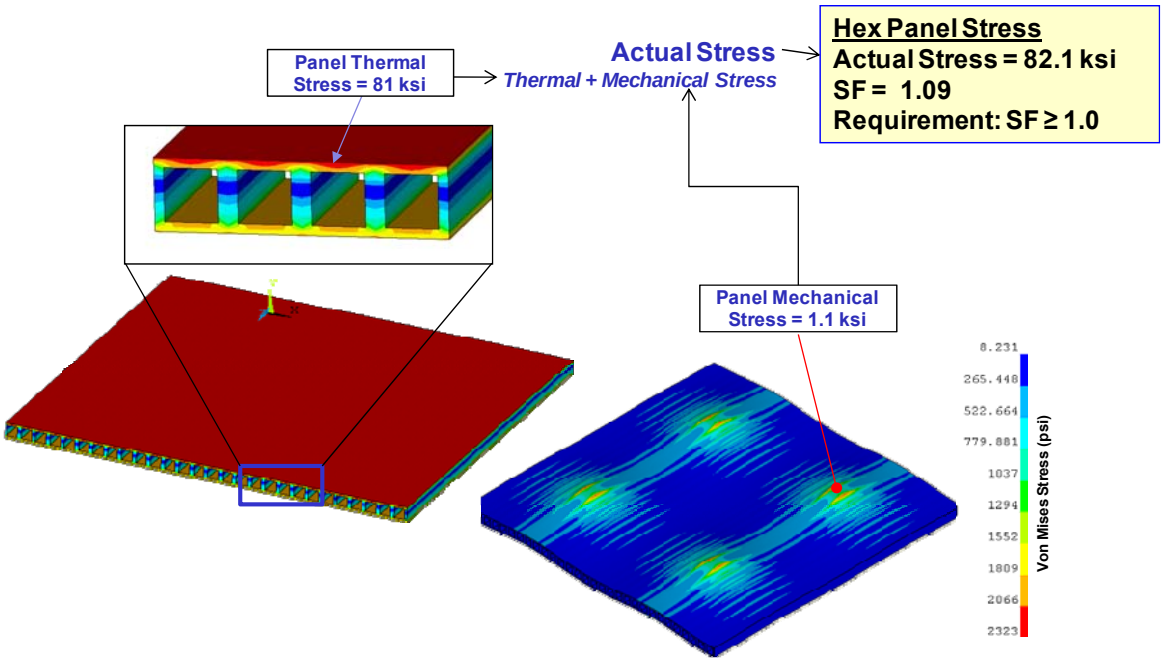


Figure 17: Nozzle Sidewall Panel Structural Results

During the process of structurally assessing components within *SRHEAT*™, the code utilizes average metal temperature to determine the structural allowable basis for limit load and ultimate load allowables. For each HEX component, *SRHEAT*™ determines the minimum of yield strength and 1% creep strength (at a user-defined life span) for the limit load allowable, and the minimum of ultimate strength and creep rupture strength (at the user-defined life span) for the ultimate load allowable. For the Nozzle Sidewall panel, the allowables were based on yield and ultimate material allowables for the predicted metal temperatures.

In addition to the Nozzle Sidewall panel, the isolator sidewall panel was selected for examination for a case in which the material allowable basis was a 10hr creep strength requirement. Haynes 282 was assumed for the material. The average material temperature was approximately 1400°F while the through-thickness gradient was approximately 140°F. The panel geometry was modeled in FEA using the same techniques as used for the Nozzle Sidewall analysis. The appropriate sidewall thermal and panel pressure loads were applied. The resulting stress was determined (Limit stress = 29 ksi, Ultimate Stress = 34.8 ksi) and compared to the appropriate 10 hr, 1% Creep strength (65 ksi) for the limit load allowable and creep rupture strength (70 ksi) for ultimate allowable.

Typical to a design review process, the various components of a design are summarized into a tabular form in order to give the reviewing audience a condensed, concise summary, culminating in a go/no-go status (as seen in the right-most columns of Figure 18). As shown in Figure 18, the structural results of the nozzle and isolator sidewall panels have been used to populate a structural audit sheet detailing the results. *SRHEAT*™ also includes a structural audit summary. As shown, the parallel design stress results agree with those obtained from *SRHEAT*™ within 2% for the nozzle sidewall and 4% for the isolator sidewall.

Parallel Design Structural Audit Sheet

Objective Concern	Component	Criterion	Material	Metal Temp	Stress Allow	Actual Stress	Safety Factor (SF)	Meets allowable? (Yes / No)
1% Creep	Isolator Sidewall	SF ≥ 1.0 on 1% Creep in 10hr	Haynes 282	1412 °F	65 ksi	29.0 ksi	2.24	Yes
Creep Rupture		SF ≥ 1.2 on Creep Rupture in 10hr	Haynes 282	1412 °F	70 ksi	34.8 ksi	2.01	Yes
Yield Strength	Nozzle Sidewall	SF ≥ 1.0 on Yield Strength	Haynes 282	1187 °F	89 ksi	82.1 ksi	1.09	Yes
Ult. Strength		SF ≥ 1.2 on Ult. Strength	Haynes 282	1187 °F	141 ksi	98.5 ksi	1.45	Yes

SRHEAT™ Structural Audit Sheet

Structural Audit Sheet

Component	Durability Criterion	Life Criterion	Material Average Temp. (°F)	Matl.	Limit Stress Allowable (ksi)	Stress Allowable Basis	Ultimate Stress Allowable (ksi)	Stress Allowable Basis	Limit Stress Calculated (ksi)	Ultimate Stress Calculated (ksi)	Meets Limit Allowable?	Meets Ultimate Allowable?
Forebody	Exp.	Hr1	1293	Haynes282	90.4	Yield	137.0	Ultimate	22.4	26.8	YES	YES
Inlet body	Exp.	Hr1	1307	Haynes282	90.2	Yield	135.2	Ultimate	35.5	42.6	YES	YES
Isolator body	Exp.	Hr10	1409	Haynes282	64.5	Creep_1Percent	70.4	Rupture	30.3	36.4	YES	YES
Cavity	Exp.	Hr1	1242	Haynes282	89.7	Yield	140.4	Ultimate	33.6	40.3	YES	YES
Combustor body	Exp.	Hr1	936	Haynes282	89.9	Yield	138.5	Ultimate	110.8	132.9	NO	YES
Nozzle body	Exp.	Hr1	1149	Haynes282	89.3	Yield	141.7	Ultimate	81.1	97.3	YES	YES
Aftbody	Exp.	Hr1	1188	Haynes282	89.2	Yield	142.9	Ultimate	26.8	32.1	YES	YES
Inlet cowl	Exp.	Hr1	1307	Haynes282	90.2	Yield	135.2	Ultimate	35.5	42.6	YES	YES
Isolator cowl	Exp.	Hr10	1409	Haynes282	64.5	Creep_1Percent	70.4	Rupture	30.3	36.4	YES	YES
Combustor cowl	Exp.	Hr1	996	Haynes282	89.6	Yield	137.5	Ultimate	107.5	129.0	NO	YES
Nozzle cowl	Exp.	Hr1	1145	Haynes282	89.3	Yield	141.6	Ultimate	80.8	96.9	YES	YES
Inlet sidewalls	Exp.	Hr1	1302	Haynes282	90.4	Yield	136.1	Ultimate	35.6	42.7	YES	YES
Isolator sidewalls	Exp.	Hr10	1409	Haynes282	64.5	Creep_1Percent	70.4	Rupture	30.3	36.4	YES	YES
Combustor sidewalls	Exp.	Hr1	933	Haynes282	89.9	Yield	138.6	Ultimate	112.4	134.8	NO	YES
Nozzle sidewalls	Exp.	Hr1	1136	Haynes282	89.3	Yield	141.4	Ultimate	80.5	96.6	YES	YES
Inlet daggers	Exp.	Hr1	1302	Haynes282	90.4	Yield	136.1	Ultimate	35.6	42.7	YES	YES
Isolator daggers	Exp.	Hr10	1409	Haynes282	64.5	Creep_1Percent	70.4	Rupture	30.3	36.4	YES	YES
Combustor daggers	Exp.	Hr1	933	Haynes282	89.9	Yield	138.6	Ultimate	112.4	134.8	NO	YES
Nozzle daggers	Exp.	Hr1	1136	Haynes282	89.3	Yield	141.4	Ultimate	80.5	96.6	YES	YES

1) Durability Criterion: Safety Factors Used:

Reusable	Expendable
Limit Load Safety Factor = 1.25	Limit Load Safety Factor = 1.00
Ultimate Load Safety Factor = 1.50	Ultimate Load Safety Factor = 1.20

2) Stress Allowable Basis: if material is in creep range, allowables are the minimum of the yield limit & 1% CREEP limit, and the minimum of the ultimate limit & CREEP rupture limit respectively.

Isolator Results Comparison	
Stress Variation	4 %

Nozzle Results Comparison	
Stress Variation	2 %

Figure 18: Structural Audit Sheet Comparison

4. *Final Weight Calculation Comparison*

The overall system weight for the 2D and axisymmetric configurations were analytically determined and compared to the results determined within *SRHEAT*™, (shown in Figure 19). The 2D system weight agreed within 1% (for one sidewall panel) while that for the full axisymmetric configuration agreed within 2%, confirming that *SRHEAT*™ may be used to accurately predict the weight of the liner system as summarized in Figure 19.

Weight Comparison

	UG	SRHeat
Panel Only Weight (lbs), with channels (one sidewall only)	52.549	52.115
Hanger Weight (lbs)	2.729	2.935
Total Weight (lbs)	55.279	55.050
Surface Area (ft^2)	11.700	11.700
Liner Density (lbs/ft^2)	4.724	4.705

	UG	SRHeat
Panel Only Weight (lbs), with channels	173.195	169.353
Hanger Weight (lbs)	9.247	9.247
Total Weight	182.442	178.600
Surface Area (ft^2)	37.135	38.035
Liner Density (lbs/ft^2)	4.913	4.696

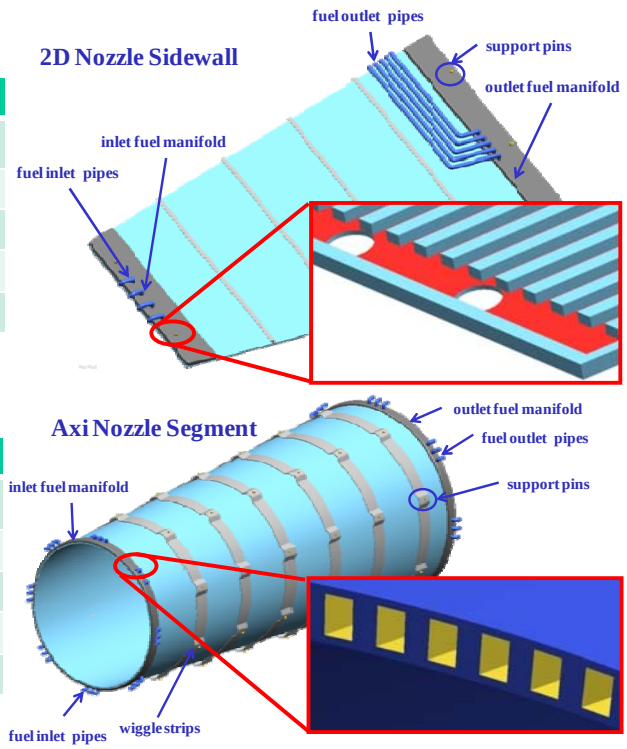


Figure 19 - Weight Comparisons for 2-D and Axisymmetric Configurations

Conclusions

A Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) has been developed for rapid structural and thermal analyses of complex thermal cooling systems. The analytical model provides a system level thermal analysis that balances the heat load from the gas path, through the liners, and into the fuel. The heated fuel is injected into the gas path for combustion to complete the closed-loop thermal system. Detailed thermal and structural analyses are performed to accurately size the system for the desired mission and life requirements.

This user-friendly design tool was developed with ease-of-use as a primary focus. Simple, drop-down menus for selecting the coolant fuel, including its associated endothermic properties, are used so that various fuels may be easily evaluated. In addition, drop-down menus are also included for selecting various high temperature material properties. The user-friendly interface simplifies the use of *SRHEAT*™ for performing large trade studies. Using numerical optimization techniques, the code can define the optimum configuration to minimize weight and required cooling fuel flow for the user-defined boundary conditions, or the user may select to run a specific configuration at off-design conditions.

SRHEAT™'s analytical models have been validated through comparison to detailed analyses performed for a parallel design validation effort. The results of this validation confirm the accuracy of *SRHEAT*™ providing the user confidence in the results of the code and the ability of *SRHEAT*™ to correctly predict liner system configurations.

The detailed heat exchanger design features included in *SRHEAT*™ (i.e. geometry, material properties, fuel/coolant properties, etc.) make the code a valuable tool in scramjet and hypersonic vehicle development, providing the low cost analytical capabilities that will make possible the efficient development of aerospace components.

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