AIAA-2009-5184

Scramjet/Ramjet Design and Integration Trade Studies Using *SRHEAT*™

Mike Willard* and David Giel†
SPIRITECH Advanced Products, Inc / Tequesta, Florida

Charbel N Raffoul, Ph.D.‡
AFRL/Wright Patterson AFB, Dayton, OH

The Scramjet/Ramjet Heat Exchanger Analysis Tool (*SRHEAT*™) developed by *SPIRITECH* allows rapid analyses of the complex integrated cooling and structural systems required for hypersonic air-breathing propulsion systems. The ability to handle detailed heat exchanger and structural design features allows for near real time evaluation of performance and weight sensitivities to geometry, coolant path properties, flight conditions, construction materials, and fuels. These features make *SRHEAT*™ invaluable for initial assessment of hypersonic propulsion systems, providing the low cost analytical capability that makes rapid evaluation of design trade space possible. The ability to perform these trade studies as part of the early conceptual design phase is crucial to making correct initial design decisions before conducting more expensive preliminary and detail design efforts. These broad capabilities of *SRHEAT*™ are illustrated with a series of example trade studies, showing how this tool can be used to insure selection of the best combination of geometry, thermal and structural designs, sizing, vehicle integration, and mission flight path.

I. Introduction

Managing the heat load to critical engine components remains a significant challenge in the design and operation of a hydrocarbon or hydrogen fueled hypersonic vehicle. Passive and active methods can be used for heat load management, but the most promising method for active cooling is to flow the 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. Once the fuel is heated by the engine structure, it is burned in the combustor to produce thrust. For an efficient closed-loop system, the flow rate of fuel required for cooling should not exceed the flow rate necessary for complete combustion of available air. Optimum efficiency is usually achieved with fuel flow at or slightly below stoichiometric values. Achieving this becomes more difficult as the flight Mach number increases due to increasing heat loads over a broader range of flow-wetted surfaces. Eventually, cooling critical areas in the engine will elevate the fuel flow requirement above the value desired for efficient combustion, resulting in the need to dump fuel overboard or recirculate hot fuel into the fuel tank, causing either reduced efficiency or loss of heat sink potential needed for cruise and/or deceleration. *SRHEAT*™ provides the propulsion system designer with a user-friendly tool to minimize these undesirable conditions by optimizing the cooling system, minimizing fuel flow and/or structural weight, through variations in basic flowpath geometry, material selection, fuel/coolant selection, heat exchanger geometry, and fuel routing.

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

- **Thermal Module** calculates heat flux and wall temperatures of a generic thermal system using various user-controllable cooling approaches (e.g., shape of passages, direction of fuel flow).
- **Structural Module** calculates the stresses in the heat exchanger panels, given input geometry.
- **Optimizer Module** optimizes the coolant circuit order, the heat exchanger passage sizes, wall thickness, panel weight, and the amount of coolant required to minimize the cooling flow requirement.
- **Properties Module** provides the user with an easy-to use library of material and fuel properties.

---

* Contract Engineer, SPIRITECH Advanced Products, Inc., member AIAA
† Aerodynamics & Heat Transfer, SPIRITECH Advanced Products, Inc., member AIAA
‡ Program Manager, AFRL, member AIAA

These modules, illustrated in Fig. 1 and previously described in detail by Gamble et al.[1-3], employ the input from a single source to evaluate the user-defined flowpath geometry for initial feasibility studies. Flowpath geometry, including shapes and lengths, can be quickly modified to meet performance and/or vehicle integration requirements during this initial study phase, allowing identification of performance and weight sensitivities to these important system variables. When the designer is satisfied with results of initial studies, *SRHEAT*™ can perform a system optimization, in both trade and final design modes, where heat exchanger performance is evaluated over an input range of design parameters to identify an optimum design, in terms of weight and/or fuel flow, for the selected flowpath geometry.

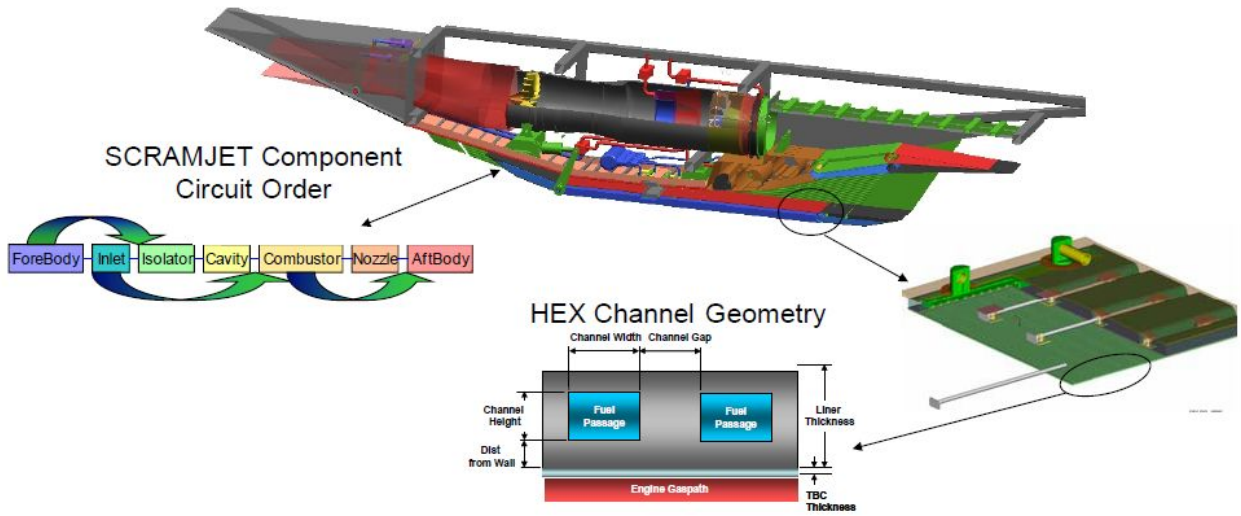


Figure 1. *SRHEAT*™ Heat Exchanger Components and Structural Geometry Definitions

This paper illustrates the utility of *SRHEAT*™ to conduct initial geometry, cooling system, and structural geometry trades, in addition to its use in evaluation of performance and weight sensitivities to basic flowpath architecture, component efficiencies, thrust size, hydrocarbon fuel type, and life requirements.

II. Technical Discussion

SRHEAT™ can be used to evaluate performance and weight sensitivities to geometry for each component in the Scramjet/Ramjet flowpath, including the effects of shape, length and non-dimensional parameters such as area ratios. Component efficiencies can be varied as part of the geometry studies to ensure that realistic flow conditions are evaluated and to accurately determine their impact on performance and weight. Effects of vehicle architecture, size, and low speed propulsion system integration constraints can also be assessed as part of these initial trade studies. Typically, these studies are focused at the maximum design Mach number for the vehicle, since cooling requirements and materials are driven by maximum heat loads, but Mach number could also be traded in the early phases of a feasibility study.

SRHEAT™ can be run in either trade study or detail design modes; in trade study mode, input is simplified and a number of optional inputs are set at default values to minimize input complexity and speed up solutions. This is the mode of operation that was run for all cases presented in this paper. In actual practice, promising cases identified in this manner would be “fine-tuned” using the detail design mode.

Results of these initial studies can be used as the basis for more in-depth optimization of heat exchanger, circuit order, and structural details, once basic shapes, lengths, and areas have been established. Finally, sensitivities to additional mission-dependent characteristics, like cruise speed, flight path, thrust size, hydrocarbon fuel type, or vehicle life requirements can be assessed, leading to identification of a lowest risk propulsion design approach prior to committing large investment in detail design, fabrication and technology maturation tasks.

Examples of *SRHEAT*™ utilization to conduct these types of trade studies are presented and discussed in this section, including typical results for these generic trades.

A. Baseline Configuration Development

Prior to conducting sample trade studies, a realistic baseline configuration was needed with relevance to on-going hydrocarbon fueled hypersonic engine technology programs. Initial *SRHEAT*™ studies were conducted with this baseline, and alternative configurations were then developed to evaluate sensitivities to geometry, component efficiencies, design Mach number, scale, construction materials, life, and fuel variables. The size and geometry selected for this baseline were based on a Mach 7 inlet design developed at NASA-GRC under the Scientific and Technology Information (STI) program[4]. This hypersonic inlet for a small turbine-based combined-cycle (TBCC) engine, Fig. 2, was developed at a size that will be referred to as "1X" in subsequent scale effect discussions. The split-flow inlet provides flow to an over-under propulsion system with a small-scale turbine engine (turbojet or turbofan, ~12" flowpath ID) and a dual-mode scramjet engine (DMSJ) for air breathing propulsion from takeoff to Mach 7. The high speed inlet consists of three external ramps and an internal contraction section that turns the flow back while cancelling shocks, for a total of 30.5° of turning and a nominal overall contraction ratio of 11. The design includes all the kinematic features necessary to provide an efficient low speed inlet from take-off to Mach 2.5, and a combined flow inlet for simultaneous over-under operation up to Mach 4, at which point the low speed inlet is closed and all flow is directed to the DMSJ flowpath.

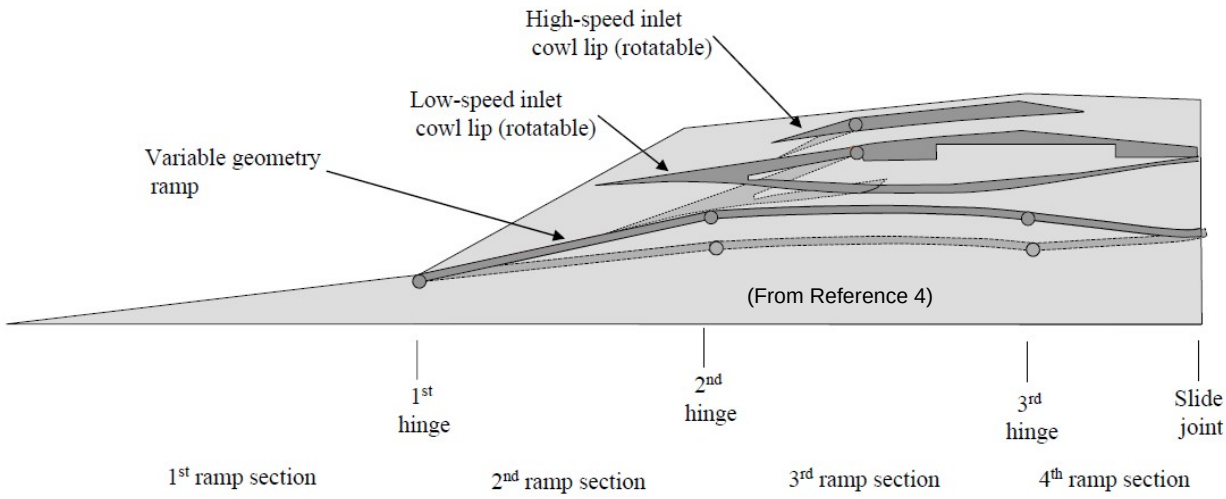


Figure 2. LIMX Inlet Geometry and Over-Under Variability (shown inverted)

This inlet was mated to realistic isolator, combustor, and nozzle flowpath elements to develop the complete baseline Mach 7 flowpath, as illustrated in Fig. 3. The isolator length of 25" is 8.33 times the flowpath height and was selected based on results of numerous programs, dating back to NASA-LRC research[5] and similar experimental programs that supported the National AeroSpace Plane program[6]. The combustor element was modeled with a 4.5° divergence and an area ratio of 2.33, again following historical and recent designs, resulting in a 51" length. An ignition stabilization cavity, not shown in Fig. 3, is located at the upstream end of the combustor and included in the *SRHEAT*™ geometry model and analysis. Length and surface area values for this cavity are user inputs. Finally, the nozzle is modeled as a Single Expansion Ramp (SERN) with both internal and external expansion zones. Internal and external chordal angles of ~22° and ~13° were selected, respectively, again based on historical data. The actual final divergence angle would be ~4° with this chordal angle arrangement . The projected nozzle exit area was selected to equal the capture area, consistent with vehicle integration requirements for hydrocarbon-fueled DMSJ designs. This combination of divergence angles and area ratio resulted in an external nozzle length (70") that was 50% of the external inlet length, which is again very similar to both historical and current hydrocarbon-fueled DMSJ engine designs for this speed regime.

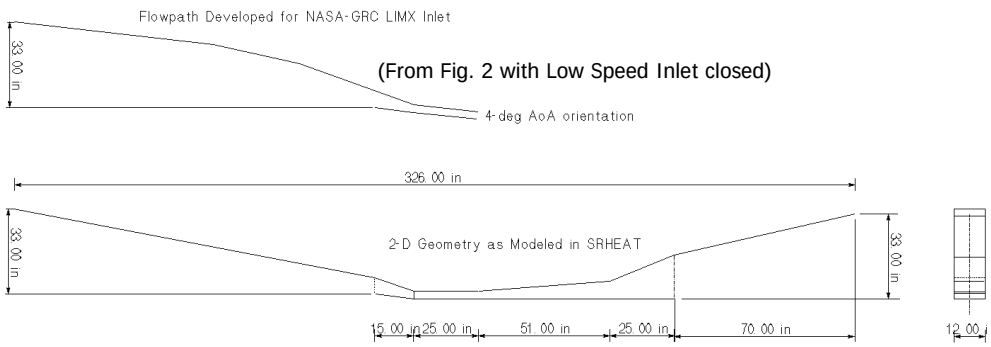


Figure 3. Comparison of LIMX Inlet Geometry and Baseline 1X DMSJ Flowpath

The baseline geometry described in Fig. 3 was developed for Mach 7 shock-on-lip (SOL) conditions, so *SRHEAT*™ was initially exercised at Mach 7 and a flight dynamic pressure of ~1500 psf. Although it is possible to request simultaneous optimization of both cooling circuit order and cooling passage structural geometry, this can often result in significant run times, and little is learned about sensitivity to design parameters in the process. On the other hand, *SRHEAT*™ usually converges in less than one minute with known values for both circuit order and passage structural geometry input (depending on processor speed), so it is often more time effective to try a number of feasible combinations before focusing on specific values of design variables. This also allows the user to observe weight and performance trends as functions of input parameters, allowing identification of the most promising values to investigate using the optimization and detail design routines, and saving time by facilitating more rapid convergence to optimal combinations. This approach was taken to find viable solutions and weight-performance trades for the baseline geometry before proceeding to the sample trade studies.

Through this process, the baseline engine was found to be extremely robust, providing the ability to cruise at Mach 7 with fuel flow at ~80% of stoichiometric levels over a wide range of circuit and coolant passage geometries. It is important to keep the minimum fuel flow at or below the stoichiometric (Phi = 1.0) ideal fuel-to-air ratio for both performance and operability reasons. These studies were conducted using the "expendable engine" life option, so safety factors are low and material creep is not an issue. The range of performance parameters shown in Fig. 4, a screen capture from the output module, illustrates this robustness and the type of output which is obtained directly from *SRHEAT*™ in real time. Important Phi, Thrust and Weight columns are shaded blue for emphasis. Note that Phi and Thrust variations are within a 2% standard deviation for a wide range of cooling flow circuits and structural arrangements, illustrating design robustness facilitated by this engine size and geometry. This is a very desirable condition, since it allows the designer freedom to select the configuration that is best from other perspectives, such as fuel supply pressure, fuel tank feed location(s), or manufacturing costs.

File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL0	41.1	2.24	0.8059	1962	2313	2.3	3.7	6.0	166.4	172.4
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BL2	41.13	2.14	0.7694	1912	2329	2.8	6.0	8.8	187.1	195.9
TBCC-BL_04x07	41.13	2.19	0.7874	1951	2331	2.1	3.4	5.6	163.5	169
BL_05x05	41.13	2.2	0.791	1947	2330	2.1	3.3	5.3	180.9	186.2
TBCC-BL-Struc_Op	41.13	2.11	0.7586	1974	2258	2.6	1.4	3.9	190.2	194.1
TBCC-Struc_Opt_1X	41.13	2.23	0.8018	1957	2323	2.6	5.9	8.5	168.5	177
TBCC-BL_Opt_CS	41.13	2.13	0.7658	1942	2328	4.0	1.7	5.7	205.9	211.6

Figure 4. Wide Range of Viable Baseline Engine Cooling System Designs Identified

The eight configurations summarized in Fig. 4 represent a wide range of cooling circuit orders, and several different structural arrangements, as suggested by their file names. The range of cooling circuits, shown in Fig. 5 in another example of *SRHEAT*™ output, varied from simple "front-to-back" or "back-to-front" arrangements that would simplify plumbing, to optimized circuits found by the flexible built-in optimizing routine. Coolant passage geometries ranged from .04"H x.06"W for the nominal baseline, to cases with variations in both height and width, while holding area nearly constant. Face and backing sheet thicknesses were optimized at .03" and the web between cooling passages was optimized at the .06" minimum value imposed for fabrication feasibility. Passage area was maintained at a level that resulted in a fuel pump pressure of ~3000 psi, ensuring system realism. Although higher pump pressure solutions could be obtained, the 3000-4000 psi range was found to be a good compromise since manifold and plumbing weights increased dramatically for higher values of fuel pressure.

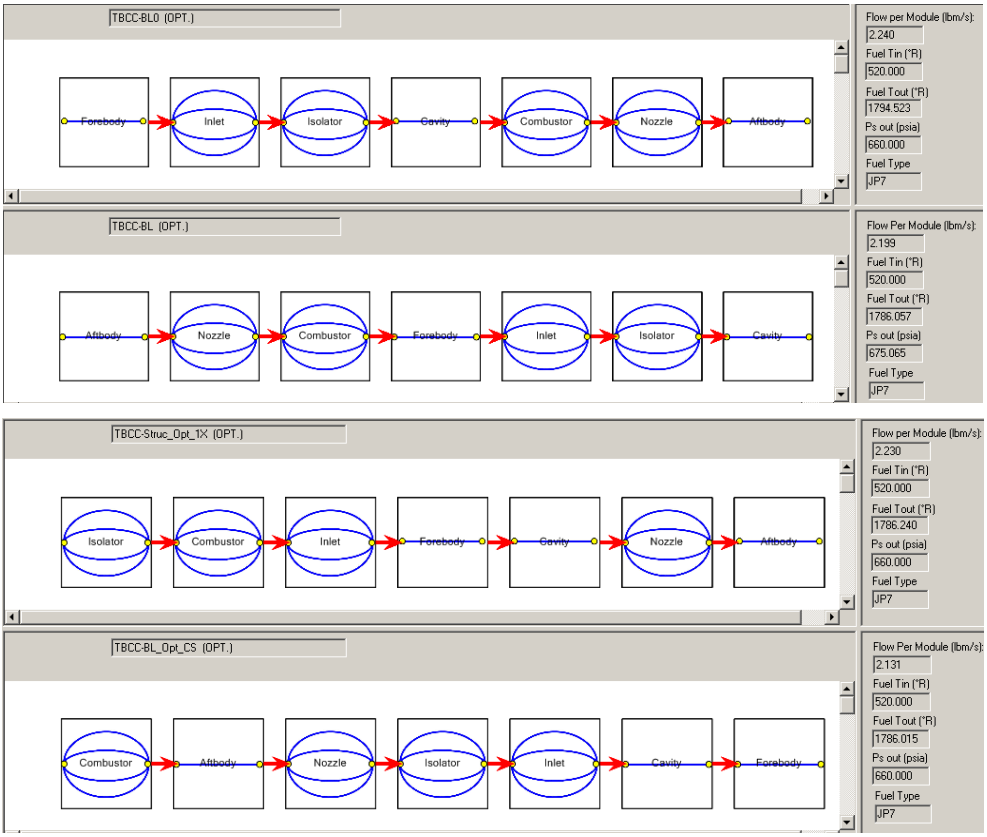


Figure 5. Wide Range of Fuel Circuits Provide Acceptable Performance for Baseline

B. Flowpath Shape and Component Efficiency Trades

1. Flowpath Shape

Recent studies and research programs[7] have identified advantages for replacing the baseline 2D flowpath with round DMSJ flowpath components mated to 3D inlet and nozzle elements. Potential advantages include reduced cooled surface area and improved structural efficiency, but these potentials have to be weighed against liabilities such as integration and component lengths. *SRHEAT*™ can be used to quickly evaluate this trade space, since round flowpath elements can be modeled, in addition to transitional regions going from 2D to 3D cross-sections. A study was conducted for a 3D flowpath sized to replace the baseline configuration to illustrate this capability.

A circular enclosed flowpath geometry, Fig. 6, was developed to be aerodynamically equivalent to the baseline 2D DMSJ. The external inlet and aftbody components were modeled as transitional elements, effectively starting 2D and ending mating with circular enclosed flowpath inlet and nozzle elements, respectively. The design rules that were described for the 2D flowpath were applied for the axisymmetric design, replacing height with diameter.

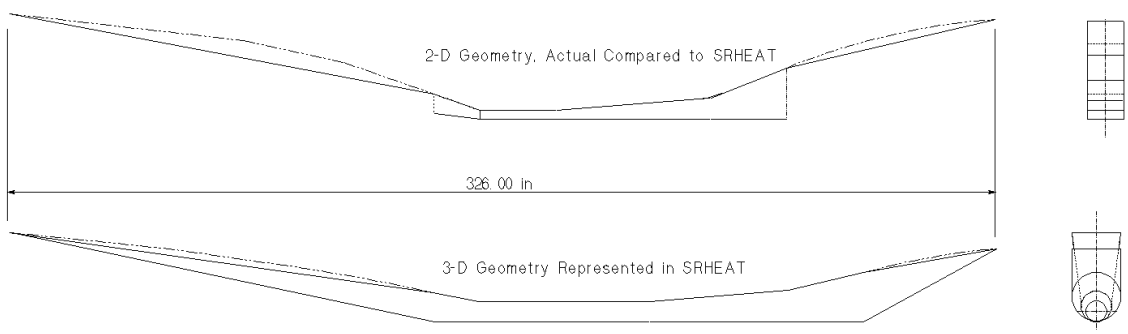


Figure 6. Comparison of 1X Baseline 2D Geometry and Equivalent Axisymmetric Flowpath

Note that the overall flowpath length was not changed, although the length of the important internal flowpath elements – the isolator and the combustor – increased significantly to achieve the same L/H (or L/D for circular components) and area ratio, respectively. The additional length required for these axisymmetric components was compensated by a shortened external nozzle surface required to achieve the same total projected area. A similar shortening of the external compression system might be possible, but this would make significant changes in the aerodynamics and starting characteristics of the inlet, so it was not included. *SRHEAT*™ predictions for the axisymmetric flowpath show a 5% reduction in fuel flow required to cool the structure, accompanied by a 2% thrust improvement. However, even though the axisymmetric structure is more efficient, the weight increased by 21% due to the increased length of high pressure isolator and combustor elements.

One of the standard output screens of *SRHEAT*™ provides comparison of flowpath conditions, as illustrated in Fig. 7 for the baseline 2D and axisymmetric flowpath engines. These predictions are used internally in the calculation of thermal and structural loads, and they also provide the user with a quick sanity check on the correct operation of components, and a direct comparison of conditions for different flow paths. This information is a valuable aid in the understanding of why engine performance and weight characteristics change. In this case, the impacts of the longer isolator and combustor are clearly seen by differences in the calculated flow field conditions. The effects of the flame-holding cavity are also clearly shown as abrupt step functions in parameter values.

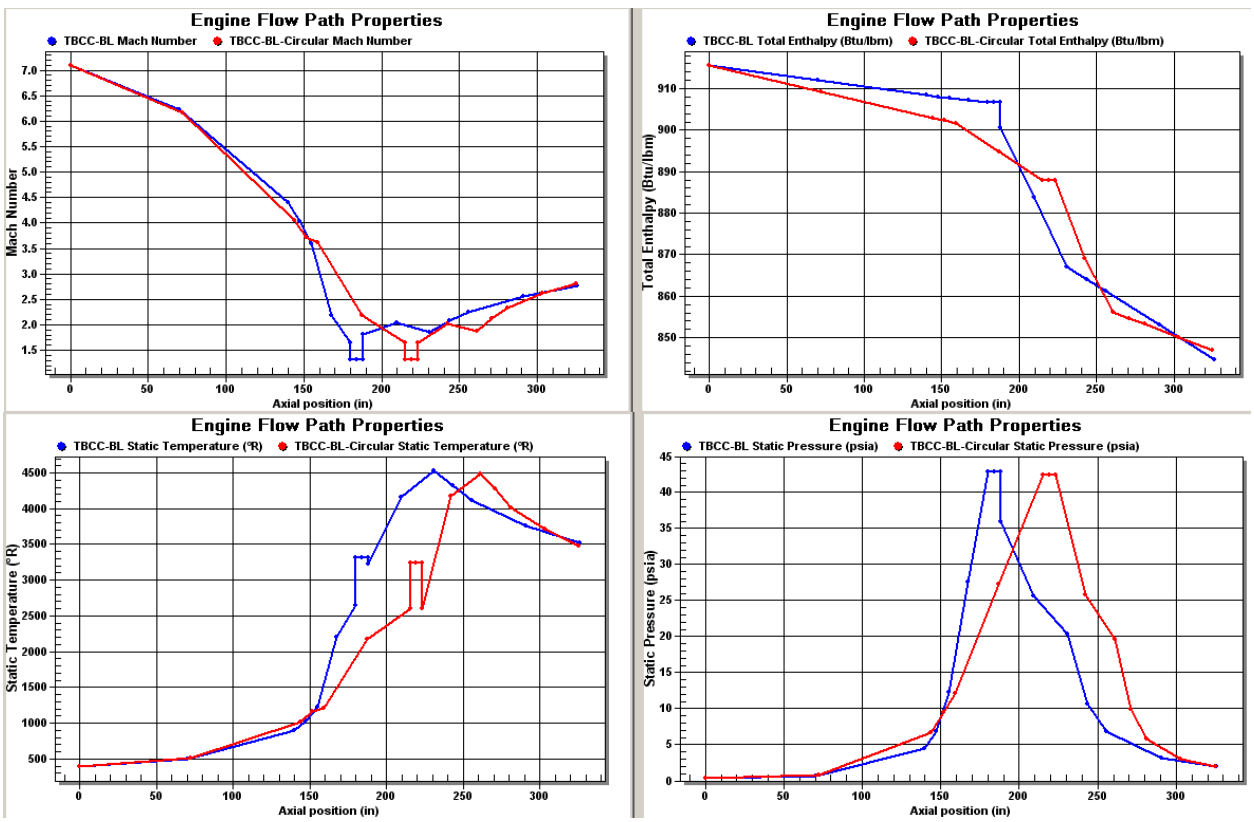


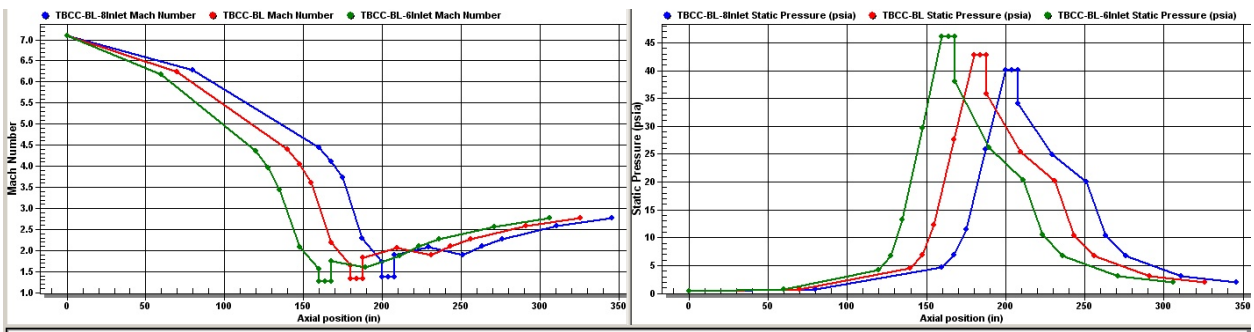
Figure 7. Comparison of 1X Baseline 2D and Equivalent Axisymmetric Engine Internal Conditions

2. Component Efficiencies

System performance is the sum total of many components working together, and it is valuable to understand the relative importance of each component's efficiency so that the right emphasis is placed on its design and integration. Using either user specified flow field conditions or RJPA[8] inputs, *SRHEAT*™ provides capability to evaluate performance and weight sensitivities to inlet, isolator, combustor, and nozzle component efficiencies. Different component lengths and/or area ratios can be input, along with how they affect efficiencies, to simultaneously evaluate overall system performance and weight trades. Examples of these types of trades are presented in the following paragraphs to illustrate the types of studies that can be conducted in a matter of minutes using *SRHEAT*™, replacing weeks or months of effort that would be required using conventional conceptual design techniques.

Inlet Efficiency Trades – Inlet efficiency can be improved by increasing the number of compressive turns used on the forebody, increasing length in the process, since a larger number of smaller individual angles results in lower total pressure losses. This improved pressure recovery has to be traded against increased cooling and weight associated with larger surface areas, and it is not intuitively obvious that increased inlet recovery will result in improved system performance. *SRHEAT*™ was used to quickly evaluate this trade for the baseline 1X 2D engine geometry, and the results indicate an extremely low sensitivity to inlet efficiencies for a large range of recoveries.

Two alternative forebody lengths were evaluated, one shorter and one longer than the baseline by 20", with total pressure recoveries ranging from 0.6 to 0.8. Flow field conditions and performance summaries, Fig. 8, show surprisingly little change in performance for such large changes in inflow conditions, with less than a 1% variation in thrust from lowest to highest recovery, and essentially no change in fuel flow required for cooling. However, a weight increase of nearly 8% is indicated due to the increased forebody length, accruing from both cooling panel and plumbing weight increases caused by increased fuel pressure. The increased fuel pressure could be mitigated by increasing fuel passage dimensions, but this could cause an additional structural weight penalty. Viscous effects, not included in this study, would make this comparison favor the shorter configuration even more since the assumed recovery improvement would be diminished by increased boundary layer losses for the longer configurations.

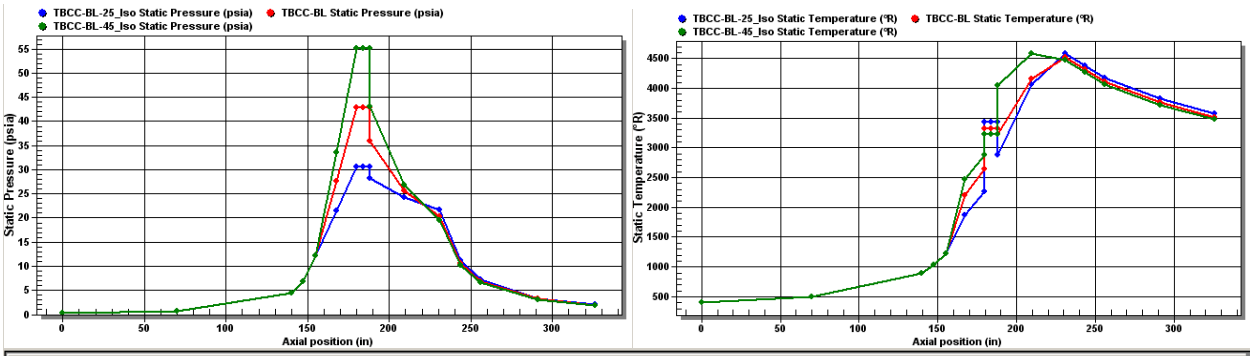


File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL-6Inlet	41.1	2.18	0.7844	1947	2317	2.3	3.6	5.9	160.8	166.7
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BL-8Inlet	41.09	2.18	0.7845	1946	2332	2.5	4.8	7.4	172.3	179.7

Figure 8. Example of *SRHEAT*™ Evaluation of Inlet Length and Recovery Trade Sensitivities

Isolator Pressure Rise Trades – The constant area section separating the inlet and the combustor provides the supersonic diffusion to sustain pressure rise caused by combustion-induced back-pressure, effectively acting like a normal shock at maximum pressure rise, while acting as a "cushion" when less static pressure rise is needed. Since this section must be long enough to contain any upstream influence of the shock train it contains to eliminate potential inlet unstart, it is commonly called an "isolator". Once the maximum pressure rise is achieved, there is no benefit in making this section longer, since it adds both weight and additional heat load, but finding the optimum length is difficult because the fluid mechanics involved are so complex, and they change with Mach number. A correlation[9] was developed to estimate required isolator length as a function of inlet Mach number and boundary layer momentum thickness for a desired pressure rise, and use of this equation and wind tunnel model data[5] led to selection of the 8.5 L/D length for the baseline engine.

A static pressure rise value of 3.5 was assumed for the baseline 1X engine, but this value could vary depending on inlet Mach number, inlet shock locations, boundary layer thickness, and combustion-induced back pressure. Since there is some uncertainty in these values, *SRHEAT*™ was used to investigate sensitivity of performance and cooling requirements to the isolator pressure rise. Values of 2.5 and 4.5 were input to the RJPA module, holding all other input parameters constant. Results, summarized in Fig. 9, showed an expected thrust improvement with increasing pressure, but the change was a modest 3% thrust increase going from a 3.5 to a 4.5 pressure rise. There was no change in engine weight. Note that the temperature rise in the combustor is non-linear, with a significant increase occurring with the 4.5 static pressure rise compared to the change from 2.5 to 3.5. This is caused by the fact that the combustion goes subsonic for this case, while remaining supersonic for the 2.5 and 3.5 pressure rise cases. Even with these higher pressures and temperatures, the predicted fuel flow required for cooling did not increase (in fact, it was reduced at the 4.5 pressure rise), suggesting that the limiting conditions that drive Phi were in other components and not affected by this change. Again, this is an encouraging result, showing that this 1X design is extremely robust, and able to handle a wide range of potential flow conditions.



File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL-25_Iso	41.13	2.19	0.7874	1928	2253	2.4	4.2	6.7	166.0	172.7
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BL-45_Iso	41.13	2.13	0.7658	1950	2396	2.4	3.9	6.3	166.7	173

Figure 9. Example of *SRHEAT*™ Evaluation of Isolator Pressure Rise Sensitivities

Combustor Efficiency Trades – Whereas the isolator is a *passive* component, with the sole purpose of preventing inlet unstart, the combustor is an *active* component, where the process that causes the generation of back-pressure and net positive thrust occurs[10]. Combustion efficiency is a primary parameter in determination of DMSJ performance, and it also plays a large role in determining the overall engine heat load. Combustion efficiency is dependent on a number of design parameters, including fuel injector geometry and location(s), piloting geometry, chemical kinetics, combustor length, and combustor area ratio. While *SRHEAT*™ does not include the ability to vary injector geometry, the effects of pilot geometry, length and area ratio are captured. An efficiency of 0.7 was used as input to the RJPA module for the baseline 1X configuration, and it was desired to investigate the effects of increasing assumed efficiency and length to determine their impacts on engine operation.

The combustor efficiency is a significant driver on Phi and thrust, as shown in Fig. 10 comparing the baseline with two increased efficiency cases (η_c=0.9) – one with no change in length (TBCC-BL-9Comb_no-L), one with a 20" length increase. The heat load added by the 0.9 efficiency raises required cooling Phi by 5% when length is held constant, and over 25% with a 20" increase in combustor length. Thrust increases by nearly 10% with the same length combustor, but this erodes to 6% if the longer combustor is required to increase efficiency. Similarly, the weight change is negligible when length is held constant, but increases by 13% when the combustor length increases by 20". Clearly, it is important to maximize combustion efficiency if it can be achieved in a reasonable length, but it may not payoff, from a system perspective, if increased length is required.

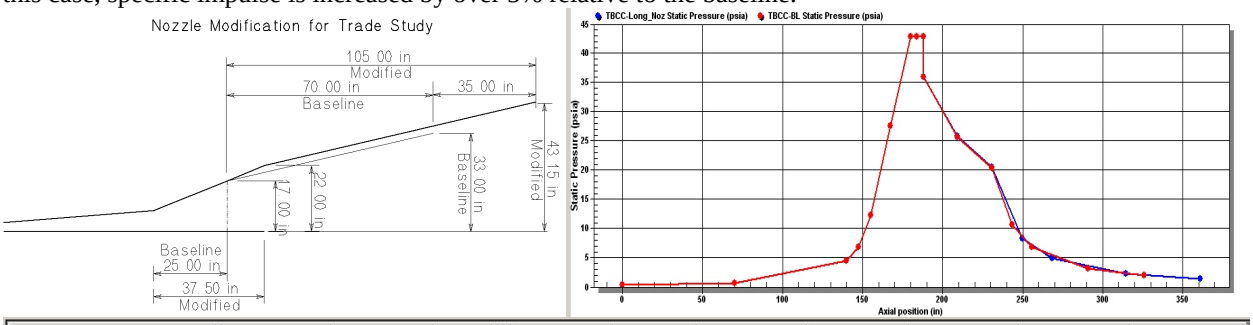
File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BL-9Comb_no-L	41.13	2.31	0.8305	1943	2553	2.6	4.9	7.5	167.2	174.7
TBCC-BL-9Comb	41.13	2.76	0.9923	1933	2475	3.2	8.4	11.6	184.3	195.9

Figure 10. Example of *SRHEAT*™ Evaluation of Combustor Efficiency Sensitivities

Nozzle Trades – Nozzles are expansion devices designed to convert the energy released in the combustor to a maximum exhaust velocity, thereby creating the gross thrust that more than counteracts the drag associated with the inlet compression process, resulting in a net positive propulsive force. To accomplish this, the nozzle should ideally have sufficient area to achieve an exit static pressure equal to local ambient conditions, and a contour shape that accomplishes this expansion with minimal shock and viscous losses while directing the exit flow to be perfectly axial. This combination of conditions is rarely achieved, since a different nozzle area and contour would be required for each operating condition along the flight path. It also requires a much longer length to achieve than is usually available due to the vehicle integration, cooling, and weight constraints. Because of this, the nozzle is always a compromise, and *SRHEAT*™ is well suited to find the best compromise geometry.

The baseline 1X configuration is very representative of current small expendable DMSJ flowpath designs, and the nozzle in this geometry is much shorter than it would be under ideal conditions. Because of this, the exit area is smaller than desired for optimal performance, since the contour required to increase exit area would result in large flow divergence losses. An increased length and area ratio nozzle was configured to evaluate the system impacts for

a larger nozzle. The new geometry, pressure distribution, and resulting performance and weight estimates, Fig. 11, show significant performance gain potential for this modification. All nozzle component lengths were increased by 50%, resulting in a 30% increase in area ratio and a 5.5% thrust gain. On the negative side, this change caused a 10% increase in fuel flow, and a 15% increase in weight. Also, it must be remembered that increased exit area will probably increase transonic drag, when the nozzle is almost always over-expanded. Thus, a full vehicle assessment would be required to determine whether the increase in Mach 7 gross thrust would buy its way in with these penalties. The third row of tabular data shows results for the same length increase, substituting an uncooled Carbon-Carbon aftbody for the cooled Inco625 nozzle in the second row. Note that the fuel flow penalty is essentially eliminated, thrust is increased an additional 1%, and the weight penalty is reduced from 15% to less than 8%. So for this case, specific impulse is increased by over 5% relative to the baseline.



File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-Long_Noz	41.13	2.42	0.8701	1940	2460	2.9	6.3	9.2	190.9	200.1
TBCC-Long_Noz-Uncool_Aftbody	41.13	2.2	0.791	1943	2463	3.1	3.3	6.4	180.6	186.9

Figure 11. Example of *SRHEAT*™ Evaluation of Nozzle Area Ratio Sensitivities

C. Design Mach Number and Material Trades

The baseline engine, shape and component efficiency trades presented above are all for a Mach 7 shock-on-lip design point. Since closures were obtained at Phi levels less than one (below stoichiometric fuel/air ratios), it would be feasible to exceed Mach 7 with these designs. Although this might be achieved by "over-speeding" the inlet, it is also of interest to investigate point designs for different flight speeds, so both Mach 6 and 8 designs were derived from the baseline 1X configuration to illustrate the utility of *SRHEAT*™ to quickly assess different flight conditions and geometries. For the Mach 8 cases, it was found that Phi values exceeding one are required if active cooling is used for all components, so the use of uncooled ceramic materials on select components was also evaluated.

1. Design Mach Number

Inlet designs for Mach 6 and 8 shock-on-lip configurations are compared to the Mach 7 baseline in Fig. 12, and were derived using the same design guidelines developed for the 1X flowpath. Capture area was held constant, and contraction ratio was varied to maintain a similar isolator entrance Mach number. Forebody ramp angles would be changed as needed to maintain the same cowl lip location. Using the same isolator 8.33 L/H design criteria, this causes a length increase for the Mach 6 flowpath, and a similar length reduction for the Mach 8 design. The actual isolator lengths are shown in Fig. 12 to illustrate the effect of this modification. This reduces the cooled surface area required for the Mach 8 design, which helps to minimize required cooling flow.

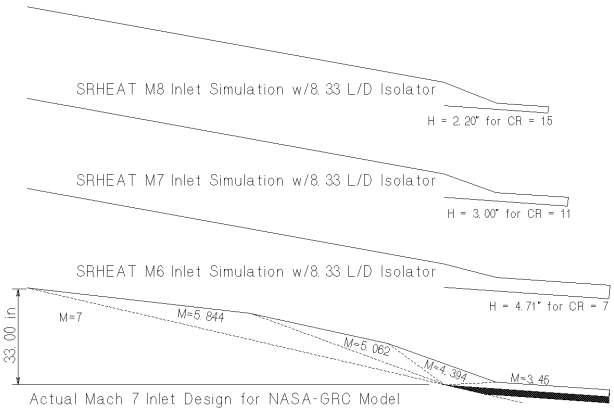


Figure 12. *SRHEAT*™ Inlet Modifications for Mach 6 and 8

These simplified inlet and isolator configurations were then linked to modified combustor and nozzle components, using the same design rules-of-thumb employed for the baseline Mach 7 case. The resulting DMSJ flow path geometries are compared in Fig. 13 to illustrate another of the useful output screens available in *SRHEAT*™. Note that the length modifications associated with the different contraction ratios are maintained

throughout the flow paths, resulting in a Mach 8 design that is 7” shorter overall than the Mach 7 engine, and a Mach 6 design that is 14” longer. Since sidewall heights are also reduced with increasing Mach number, cooled surface areas are reduced by a greater proportion than the length differences alone would indicate. Even so, fuel flow rates, also shown in Fig. 13, increase with increasing Mach number due to the increased heat loads encountered in the entire flowpath at higher Mach numbers. All three cases were run at similar dynamic pressures of ~1500 psf, correctly modeling the different flight paths that would be taken.

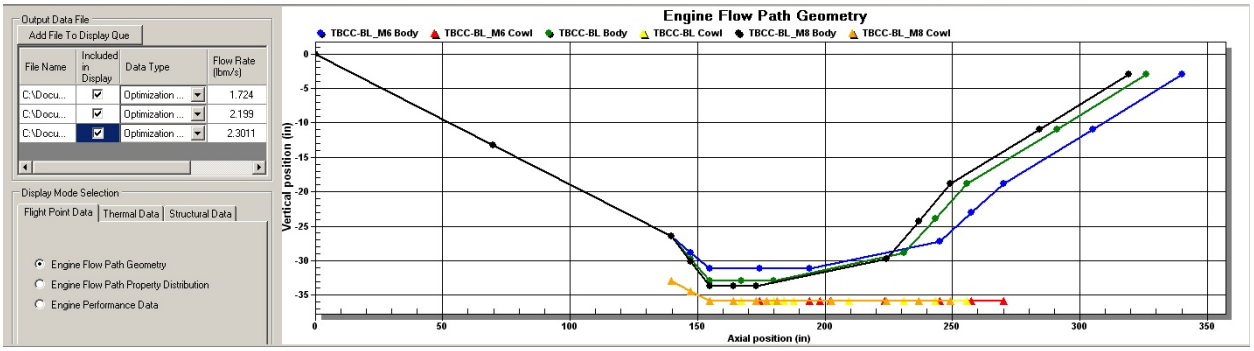
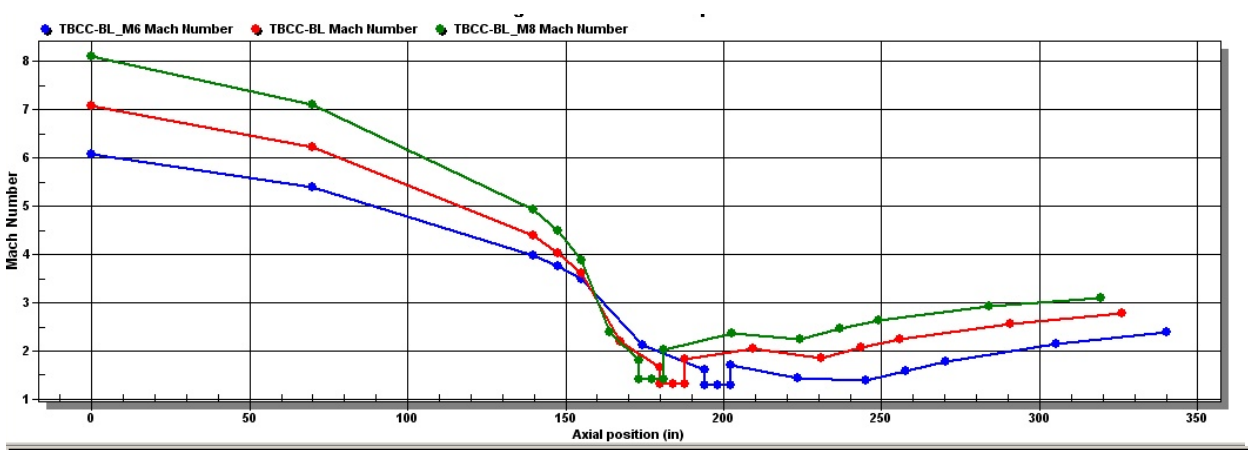


Figure 13. *SRHEAT*™ Output Comparing Mach 6, 7 and 8 Flowpath Geometries

Mach number plots for each engine, Fig. 14, show how the increasing contraction ratio makes the combustor entrance conditions nearly identical, although higher velocities are maintained through the combustor as Mach number increases. The assumed inlet recovery was adjusted for each design to be consistent with total turning required, as computed using the *Hypersonic Airbreathing Propulsion (HAP)*[10] program, but isolator pressure rise, combustor efficiency, and nozzle thrust coefficient assumptions were not changed. Performance results, shown in the lower portion of Fig. 14, show a rapid increase in Phi, or fuel required for minimum cooling, exceeding the desired maximum of 1.0 at Mach 8. Thrust is also reduced with increasing Mach number for constant capture area because airflow is reduced. Maximum metal temperatures increase rapidly too, but total cooling system weight is reduced with increasing Mach number due to the length and sidewall height reductions. The increase in maximum metal temperature is also an indication that this is not the limiting factor in establishing the Phi values. Examination of results indicates that fuel coking temperature is the limiting factor driving the Phi increase. Note that cooling passage geometries were not changed for these cases, so fuel pressure also increased with Mach number since fuel flow was higher, although this trend was partially mitigated by the length reductions. Fuel pressure requirement varied from 2500 psi to 3600 psi going from the Mach 6 to Mach 8 designs for minimum Phi.

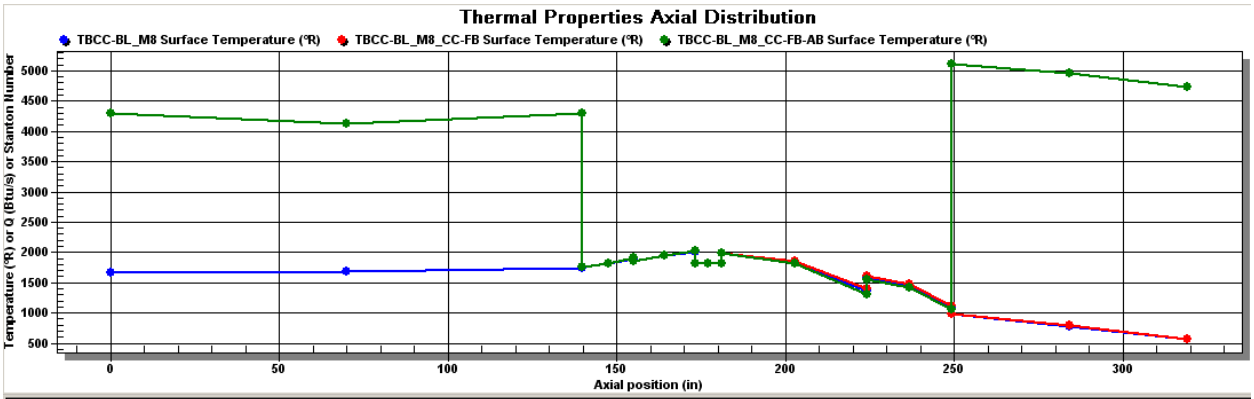


File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL_M6	44.65	1.72	0.5696	1865	2716	2.0	2.7	4.7	185.5	190.2
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BL_M8	30.84	2.3	1.1028	2015	1576	2.5	4.4	6.9	158.4	165.3

Figure 14. *SRHEAT*™ Output Comparing Mach 6, 7 and 8 Mach Numbers, Performance and Weight

2. *Material Substitutions*

The potential for use of higher temperature low density materials, like Carbon-Carbon (C-C), was established in the nozzle length trade (Fig. 11), where it was shown that use of a C-C uncooled aftbody could improve thrust while reducing both Phi and weight, resulting in significant gains in both Isp and thrust-to-weight ratio. A similar study of C-C substitution was conducted for the Mach 8 DMSJ, since the metal version required a minimum Phi that exceeded one. Carbon-Carbon substitution was evaluated in two steps: replacing the forebody alone, and then replacing both the forebody and the aftbody with uncooled C-C. Results of this study, Fig. 15, show the potential to achieve the desired Phi value by use of C-C for both forebody and aftbody components, but extremely high temperatures (even for C-C) are predicted for the uncooled components. The "Thermal Properties" chart is another standard output option of *SRHEAT*™, providing immediate visibility of temperatures and gradients, and a pull-down menu (not shown) gives the user many choices of temperature and parameter plots. The tabulated performance summary below the chart shows how Phi and weight are reduced as first the forebody, and then the aftbody are replaced with the uncooled ceramic. A thickness of 0.25" was assumed for these monolithic structures, resulting in significant weight savings in addition to the cooling reductions. Since these are lightly loaded components, the structural evaluation indicates that this is a sufficient thickness. Further weight reductions may be possible by optimizing the C-C structural shape.



File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL_M8	30.84	2.3	1.1028	2015	1576	2.5	4.4	6.9	158.4	165.3
TBCC-BL_M8_CC-FB	30.82	2.18	1.046	2025	1554	1.5	1.0	2.6	148.9	151.4
TBCC-BL_M8_CC-FB-AB	30.82	2.01	0.9644	2023	1562	1.5	0.5	2.0	144.6	146.6

Figure 15. *SRHEAT*™ Output Examples for Mach 8 Material Substitution Trade Study

D. Scale, Life and Fuel Trades

All trades presented to this point have been for the relatively small 1X DMSJ configuration, assuming use in an expendable, single-use configuration, like a missile or a technology demonstrator such as the X-43[11]. Future applications of this hypersonic engine technology may involve larger, reusable vehicles, so it is of great interest to investigate larger geometries and increased life requirements. All 1X configurations also used JP7 fuel, since it has particularly good properties for this application, so limited fuel substitution studies were also conducted to determine performance sensitivity to hydrocarbon fuel type.

1. *Scale Trade Studies*

The 1X DMSJ flowpath, shown previously in Fig. 3, proved to be extremely robust, with acceptable performance and weight solutions for a wide variety of structural and cooling circuit alternatives as summarized in Figures 4 and 5. The first step in evaluation of larger size DMSJ engines was to configure realistic alternative geometries that could achieve the desired 10X and 100X thrust increases to see if the type of scaling would influence the viability and robustness of these larger engines.

10X Scale - It was found that there are an essentially infinite variety of two-dimensional variants that can achieve the desired thrust scaling, since height and depth scales can be varied independently to achieve a product of 10. A representative cross-section of the possibilities is presented in Fig. 16 to illustrate the range investigated here. Final selection of the scaling approach would probably be driven by vehicle integration considerations, so it is valuable to consider a wide range of approaches in this study to gain insights to the performance and weight trades represented. Note that representative low speed accelerator engines are also pictured with all DMSJ's to show how they would integrate with the high speed configurations.

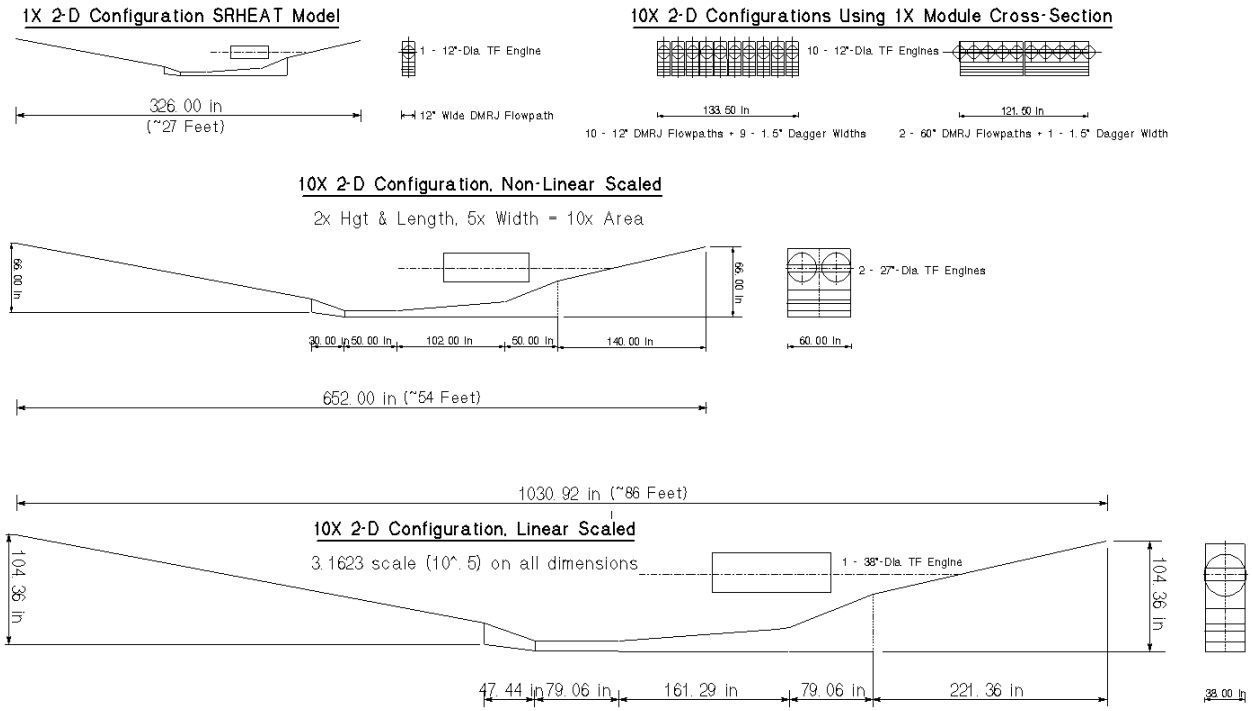


Figure 16. Multiple 10X Scaling Approaches Evaluated in *SRHEAT*™ Trades

The first and most obvious approach, the top/middle of Fig. 16, is to simply stack 10 of the 1X engines side-by-side, thereby achieving the desired thrust and the same thrust-to-weight ratio, assuming the integration can be achieved without increasing individual flowpath weight. A "dagger" width of 1.5" was assumed between individual flow-paths for this case based on structural studies conducted in the past for a similar engine design, resulting in a total engine width of 133.5" excluding end walls. The second approach is a variant of the first, shown at the top/right of Fig. 16, maintaining the same shear section view dimensions while increasing the width of the individual modules from 12" to 60". This results in a two-module engine, with the same 1X cross-section and only one embedded dagger, thereby reducing overall width to 121.5" and eliminating eight daggers and associated structure and cooling. Finally, a single 120"-wide module was evaluated as the most extreme variant of the 1X flowpath possible. Evaluation of these 1X variants was easily conducted with *SRHEAT*™ to provide immediate scaling insights for these relatively short and wide 10X designs, holding cooling passage geometry and circuit order constant. In practice, mechanical considerations, like integration and actuation of variable inlet and nozzle cowl flaps, might determine the maximum feasible module width.

Results, summarized in Fig. 17, show an expected Phi reduction as the number of modules is reduced, and a surprising weight trend that suggests the engine with two 60"-wide modules may be optimal. The three cases to compare directly are shaded, and the 1st and 3rd rows are the single module results for reference. The fuel flow (and therefore Phi) is reduced because the cooled surface area per unit air flow is reduced as daggers are removed. The trend shows a significant benefit for going from 10 to 2 modules (eliminating 8 daggers), and a reduced benefit for eliminating the one remaining dagger, as would be expected. Thrust is also increasing due to reduction of friction losses, and again shows a diminishing return for going from two to one module. System weight is minimized with the two module geometry, as a result of manifold and pipe weight penalties that overwhelm structural weight reductions associated with removal of daggers. The large reduction in perimeter surface area going from 10 to 2 modules more than offsets the plumbing weight increase, but this trend reverses going from 2 to 1 module because only one dagger surface is eliminated. In summary, it appears that this scaling approach offers both Phi and weight advantages, with the two 60"-wide module configuration clearly providing the best system solution.

File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-BLx10	411.3	21.99	0.7906	1945	23310	24.4	42.9	67.4	1666.7	1734
TBCC-BL_5X-fix	205.44	8.32	0.5989	1952	11940	72.3	14.9	87.2	697.3	784.5
TBCC-BL_5X-fix2	410.88	16.64	0.5989	1952	23880	144.7	29.8	174.4	1394.6	1569.1
TBCC-BL_10X	410.77	16.01	0.5764	1951	23940	474.7	47.3	522.0	1360.6	1882.6

Figure 17. Performance Comparisons of Short 10X Scale Variants of Baseline 1X Engine

As previously noted, the vehicle architecture may dictate desired dimensions of the DMSJ flow paths. Because of this, other methods of scaling to achieve 10X thrust were also evaluated, as pictured in the middle and bottom sketches of Fig. 16. The nonlinear-scaled flowpath in the middle is scaled by 2X in the x-z plane, and 5X in the y plane (into the paper) to achieve the 10X area increase. This represents a midpoint between the multiple 1X engines (scaled 1X in the x-z plane) and the linearly scaled 10X geometry shown at the bottom of Fig. 16, where all 1X dimensions are scaled by √10. The module in the nonlinear configuration is 60" wide, as in the two-module engine of Fig. 17, and the module width in the linearly-scaled configuration is ~38". Although this narrow linear-scaled approach is probably unattractive for vehicle integration, it may be the most feasible building block to create a 100X engine, as will be shown. A circular 10X variant, which would have a combustor diameter of over 21", was not considered in this study because intrusive injectors would be required to reduce combustor length with this size, and *SRHEAT*™ is not configured to handle these intrusive designs, which are proprietary to propulsion contractors.

Initial findings with the increased length nonlinear and linearly-scaled 10X engines, Fig. 18, are consistent with trends shown previously in Fig. 17. The nonlinear scaled engine, geometrically between the multiple 1X and the linearly-scaled configurations, has the lowest Phi, the highest thrust, and also the lowest weight of the two 10X single module engines. However, its performance is poor compared to the two-module configuration of Fig. 17, with a 9% fuel burn penalty and a 58% weight penalty. In fact, both 10X approaches that utilize the 1X flowpath length with increased width and/or number of modules are superior to scale-up approaches that increase the flowpath height and length.

File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
TBCC-BL	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
TBCC-10X_NL12_Struc-Circ-Opt_718-Comb	410.67	18.12	0.6525	1893	23680	623.5	162.0	785.5	1689.2	2474.6
TBCC-10X_Linear_Struc-Opt2&718Comb	410.87	19.43	0.6993	1925	23560	404.4	166.0	570.4	1935.4	2505.8

Figure 18. Performance Comparisons of Non-Linear and Linearly Scaled 10X Variants with Baseline

Major changes in circuit order and combustor material were also required to achieve closure in the increased length 10X engines. Both the nonlinear and linearly-scaled variants paid large Phi penalties when the cooling circuit order that provided the best combination of Phi and weight for the 1X engines was used. When the optimum circuit order was found for these engines, it required that fuel cooling be applied to the combustor section first, and this caused an unacceptably high thermal gradient in the Inco625 material. Circuit orders for the 1X and increased length 10X engines are compared in Fig. 19 to illustrate the changes required. For this reason, Inco718 had to be used for the combustor, taking advantage of its increased ultimate tensile strength. The reduced use temperature of 718 was not an issue because the combustor was the first element cooled, so temperatures were kept below 1200°F.

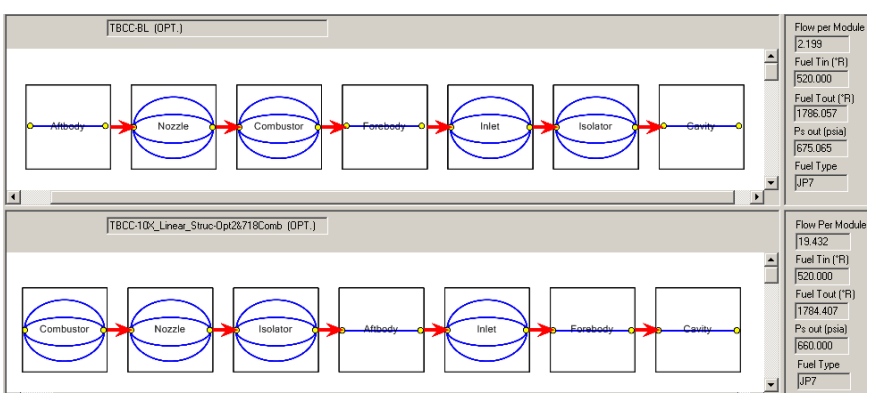


Figure 19. Cooling Circuit Comparisons for Increased Length 10X Engines

Thermal gradients for the linearly-scaled 10X engine are shown in Fig. 20, taken directly from *SRHEAT*™ output, before and after substitution of the 718 combustor material to illustrate the condition that forced this change of materials. Large negative margins shown for the combustor thermal gradients in the top indicate that this element will fail without the material change. The lower plot shows how the increased capability of Inco718 is able to eliminate this overstressing condition. The thermal gradient increase is caused by changes in both cooling circuit order and fuel flow velocity. The 10X engine circuit order locates the engine section with the highest heat flux (the combustor) first in the cooling circuits, where the fuel temperatures are lowest. The variation in fuel flow velocity is a result of two factors: differing fuel mass flow relative to channel area, and increased pressure drop with increasing panel length, affecting fuel heat transfer coefficients through property variation. Alternative cooling circuit variations might also mitigate high thermal gradients, and this could be evaluated in the Detail Design mode.

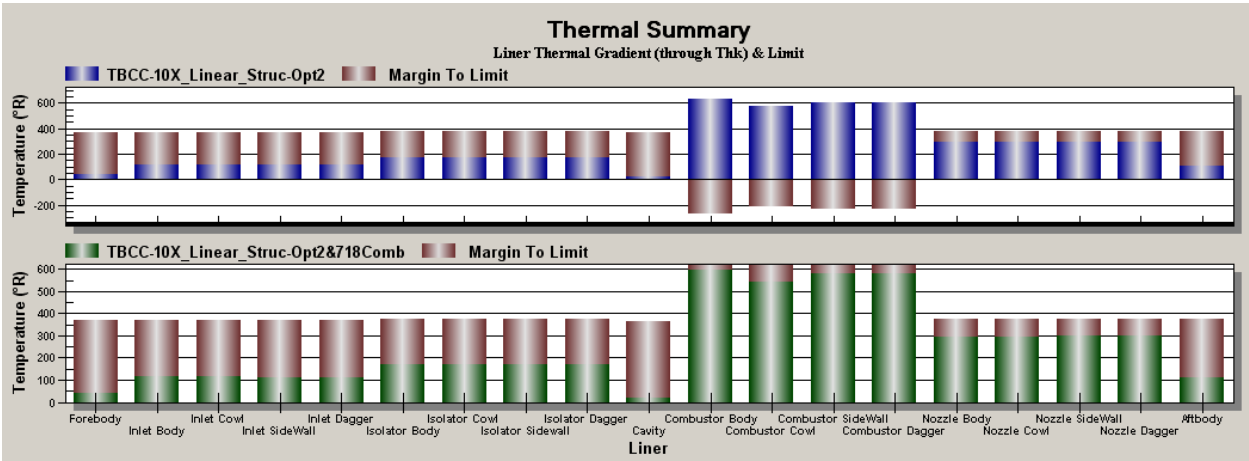


Figure 20. Comparison of Thermal Gradients Before and After Inco718 Combustor Substitution

Cooling passage areas also had to be increased to maintain acceptable fuel pressure, increasing structural depth of the cooling liners and resulting in higher weights. The area increase is also necessary because flows are greater by a factor of 10, yet perimeter is only increased by a factor equivalent to the square-root of 10 for the linear-scaled engine. This is also a contributing factor in the higher fuel side heat transfer coefficient. Some increase in depth was also required for structural reasons, since the longer flowpath elements created greater total loads to transmit into backing structure. The cooling passage geometries for these engines are compared to the baseline 1X and multi-module 10X configurations in Fig. 21 to illustrate this major difference. The flow area per passage was increased by a factor of five, and the number of passages also increased, dependent on the specific scaling approach. The net impact of all these changes is a loss of the design robustness seen in the 1X length dimensions, where a wide range of different circuit orders and passage geometries could provide acceptable design closure. Although limited design flexibility is still possible, sensitivities of Phi, thrust and weight to non-optimal circuits and areas are much higher, making the acceptable design space more restricted for these engines with longer and deeper flow paths.

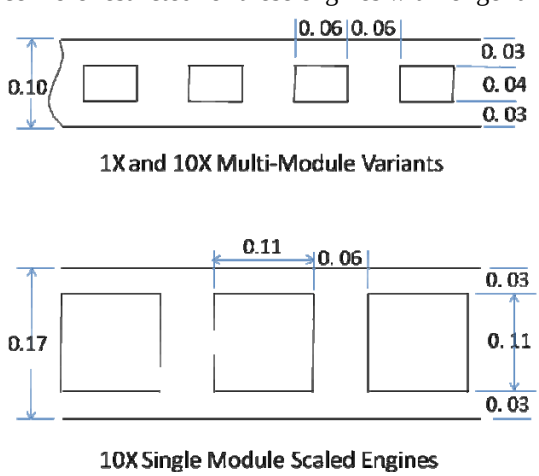


Figure 21. Comparison of 1X and 10X Engine Cooling X-Sections

100X Scale – All the same rationale developed and explained for 10X thrust scaling of the 1X baseline engine can be applied to extend the 10X size to 100X. However, the linear scaling approach may not be feasible because the length and height dimensions become unreasonable. This characteristic is illustrated in Fig. 22, where the linearly-scaled 100X engine is shown to exceed the length of a 747. As discussed in the previous section, this would also be undesirable for integration of the fuel cooling system, although use of multiple parallel cooling circuits might mitigate this concern, at the expense of increased plumbing and control system complexity.

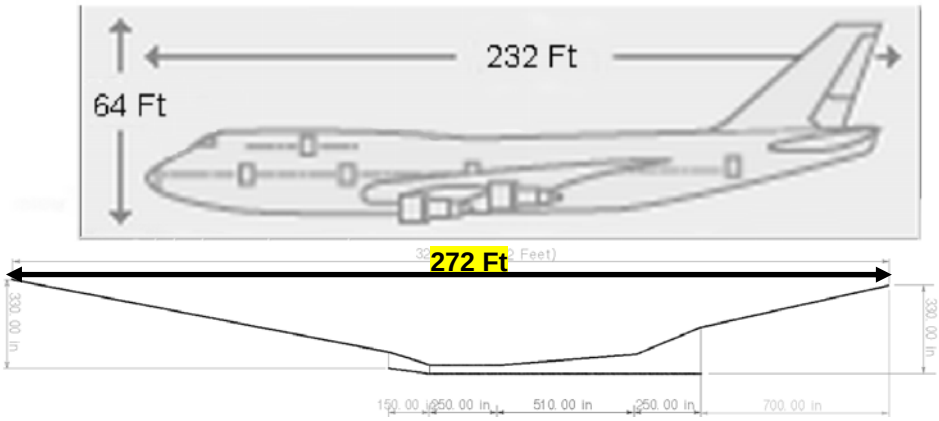


Figure 22. 100X Linear-Scaled Longer Than 747, Comparable to NASP X-30

The stacked module approach shown in Fig. 23 offers a better solution for the 100X thrust size, creating a propulsion package that is ~33' wide and 86' long by stacking ten of the linearly-scaled 10X engines. This could be provided as pictured under a blended wing-body vehicle, or as two five-module systems that would integrate into the wing root area on either side of the fuselage in a more conventional vehicle architecture. In either case, this would be an extremely large vehicle application. Packaging of the turbine-based low speed systems could be as pictured, although somewhat wider spacing might be required based on historical experience with multi-engine fighter aircraft. Performance of this system is derived directly from the linearly-scaled 10X configuration, as summarized previously in Fig. 18, multiplying thrust and weight values by 10.

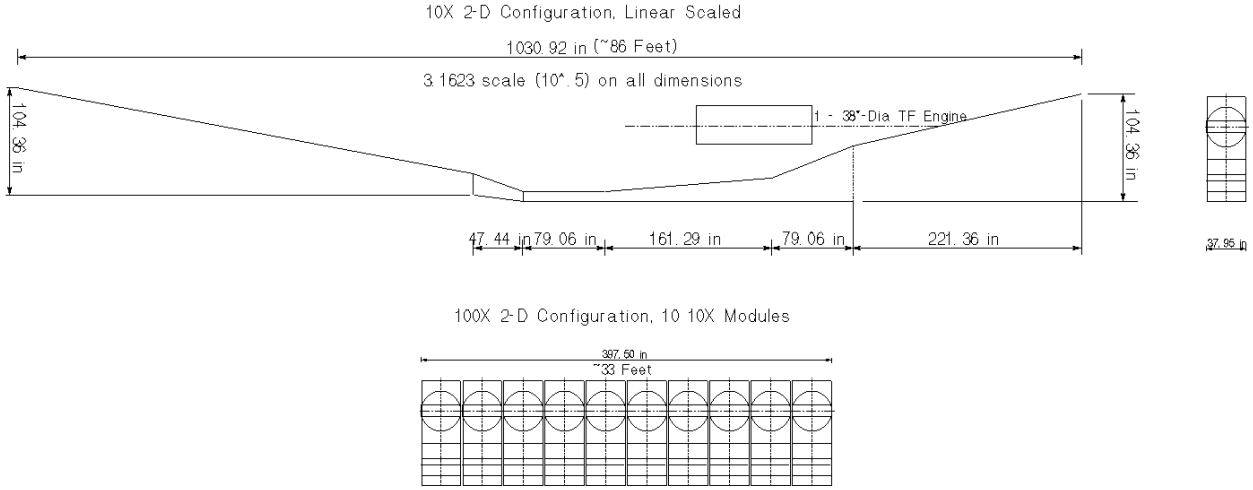


Figure 23. 100X Scaling Approach Evaluated in *SRHEAT*™ Trades

In summary, Mach 7 performance parameters for the best 1X, 10X and 100X engine configurations, Fig. 24, show greatest potential for 10X configurations synthesized from the 1X flowpath length and height dimensions. This thrust class is well suited for a wide variety of hypersonic mission applications, and excellent flexibility in vehicle integration is provided by this engine architecture. For example, the desirable two 60"-wide module configuration (shown in bold red type) is easily adapted to a "twin-engine" configuration by separating the two modules for

installation in the wing roots, as envisioned for the Falcon vehicle[7]. This would also have the advantage of separating the two turbofan engines, avoiding the spacing challenge presented by the back-to-back architecture. If the 60”-wide modules cause cowl flap actuation challenges, each engine could be broken into two 30”-wide modules with modest performance compromise, if any, based on results of this study. Performance and weight impacts of various derivative geometries with specific thrust and integration requirements could be quickly assessed with *SRHEAT*™. Regardless of module width, this approach would retain the robustness of design flexibility shown for the 1X thrust class flowpath dimensions, and this is a very desirable characteristic.

Description of Configuration	File Name in Trade Study	Length, Inches	Width, Inches	Weight, Klbs	Min Φ Value	Min Φ F_G(KLb_F)	Isp, Sec	T/W Ratio
1X-Baseline; compromise between ϕ, Wgt, cmplxity	TBCC-BL	326	12	.1731	.7906	2.331	1060	13.47
1X-Best cooling Φ in 1X engine lengths studied	TBCC-BL-Struc_Op	326	12	.1941	.7590	2.258	1070	11.63
10X-10 12” BL modules ganged side-by-side	TBCC-BLx10	326	133.5	1.734	.7906	23.31	1060	13.44
10X-2 60” wide BL modules back-to-back or separate	**TBCC-BL_5X-fix2**	**326**	**121.5**	**1.569**	**.5987**	**23.88**	**1435**	**15.22**
10X-2 L x 5 W non-linear scaling of 1X dimensions	TBCC-10X_NL12_Struc-Circ-Opt_718-Comb	652	60.0	2.48	.6524	23.68	1307	9.55
10X-Linearly-scaled 1X (Sqrt10 factor on all dim)	TBCC-10X_Linear_Struc-Opt2&718Comb	1031	37.95	2.43	.6804	23.56	1212	9.71
100X-Linearly-scaled 10X 10-ganged (or 2x5-gang)	TBCC-100X_10mod_ Cir_Opt	1031	393.0	24.1	.6804	235.9	1248	9.79

Figure 24. Performance Comparison Summary for Baseline, 10X and 100X Scale Engines

2. Life Trades

All results presented to this point assumed a single expendable mission life, but applications for the larger engines would require the capability for longer life and possibly man-rating. These requirements impose additional constraints on the structural and thermal designs, and *SRHEAT*™ includes the capability to handle these considerations. A brief trade study was conducted to evaluate the impact of life requirements on performance and weight for the linearly-scaled 10X engine design, since these results are applicable to either 10X or 100X thrust classes.

The results of this trade study, Fig. 25, suggest that adding reusability and increasing life to 10 hours will have negligible effects. No fuel flow increase would be required, and only minor weight growth occurs. This is an encouraging result since this configuration was not particularly robust, suggesting that even better results might be achieved with the shorter, more robust 1X and derivative 10X geometries. Unfortunately, this trend did not continue to the 100 hour life case, where the effects of material creep became a dominant factor. The 100-hour life case was run with the same geometry definition, resulting in high fuel pressure that drove the plumbing weight up, while still predicting structural failure. *SRHEAT*™ was then allowed to find the optimal structure to eliminate this failure for the 100 hour case, and this resulted in the unacceptable structural weight growth shown in the last row. The last two cases are unacceptable from both fuel flow and weight perspectives. This suggests that the more robust shorter flowpath derivatives may be needed if operational life of 100 hours or greater is required, using conventional materials and the assumed construction techniques. Other viable alternatives to maintain acceptable performance and weight include use of alternative uncooled materials and/or reduced design Mach number.

File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
10X_Linear_BL_1Hr-Exp	410.87	19.43	0.6993	1925	23560	404.3	195.1	599.4	1935.6	2535
10X_Linear_BL_1Hr-Reuse	410.87	19.43	0.6993	1925	23560	404.3	195.1	599.4	1983.9	2583.3
10X_Linear_BL_10Hr-Reuse	410.87	19.43	0.6993	1925	23560	404.3	195.1	599.4	1985.1	2584.5
10X_Linear_BL_100Hr-Reuse	410.88	46.63	1.6782	1571	22590	1036.8	1267.3	2304.1	2115.8	4419.9
10X_Linear_StrucOpt_100Hr-Reuse	410.88	53.56	1.9276	1558	23000	1294.2	1797.9	3092.1	4583.8	7675.9

Figure 25. Comparison of Performance and Weight Characteristics with Life Requirements

3. Fuel Trades

The last sample trade to be covered is design sensitivity to fuel type. All results to this point are based on the use of JP-7, the low vapor pressure fuel developed originally for use in the supersonic SR-71 powered by P&W J58 turbojet engines. No longer in production, JP-7 is unusual in that it is not a distillate fuel but is created from special blending stocks in order to have very low (<3%) concentration of highly volatile components like benzene or toluene, and almost no sulfur, oxygen, and nitrogen impurities[12]. It also has high thermal oxidation stability and

endothermic properties that make it desirable for cooling of the subject DMSJ engine flowpath components. Since JP-7 is no longer available, different hydrocarbon fuels will be needed for future DMSJ applications, and *SRHEAT*™ includes the capability to evaluate commonly available alternatives. Future versions of *SRHEAT*™ will also include the ability to synthesize and evaluate new fuels.

The 1X baseline flowpath architecture was exercised with several alternative fuels to illustrate this valuable *SRHEAT*™ capability, and results are summarized in Fig. 26. The baseline case, shown in the first row, achieves thermal equilibrium at a Phi value of 0.79, while weighing just 173.4 Lbs. Substitution of RP1 for JP7 with no changes in cooling system circuit or geometry results in very similar equilibrium conditions, with a Phi increase of ~1% required. This is an expected outcome since RP1 is chemically similar to JP7. Similarly, no difference would be expected for RP2 since it is a reduced sulfur variant of RP1, which should be even closer to JP7. Results were much different for JP10, however, where Phi is seen to increase to 1.38 (a 74% increase), and weight increases by 34%. A significant structural redesign was required to achieve this closure, doubling the flow passage area and increasing the liner thickness by 30% in the process.

File Name	Total Air Flow Rate (lbm/s)	Total Fuel Flow Rate (lbm/s)	Phi	Max Metal Temperature (°R)	Total Thrust (lbf)	Total Manifold Weight (lbs)	Total Pipe Weight (lbs)	Total Plumbing Weight (lbs)	Total Structural Weight (lbs)	Total Cooling System Weight (lbs)
1X_BL_JP7	41.13	2.2	0.791	1945	2331	2.4	4.3	6.7	166.7	173.4
1X_BL_RP1	41.13	2.25	0.8015	1956	2340	2.4	4.1	6.5	166.7	173.1
1X_BL_JP10	41.09	4.01	1.3773	1907	2340	4.6	5.3	9.9	221.6	231.5

Figure 26. Comparison of Design Sensitivities to Fuel Type

III. Conclusions

The Ramjet/Scramjet Heat Exchanger Analysis Tool, *SRHEAT*™, is an extremely flexible tool for conceptual design and analysis of thermally balanced hypersonic propulsion systems. Developed by SPIRITECH under AFRL SBIR funding, this physics-based tool provides a system level thermal analysis that balances the heat load from the gas path, through the liners, and into the fuel. With capability for rapid, yet accurate, structural and thermal analyses, *SRHEAT*™ can identify complex cooling system trades early in the conceptual design cycle, allowing both the propulsion system and air vehicle designers to evaluate a wide range of design options without the large engineering time expenditures normally required for in-depth trade studies.

This user-friendly design tool was developed with ease-of-use as a primary focus. Simple drop-down menus are included for a number of inputs, including coolant fuel and construction materials. Flowpath geometry input is also simplified, but not compromised, and includes a graphic representation of most input characteristics. Major component parts (i.e., forebody, inlet, isolator, cavity, combustor, nozzle and aftbody) are handled separately, and different materials, coolant flow directions, and construction details can be input independently for each. Ramjet or scramjet cycle conditions can be input directly or assessed transparently by RJPA using input component efficiency estimates. A GUI interface is provided for all inputs, including initial estimates of both coolant circuit order and structural dimensions. Alternatively, optimal circuit order, structural details, and coolant passage dimensions can be determined automatically, based on user input of allowable ranges and relative importance of fuel flow and weight.

Preliminary trade studies were conducted over a wide range of parameters, from flowpath shape and thrust size to construction material and fuel type, to illustrate the utility of *SRHEAT*™. Results presented illustrate the range of variables and conditions that can be rapidly evaluated in the trade study mode. A number of significant conclusions have been drawn based on results of these sample trade studies:

- The baseline 2D flowpath evaluated, with a 3-inch combustor height, is an extremely robust design with low minimum cooling flow sensitivity to a wide range of primary design parameters, including circuit order and coolant passage geometry details. This makes it a good candidate for derivative engine configurations.
- Engines with larger flowpath length dimensions show greater sensitivity to circuit order and coolant passage structural dimensions, and may require material substitutions or alternative cooling circuit design approaches for components with high heat transfer rates to achieve acceptable design closure.
- Use of uncooled flowpath elements is probably required to achieve steady-state operation at Mach 8 and above without resorting to more exotic cooling systems or fuel recirculation. At lower speeds, many viable trades are possible between flowpath geometries, fuels, and construction materials.

While a large number of trade study examples were presented, many additional trades are possible with the range of input parameters offered in *SRHEAT*™, and on-going improvements in fuel and construction material capabilities will further increase the utility of this powerful conceptual design tool.

References

[1] E.J. Gamble, J.L. Gutierrez, J. Bachmann, T. Jobin, D. Williford, "*A Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)*", JANNAF, December 2005

[2] E.J. Gamble, J.L. Gutierrez, D. Giel, J. Bachmann, T. Jobin, D. Williford, C. Raffoul, "*Development of a Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)*", AIAA-2008-4614, July 2008

[3] E.J. Gamble, D. Giel, C. Raffoul, "*Systematic Optimization Approach for Scramjet/Ramjet Heat Exchanger Analysis Tool (SRHEAT™)*", AIAA-2008-5173, July 2008

[4] Bobby W. Sanders, Lois J. Weir, *"Aerodynamic Design of a Dual-Flow Mach 7 Hypersonic Inlet System for a Turbine-Based Combined-Cycle Hypersonic Propulsion System"*, NASA/CR-2008- 215214, June 2008

[5] Saied Emami, Carl A. Trexler, Aaron H. Auslender, and John P. Weidner, *"Investigation of Inlet-Combustor Isolators for a Dual-Mode Scramjet at a Mach Number of 4"*, NASA Technical Paper 3502, May 1995

[6] Wikipedia article, "*Rockwell X-30*", http://en.wikipedia.org/wiki/Rockwell_X-30

[7] DARPA Tactical Technology Office (TTO) Falcon program, http://www.darpa.mil/tto/programs/Falcon.htm

[8] P.P. Pandolfini, F.S. Billig, G.P. Corpening, and M.A. Friedman, "*Analyzing Hypersonic Engines Using the Ramjet Performance Analysis Code*", APL Technical Review, Vol. 2, No. 1, 1990, pp.118-126

[9] P.J. Waltrup, F.S. Billig, "*Prediction of Precombustion Wall Pressure Distributions in Scramjet Engines*", Journal of Spacecraft and Rockets, Vol. 10, No.9, Sep. 1973

[10] William H. Heiser, David T. Pratt, "*Hypersonic Airbreathing Propulsion*", AIAA Education Series, ISBN 1-56347-035-7, 1994, pp.346-355

[11] David E. Reubush, *"Lessons Learned from the X-43"*, NIA Short Course on Advanced Hypersonic Propulsion, October 25, 2007

[12] Wikipedia article, *"JP7"*, http://en.wikipedia.org/wiki/JP-7