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SCCREAM (Simulated Combined-Cycle Rocket Engine Analysis Module): A Conceptual RBCC Engine Design Tool

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SCCREAM (Simulated Combined-Cycle Rocket Engine Analysis Module): A Conceptual RBCC Engine Design Tool

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ABSTRACT

Rocket-based combined-cycle engines are currently under consideration for use on future, reusable launch vehicles. By combining traditional rocket and airbreathing operating modes into a single engine, multi-mode RBCC engines offer a number of advantages for launch vehicle designers including higher trajectory averaged I_{sp} than pure rockets and higher installed thrust-to-weight ratios than pure airbreathers.

This paper presents a new computer tool capable of predicting RBCC engine performance (thrust and I_{sp}) over a wide range of flight conditions and engine operating modes. The tool is called SCCREAM — Simulated Combined-Cycle Rocket Engine Analysis Module. SCCREAM is an object-oriented workstation-level code written in C++. It uses quasi-1D flow analysis, component and combustion efficiencies, and an inlet pressure recovery schedule as simplifying assumptions. SCCREAM was created for the conceptual launch vehicle design environment and is capable of quickly generating large tables of engine performance data for use in trajectory optimization.

An overview of SCCREAM and the program logic is presented. Results from SCCREAM are favorably compared to historical RBCC engine performance data and to data generated by other engine design tools.

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NOMENCLATURE

A_i	engine cross-sectional area at station *i* (ft^2)
C_p	constant pressure specific heat (BTU/slg-R°)
C_t	thrust coefficient (thrust/q*A_1)
ERJ	ejector ramjet
ESJ	ejector scramjet
I_{sp}	specific impulse (sec)
LH2	liquid hydrogen
LOX	liquid oxygen
P_t	total pressure
phi	combustor equivalence ratio
POST	Program to Optimize Simulated Trajectories
q	freestream dynamic pressure (lb/ft^2)
RBCC	rocket-based combined-cycle
SERJ	supercharged ejector ramjet
SESJ	supercharged ejector scramjet
SSTO	single-stage-to-orbit
γ	ratio of specific heats

RBCC BACKGROUND

Rocket-based combined-cycle engines are unique in that they combine the most desirable characteristics of airbreathing engines and rocket engines into a single, integrated engine. RBCC engines have the advantage of high average specific impulse (I_{sp}) in comparison to rockets, and high thrust-to-weight ratios in comparison to airbreathers.

The concept of combined-cycle engines has existed since the mid-60's. During this inception phase, an extensive study was conducted by the Marquardt Corporation, Lockheed-California, and the U.S. Air Force on various 'composite engine' designs, as they were formerly called [1]. This study initially analyzed 36 different variants of combined-cycle engines. At the study's conclusion, two types of RBCC engines were

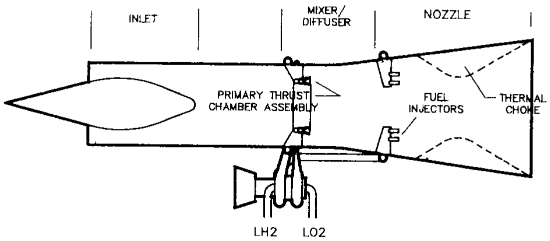

Figure 1 - Supercharged Ejector Ramjet Engine [ref. 1]

selected as the most interesting options — a near-term option and a far-term option. The decisions were made based on technological feasibility and resulting performance on a representative two-stage-to-orbit launch vehicle. The two final selections were the Supercharged Ejector Ramjet (SERJ) configuration (figure 1), and the more technically challenging Supersonic Combustion Ramjet with Liquid Air Cycle (ScramLACE) configuration. The SERJ engine configuration is composed of four operating modes: ejector, fan-ramjet, ramjet, and pure rocket. A derivative of the SERJ is the Supercharged Ejector Scramjet (SESJ). This configuration consists of five operating modes, the four from the SERJ and an additional scramjet mode.

During ascent phase, the RBCC engine initially operates in ejector mode. The ejector mode utilizes the rocket primaries (figure 2) as the main source of thrust. Entrained air from the inlet and fuel from the secondary fuel injectors is also burned in the combustor to provide additional thrust. A low-pressure

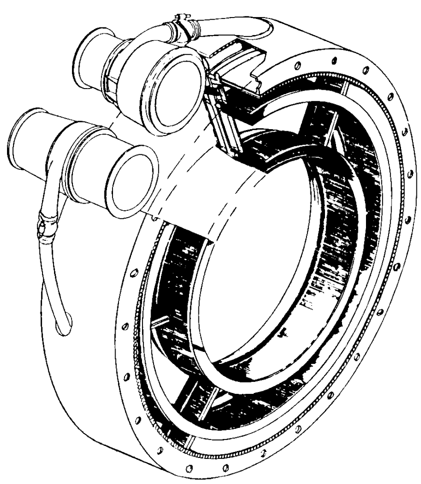

Figure 2 - Rocket Primary [ref. 2]

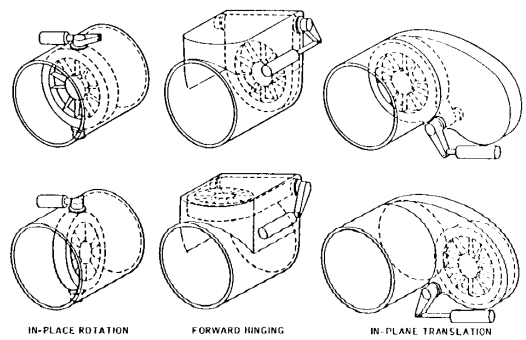

Figure 3 - Fan Storage Methods [ref. 2]

ratio fan, located between the inlet and primary, may also be used. Once significant ram pressure is achieved from the surrounding air, typically occurring around Mach 2 to 3, the rocket primaries are shut off. The fan remains functioning up to about Mach 3, constituting the fan-ramjet mode. At Mach 3, the fan is removed from the flow path or perhaps windmilled in place to as high as Mach 6. Figure 3 shows possible methods for removing the fan from the flow path should that be necessary. The engine operates in pure ramjet mode up to around Mach 6. At Mach 6, depending upon the engine type (SESJ or SERJ), the engine will transition either to scramjet mode or directly to rocket mode. If scramjet mode is available, the engine will continue operating as an airbreather with supersonic combustion up to an optimal transition Mach number. Recent conceptual vehicle designs have suggested transition to pure rocket mode might optimally occur between Mach 10 and Mach 15. While transitioning to rocket mode, the inlet face is closed and the rocket primaries are restarted. Vacuum Isp’s in the range of 410-470 seconds are typical values during rocket mode.

PREVIOUS RESEARCH

Engineers in a conceptual RBCC launch vehicle design environment need to be able to assess engine performance at each point in the ascent trajectory. That is, for a given altitude, flight velocity, and engine operating mode, what thrust and I_{sp} are produced by the engine? This data is typically used in a trajectory optimization code to determine a minimum fuel flight path to orbit. Figure 4 from reference 3 gives typical RBCC engine I_{sp}’s for a representative vehicle flight profile.

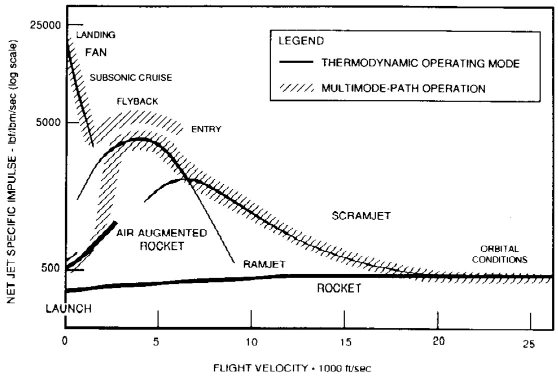

Figure 4 - Typical RBCC I_{sp} Performance [ref. 3]

Due to computing speed limitations, the required engine data is commonly generated off-line for a range of expected altitudes and flight speeds. The resultant database is formatted into a tabular form. Data is interpolated from the tables as needed by the trajectory optimization code.

The current engine analysis tool, SCCREAM, is a descendant of tools generated under earlier research efforts. Original research in 1993 resulted in a simple spreadsheet model that was capable of predicting RBCC engine performance in ejector mode only [4]. The original model could also incorporate a supercharging fan if required. The spreadsheet consisted of approximately 2,500 iterative calculation cells to perform the internal engine flow calculations. The spreadsheet generated properly formatted tabular data that could be electronically transferred to a workstation class computer and imported into a popular trajectory optimization program, POST [5].

Subsequent research extended the original spreadsheet model to include fan-ramjet and ramjet modes of operation [6]. The number of iterative spreadsheet cells increased to approximately 10,000. As in the original tool, this spreadsheet produced a properly formatted POST engine table that could be electronically transferred to a workstation for trajectory optimization. Unfortunately, recalculation of this expanded spreadsheet was slow. In addition, for certain initial guesses of flow conditions, the automatic internal spreadsheet iteration was often unstable. That is, the internal pressures, velocity, and Mach number iteration could easily diverge for certain flight conditions. To remedy the situation, a new standalone RBCC engine analysis tool was developed.

The newest tool, SCCREAM (Simulated Combined-Cycle Rocket Engine Analysis Module), is an object-oriented code written in C++. The code runs on a UNIX workstation, runs a full range of flight conditions and engine modes in under 30 seconds, has more stable internal iteration schemes, and retains the ability to output properly formatted POST engine tables. SCCREAM is not intended to be a high-fidelity propulsion tool suitable for analyzing a particular RBCC engine concept in great detail. Rather, it is a conceptual design tool capable of quickly generating a large number of reasonably accurate engine performance data points in support of early launch vehicle design studies.

SCCREAM

Overview

SCCREAM has the capability to model the performance of four types of LOX/LH2 RBCC engines. One is the configuration identified in the Marquardt study —the supercharged ejector ramjet (SERJ). The other three are the (non-supercharged) ejector ramjet (ERJ), the ejector scramjet (ESJ), and the supercharged ejector scramjet (SESJ). While SCCREAM does not model supersonic combustion directly, scramjet mode data for the latter two engine types is scaled from a previously published database of scramjet performance from NASA - Langley [7].

SCCREAM operates by solving for the fluid flow properties (velocity, temperature, pressure, mass flow rate, gamma, specific heat capacity, etc.) through the various engine stations for each of the engine operating modes. Equations for conservation of mass, momentum, and energy are used. This process is often iterative at a given engine station or between a downstream and an upstream station. The flow properties are calculated using quasi-1D flow equations. Engine cross-sectional area is the only geometry variable along the stream direction. Component inefficiencies are used to simulate losses of total pressure in the mixer and nozzle, and reduced enthalpy in both the rocket primary and main combustor. The inlet is simulated by a simple total pressure recovery schedule. Thrust and I_{sp} are determined using a control volume analysis of the entering and exiting fluid momentum and the static pressures at the inlet and exit planes.

Most internal areas in SCCREAM are determined based on ratios to the inlet/cowl cross-sectional area. Default area ratios are supplied, so typically a user enters only the inlet area. The size of the rocket primary unit is based on a user-entered propellant mass flow rate for the rocket primary. These two independent variables can be varied to produce an engine with a desired sea-level static thrust and secondary-to-primary mass flow ratio. In practice, however, the inlet area is often limited by overall vehicle geometry or shock-on-lip conditions. Optionally, the user can enter a desired sea-level static thrust and inlet area, and SCCREAM will iterate to determine the primary mass flow rate required.

In order to generate a POST engine table, a candidate engine's performance is evaluated over a range of altitudes and Mach numbers. These Mach number and altitude ranges can be set by the user. For example, a ramjet's operational Mach numbers might be set from 2 to 6, with altitude ranges from 30,000 feet to 150,000 feet. Overlapping Mach numbers and altitudes between various operating modes allows POST to select optimum engine mode transition points if desired. Default Mach number and velocity ranges are provided for each mode.

Performance in pure rocket mode is determined using flow equations for a high expansion ratio rocket engine operating in a vacuum. A user-enterable nozzle efficiency is used to account for losses associated with the expansion of the primary exhaust through the engine and then onto the aftbody.

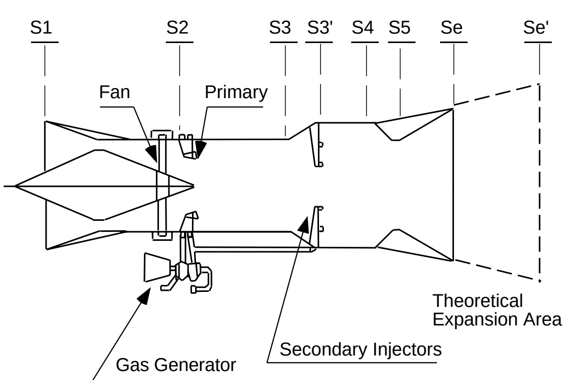

Figure 5 - SCCREAM Station Locations

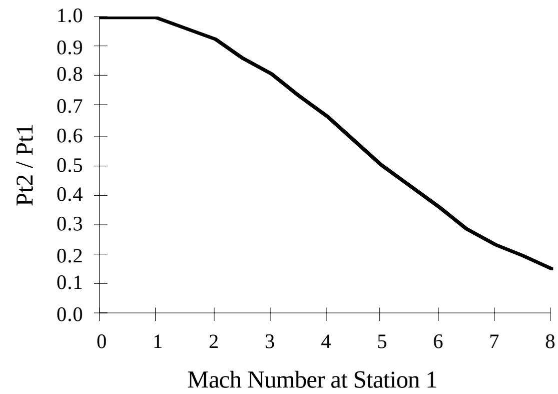

Figure 6 - MIL-E-5007D Inlet Pressure Recovery

<u>Station Calculations</u>

Figure 5 shows the station numbers and reference locations for a generic RBCC engine used by SCCREAM. Station 1 is the inlet plane of the engine. Freestream flow conditions at station 'infinity' are modified by a single shock wave to simulate the precompression effect of a vehicle forebody on the engine. The forebody shape (wedge or cone) and the forebody angle are entered by the user. Therefore the flow conditions at station 1 are typically not the same as the freestream flight conditions.

From station 1 to station 2, the total pressure recovery through the inlet is determined using a standard Mil-Spec recovery schedule for an inlet terminating with a normal shock (figure 6). Pressure recovery is defined as the total or stagnation pressure at station 2 divided by the total pressure at station 1. If a supercharging fan is present and operating, the total pressure at station 2 is subsequently adjusted by the fan pressure ratio. Typical single-stage fan pressure ratios are 1.3 to 1.5. Total enthalpy from station 1 to station 2 is constant. The mixer is assumed to be of constant cross sectional area, but the flow area at station 2 is reduced by the total exit area of the rocket primaries. That is,

$$A_2 = A_3 - A_p \quad (1)$$

where A_p is a function of the size of the rocket primaries. A_2 is therefore a 'pinch point' in the engine inlet due to the blockage caused by the rocket primary.

In ejector mode, the secondary mass flow (i.e. the mass flow rate of air through the inlet) is determined by the minimum inlet area or 'inlet throat' area. The flow is assumed to be choked at this point. By default, the inlet throat area is assumed to be 25% of the inlet area in ejector mode. Should the combination of rocket exhaust from the primaries and secondary air flow through the inlet exceed that amount which can be passed through the mixer exit (A_3) for a given flight condition, SCCREAM automatically reduces the inlet throat area and thus the secondary airflow through the engine until the flow is just choked at station 3.

In fan-ramjet and ramjet modes, the default inlet throat area is assumed to be equal to A_2. That is, the inlet is opened up until the minimum inlet area occurs at the pinch point around the rocket primaries. In this case, the secondary airflow through the engine is either the mass flow rate that can be passed through station 2 or the maximum mass flow rate captured by a wide open inlet area — whichever is less. At flight Mach numbers up to 3 or 4, the secondary mass flow tends to be limited by the pinch point at A_2 (note that the inlet area A_1 must also be reduced in this case). At higher Mach numbers, the secondary mass flow is generally limited by the maximum inlet area and is more typical of standard ramjet analysis.

Knowing total pressure, total enthalpy, secondary mass flow, and area, the solution for the Mach number at station 2 is iterative. For a guessed Mach number, the flow velocity at station 2 can be calculated in two ways — one using the temperature and Mach number (i.e. the definition of Mach number) and the other using pressure, temperature and mass flow rate (i.e. conservation of mass). SCCREAM uses a bisection routine to find the Mach number that drives the difference between the two calculated velocities to zero. For ejector, fan-ram, and ramjet modes, the subsonic solution for Mach number is always selected.

Between stations 2 and 3, the primary rocket exhaust (if present) is mixed with the secondary air from the inlet. SCCREAM assumes that the rocket primaries operate stoichiometrically (LH2/LOX = 1/8 by weight) and that no combustion occurs in the mixer. This is known as the diffusion-then-afterburning cycle. Again, the equations for conservation of mass, momentum, and energy are used to iteratively solve for the static pressure, temperature, and velocity at station 3 using the Mach number as an iteration variable. New primary + secondary flow specific heat (C_p), ratio of specific heats (γ), and molecular weight are also calculated at station 3 during the iteration process. Mass averaging techniques are used for C_p and molecular weight. The primary rocket mass flow rate (set by the user), the exhaust velocity, enthalpy, and pressure, the primary exit area, and the secondary flow conditions at station 2 are all knowns in the station 3 iteration process. As previously mentioned, if the total mass flow rate in ejector mode is too large to be passed through station 3, the inlet throat area is reduced until the flow is just choked at station 3. The total pressure calculated at station 3 after the solution has converged is multiplied by a mixer efficiency to account for viscous losses, etc.

The flow undergoes a simple isentropic expansion from station 3 to station 3' — just before the secondary fuel injectors. The combustor is assumed to be constant area. Therefore,

$$A_{3'} = A_4 \qquad (2)$$

The combustor area is input by the user as a ratio to the mixer area (A_4/A_3). The mixer ratio is specified as a ratio to the inlet area (A_1/A_3). Default area ratio values are provided.

The combustor operates at a user-defined maximum equivalence ratio, phi. Phi is the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. A phi of 1 indicates stoichiometric combustor operation. For a given phi, SCCREAM uses the conservation equations for heat and mass addition in a 1-D flow to determine the exit conditions from the combustor (station 4). As with other stations, these equations require an iterative solution. The combustion of hydrogen fuel with atmospheric oxygen is modeled as a heat release based on the fuel flow rate and the heat of reaction. An efficiency is included on the heat of reaction. Combustion is assumed to be complete and one way. O_2, H_2, H_2O, and N_2 are the only valid combustion species. A phi = 1 therefore results in

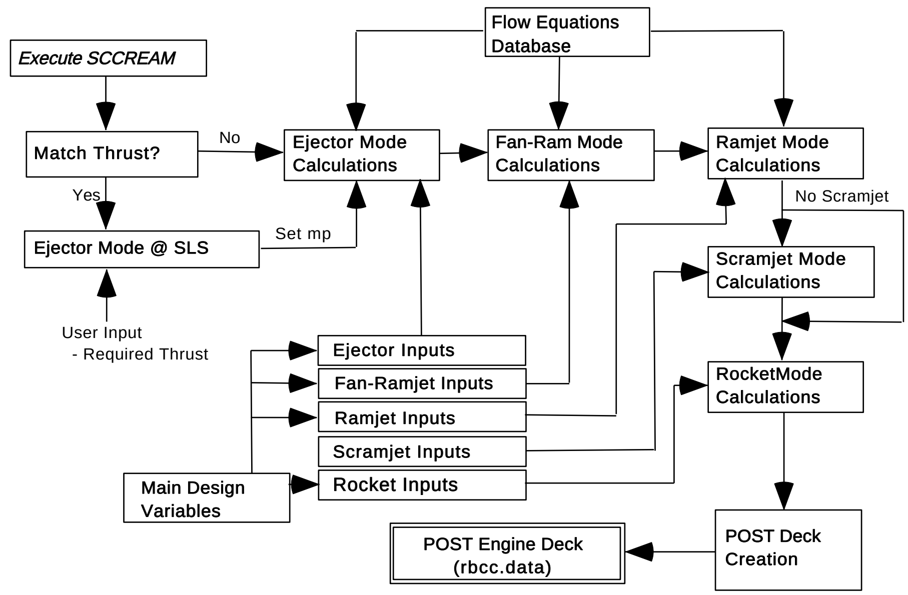

Figure 7 - SCCREAM Execution and Data Flow

only H_2O and N_2 products of combustion. A new γ, C_p, and molecular weight are also calculated at station 4.

If the user-input maximum phi results in a mass flow rate that cannot be passed through the combustor exit, SCCREAM automatically reduces phi at that flight condition until the flow is just choked at station 4. This typically occurs at the lower Mach numbers in fan-ramjet and ramjet modes.

The total pressure entering the nozzle (just past station 4) is reduced by a nozzle efficiency to account for viscous losses in the nozzle. Otherwise, the chemistry of the nozzle is assumed to be frozen at the composition exiting the combustor. The nozzle is a simple converging-diverging nozzle that expands the flow to supersonic speeds. At lower altitudes, the nozzle expands the flow to atmospheric pressure (ideal expansion). At higher altitudes, nozzle expansion is limited by a maximum exit area and the flow is often underexpanded. SCCREAM allows a user to model the effect of vehicle aftbody expansion by including a 'maximum theoretical expansion area' that increases with altitude. The rate at which the theoretical exit area increases and it's maximum value are user inputs. The exit pressure, exit velocity, and exit mass flow rate are used in a control volume equation along with the inlet conditions to determine the overall engine thrust, thrust coefficient (C_t), and I_{sp}. Thrust coefficient in the airbreathing modes is defined as,

$$C_t = \frac{\text{Thrust}}{q * A_1} \qquad (3)$$

where A_1 is a fixed constant (the inlet area). C_t is a common way to non-dimensionalize engine thrust to enable parametric scaling by inlet size and flight path.

<u>Program Execution</u>

Figure 7 is a flowchart that describes the general execution logic of SCCREAM. The flow diagram begins with the 'Execute SCCREAM' block and proceeds through each operational mode of the engine, with a few contingencies depending upon the engine configuration selected. Worth noting is the 'flow equations database' block. This block represents a C++ class object that contains all the necessary equations to determine temperatures, pressures, Mach numbers, etc. at each station inside the engine. The equations in this shared database are used in determining performance in the ejector, fan-ramjet, and ramjet modes. The use of C++ and the class construct eliminates the need for excessive variable passing, as all variables are contained in a common area accessible by each other. This feature makes SCCREAM easy to read, debug, and modify.

Note that the flowchart also includes a block labeled ‘scramjet’. While SCCREAM does not analyze supersonic combustion directly, a previously published scramjet performance database [7] generated at NASA - Langley has been included in SCCREAM for creating engine performance tables for scramjet-capable SESJ and ESJ RBCC engines. This existing data consists of a table of scramjet I_{sp} and C_t vs. Mach number. It is linearly scaled to provide a smooth transition from SCCREAM’s Mach 5 ramjet data at each altitude. That is, for scramjet engines, SCCREAM is used to generate ramjet values for C_t and I_{sp} up to Mach 5 for various altitudes. Then the NASA scramjet data is scaled up or down and appended to the SCCREAM data *at each altitude* so that no discontinuity occurs in C_t or I_{sp}, but the trends in the NASA data are maintained.

SCCREAM Input and Output Files

SCCREAM operates either as a standalone executable code or as a contributing analysis in a larger design process. User input data is read from several files. Each engine mode has its own input file which

```
Primary_Flow_Rate      216.0 LBM/S
Number_Throttles       1
Throttle_Setting1      1.0
Forebody_Shape         CONE
Fan_Po_Ratio           1.0
Area_Inlet             30.0 ft2
Equivalence_Ratio      1.0

eta_Mixer              0.98
eta_Combustor          0.95
eta_Nozzle             0.98
```

Figure 8 - Sample Common Input File

```
l$tblmlt genv6m=577.8,
tvc1m=5,tvc2m=1,tvc3m=1,
 $
0,
        0,  80351.4
    0.25,  78268.2,
    0.50,  81398.3,

        6,  2611.57,
 $end
l$tab table=4hae2t,0,150 $
l$tab table=4hae3t,0,88.1674 $
```

Figure 9 - Sample Output (POST Engine File)

contains that particular mode’s requested Mach number and altitude ranges. A common input file for the main design variables (figure 8) is used by all modes except for scramjet. Included in this file are the primary flow rate, engine geometry, and station efficiencies. After each engine mode has been analyzed, a properly formatted POST engine file (figure 9) and additional data analysis files are created. SCCREAM runs very quickly. 100 different flight conditions and operating modes can be analyzed in about 30 seconds on a Silicon Graphics Indigo^2 workstation.

RESULTS

Reference Vehicle

To compare the RBCC engine data generated by SCCREAM to data available from other sources, a test case vehicle was adopted. Figure 10 shows a packaging view of the Hyperion launch vehicle. Hyperion is an advanced single-stage-to-orbit (SSTO) launch vehicle currently being investigated by students in the Aerospace Systems Design Laboratory at Georgia Tech. The vehicle is fully reusable and takes off and lands horizontally. It uses five LOX/LH2 ejector scramjet (ESJ) RBCC engines for primary propulsion. Small rocket engines are provided on the top of the aftbody to provide trim on ascent. The forebody has a conical lower surface with a 10° cone half angle and a shallow elliptical upper surface.

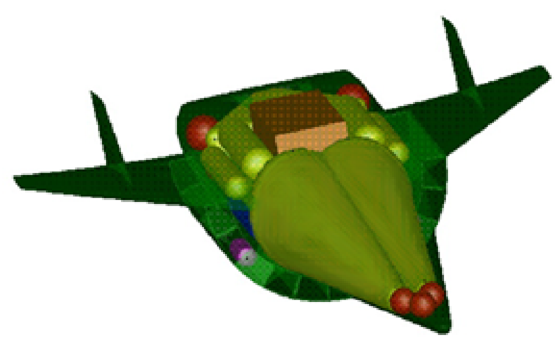

Figure 10 - Hyperion SSTO Launch Vehicle

Hyperion is capable of powered landing and self-ferry using four small hydrocarbon-fueled ducted fans mounted under the wings. These engines are protected by a retractable inlet cover during ascent and entry.

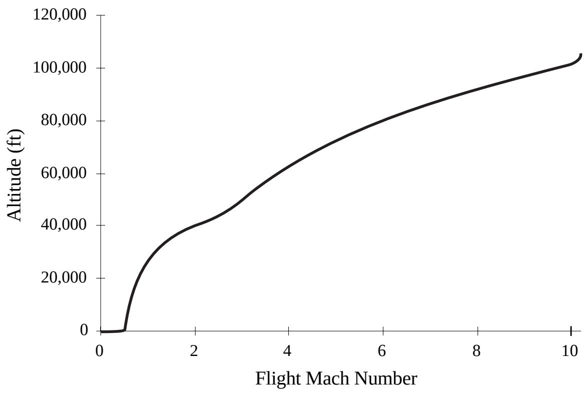

Figure 11 - Hyperion Ascent Trajectory

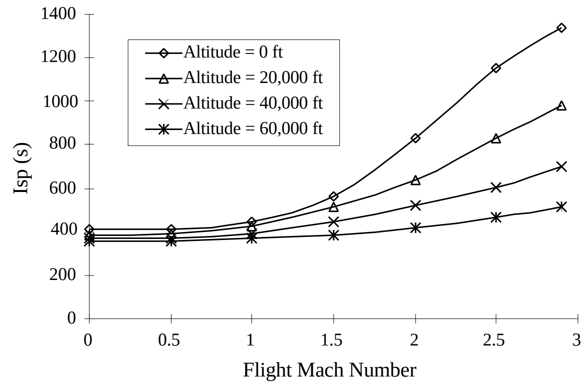

Figure 12 - Ejector Mode I_{sp} Results

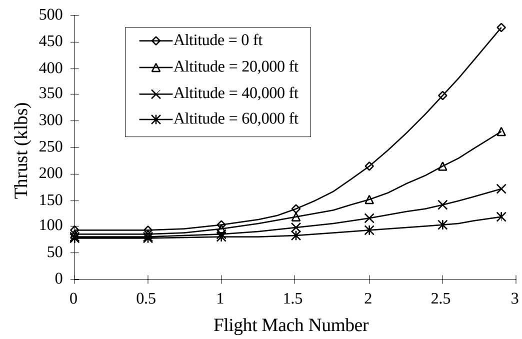

Figure 13 - Ejector Mode Thrust Results

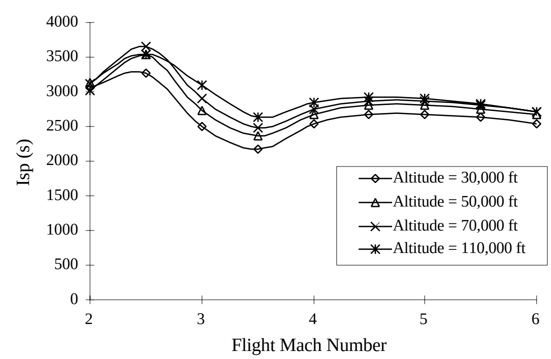

Figure 14 - Ramjet Mode I_{sp} Results

Hyperion is designed to deliver 10,000 lb to the International Space Station (220 nmi. x 220 nmi. x 51.6°) from Kennedy Space Center. It is unpiloted and could be operational by the year 2010. In ramjet and scramjet modes, the vehicle flies a constant dynamic pressure boundary trajectory of 1,500 psf (figure 11). Transition from scramjet mode to pure rocket mode occurs at Mach 10.

Table 1 summarizes the per engine ESJ engine characteristics for each of the five RBCC engines on the Hyperion. Note that the combination of required sea-level static thrust and fixed inlet area resulted in an ejector mode primary mass flow rate of 216 lbm/s. A pure rocket mode vacuum I_{sp} of 462 sec. was assumed.

Table - 1 Hyperion (Reference) ESJ Engine Data

inlet area, A_1	27 ft^2
'pinch point' area, A_2	8.24 ft^2
mixer area, A_3	11.25 ft^2
combustor area, A_4	22.5 ft^2
maximum exit area	95 ft^2
required sea level thrust	92,650 lb
nominal maximum phi	1.0

SCCREAM was run to generate engine performance data sets in ejector mode (from Mach 0 to Mach 3) and ramjet mode (from Mach 2 to Mach 6) over a range of altitudes for the reference engine. A second data set for a maximum phi = 0.6 was also generated. NASA - Langley scramjet data was scaled and appended to the ramjet data between Mach 5 and Mach 10 as previously described.

Figures 12 and 13 show a sample of the data set generated for ejector mode. Note the expected improvement in ejector I_{sp} and thrust as the vehicle accelerates (increases secondary flow rate). However, this augmentation effect is reduced at higher altitudes.

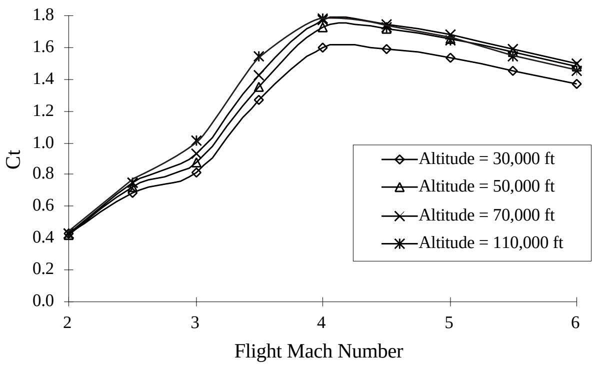

Figure 15 - Ramjet Mode C_t Results

SCCREAM generated data for ramjet mode I_{sp} and thrust coefficient are shown in figures 14 and 15. Note the unusual behavior in I_{sp} around Mach 3. As expected, the I_{sp} rises between Mach 2 and Mach 2.5 as thrust increases due to increased total pressure and secondary mass flow rate through the engine. However at around Mach 2.5, the I_{sp} unexpectedly begins to decline. A more detailed investigation of the results indicated that this decline is a result of secondary mass flow being limited by the area at station 2 — the inlet pinch point. As flight Mach number rises, the total pressure losses through the inlet increase, but in this case, the increase in secondary mass flow rate through the engine is slow to offset the losses. This effect is also evident in figure 15 as a smaller increase in C_t between Mach 2.5 and 3.

Between Mach 3 and 4, the limitation on engine secondary mass flow rate switches to become limited by the inlet area (like a more traditional ramjet), but the combustor would choke at the user-input phi = 1.0. SCCREAM has automatically throttled phi in this range. The result is a temporary increase in I_{sp} around Mach 4. I_{sp} and C_t behavior beyond Mach 4.5 is more typical of a ramjet with a phi = 1 and secondary mass flow rate limited by inlet area. Note that the effect of increased thrust coefficient with increasing altitude is primarily due to the increasing theoretical (aftbody) exit area as the vehicle ascends.

Using the phi = 1 SCCREAM data set, thrust and I_{sp} were calculated along a reference trajectory for Hyperion. Engine performance was determined at each altitude. Typical engine station flow values at two points along the reference trajectory are shown in table 2. It is important to note that a SCCREAM *data set* is not associated with a particular flight path, but is a range of thrust and I_{sp} vs. Mach number and altitude. Flying an optimum trajectory though the data set results in a specific history of I_{sp} and C_t (or thrust) vs. Mach number.

Table 2 - Sample SCCREAM Station Results

Ejector Mode for Reference Hyperion SSTO

Flight M=0.5 Phi=1.0	S_1	S_2	S_4	S_e
Area (ft^2)	27.0	8.24	22.5	17.3
Local Mach Number	0.50	0.57	-	1.51
Velocity (fps)	558.1	636.5	-	5290.1
Total Pressure (lb/in^2)	17.7	17.7	50.8	50.8
Total Temperature (R°)	544.6	544.6	5544.7	5544.7

Ramjet Mode for Reference Hyperion SSTO

Flight M=3.5 Phi=1.0	S_1	S_2	S_4	$S_{e'}$
Area (ft^2)	27.0	8.24	22.5	44.3
Local Mach Number	3.02	0.63	0.90	2.08
Velocity (fps)	3278	1083	2488	4870
Total Pressure (lb/in^2)	100.4	78.2	45.3	45.3
Total Temperature (R°)	1345	1345	3446	3446

<u>Comparison with Other Engine Performance Data</u>

To validate the thrust, C_t, and I_{sp} values generated by SCCREAM, the results have been compared to engine data from other sources. The early Marquardt study [1] (referred to as NAS7-377 on the following figures) contains extensive RBCC engine performance data including ERJ ramjet and ESJ scramjet mode thrust and I_{sp} for a vehicle flying along a 1500 psf dynamic pressure boundary. The NAS7-377 data used in this paper is for an 8° half-angle wedge. The ERJ thrust data was converted to C_t using an 82 ft^2 inlet area and q = 1500 psf. The ESJ data used a 100 ft^2 inlet area.

A study of RBCC engines performed in 1988 by the Astronautics Corporation for the U.S. Air Force [3] contains C_t data for a scramjet and complete I_{sp} data for a ESJ engine over a 1500 psf trajectory. In the reference, C_t data is tabulated directly and does not have to be calculated from a known thrust. Although the vehicle baselined in that study was a 10° half-angle cone, the available tabulated I_{sp} data in the reference is for a 6° half-angle wedge.

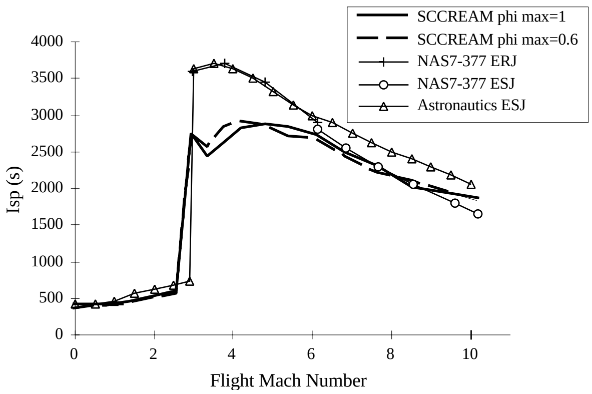

Figure 16 - I_{sp} Comparison Data (group 1)

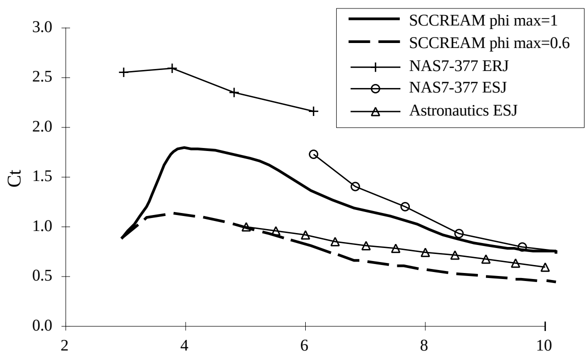

Figure 17 - C_t Comparison Data (group 1)

The effect of forebody precompression on an RBCC engine is not insignificant. Larger forebody angles tend to generate more thrust, but have a slightly lower I_{sp}. In addition, internal geometry areas and assumptions will certainly cause differences between data sets. However, the data from NAS7-377 and the Astronautics study are thought to provide a reasonably good comparison for SCCREAM appled to the Hyperion trajectory.

Figure 16 shows the engine I_{sp} for the two SCCREAM cases, the NAS7-377 ERJ and ESJ data, and the Astronautics study data for an ESJ. Figure 17 shows comparison data for C_t in ramjet and scramjet modes. C_t provides a better comparison in airbreathing modes than overall thrust due to the differences in reference vehicle size among the data sets.

Comparison of I_{sp} in figure 15 indicates good agreement in ejector mode and scramjet modes. However, SCCREAM yields a slightly lower I_{sp} in ramjet mode than the comparison data. It is thought that this effect is caused by the small A_2 in the Hyperion engine and it's effect on limiting secondary mass flow rate at those Mach numbers. However, work is continuing to verify this conclusion. The SCCREAM thrust coefficient data in figure 17 is nicely bounded by the two comparison sets. Compared to the I_{sp} results, the larger differences among the C_t data sets are probably due to different internal engine geometries and forebody precompression assumptions as previously discussed.

Comparison with Other Engine Analysis Codes

A comparison also was made to evaluate SCCREAM against other engine performance codes. SRGUL is the engine performance tool used to generate the NASA - Langley ramjet and scramjet performance data in reference 7. SRGUL is a higher fidelity code than SCCREAM, but is more time consuming to set up and run. It uses oblique shock solutions in the inlet, a marching solution for reacting flow through the combustor, and a method of characteristics solution for the nozzle. Viscous effects due to boundary layer growth are handled throughout. To achieve this extra detail, each engine flight condition requires significant setup and validation time. SRGUL is typically used in a *preliminary* design effort where the vehicle, engine geometry, and the flight profile are better established rather than in the *conceptual* environment for which SCCREAM was developed.

Note that the SRGUL data from reference 7 is also the data internally scaled by SCCREAM to predict scramjet performance above Mach 5. However, the SRGUL data presented in the following charts is the raw data (unscaled) from reference 7 for both ramjet and scramjet modes. The SRGUL data was generated for a 5° half angle cone. However, it is not for an RBCC engine. That is, the engine is a straight dual-mode ramjet/scramjet. There are no rocket primaries in the flow and therefore no pinch point in the inlet.

RAMSCRAM [8] is a ramjet and scramjet analysis tool developed by the NASA - Lewis Research Center. It is also capable of modeling ejector mode. RAMSCRAM is similar to SCCREAM, in that it was created for use in the conceptual design environment. It uses a pressure recovery through the inlet (or a kinetic energy efficiency) and quasi -1D flow throughout. The combustion model in RAMSCRAM is more detailed than that used in SCCREAM, and accounts for equilibrium chemistry. That is, the composition of the flow leaving the combustor is a function of chemical equilibrium determined from pressure and temperature. Recall that SCCREAM assumes the reaction is complete and that only major constituents are produced in the combustor. The combustor area in RAMSCRAM can be constant or increasing.

RAMSCRAM does not automatically adjust phi or secondary mass flow rate if there is a choking problem in the engine (the user must correct the error manually), but it does have a feature to vary station area as needed to pass the mass flow (called engine design mode). The code can run a number of flight conditions at once, but the output is not formatted as a POST engine input table and must be post-processed. Typically, RAMSCRAM is run only for points along a predetermined flight path, rather than creating a broad data set over a range of Mach numbers and altitudes. RAMSCRAM is written in FORTRAN.

RAMSCRAM was used (by the authors) to model the reference Hyperion engine geometry and to predict engine thrust and I_{sp} at several points along the reference 1500 psf flight path. In ramjet mode, RAMSCRAM used the same inlet pressure recovery as that used by SCCREAM (figure 6). In scramjet mode, RAMSCRAM used a 98.5% inlet kinetic energy efficiency. The engine mixer area, pinch point area, and combustor areas according to table 1 were kept constant in RAMSCRAM. Inlet throat area and combustor phi were adjusted according to the same logic used by SCCREAM as necessary to prevent choking. Precompression effects for a 10° cone and aftbody expansion benefits were also included.

Figures 18 and 19 compare the SCCREAM results to SRGUL and RAMSCRAM for the Hyperion trajectory. The SRGUL data is for phi = 1. The RAMSCRAM data is for a maximum phi = 1. When running RAMSCRAM, the secondary mass flow rate (pinch point) and phi (combustor) both had to be reduced to prevent choking in ramjet mode at Mach 3. The phi also had to be reduced to prevent combustor choking in scramjet mode at Mach 6.

With the exception of the dip in the SCCREAM data around Mach 3, the SRGUL data and the SCCREAM data compare favorably in I_{sp}. Recall that SCCREAM and RAMSCRAM model a pinch point area due to the rocket primary and the SRGUL data does not. The RAMSCRAM I_{sp} data bounds the other two sets but at a somewhat higher than expected margin of error. However, the I_{sp} trends for all three codes appear to be similar. Note the sharp transition from subsonic to supersonic combustion operation predicted by RAMSCRAM. A smooth transition between modes was not modeled, rather the entire internal flow was either subsonic or supersonic.

SCCREAM and SRGUL C_t results compare well. As expected, the SCCREAM phi = 1 results are slightly higher than the SRGUL data due to the benefits of extra forebody compression (a cone half angle of 10° vs. 5° for SRGUL). The effects of limited secondary mass flow at the pinch point and a throttled phi to prevent choking in the constant area combustor are clearly evident in the downturns in C_t for

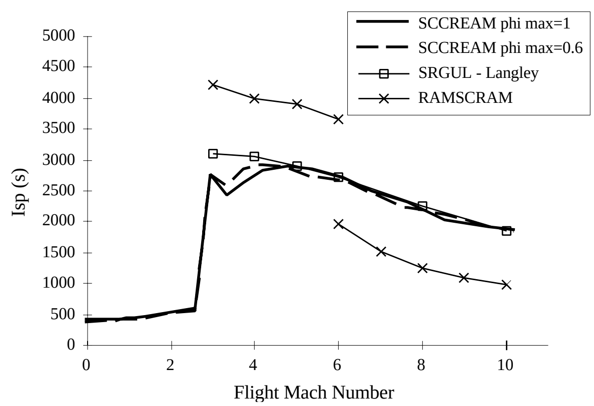

Figure 18 - I_{sp} Comparison Data (group 2)

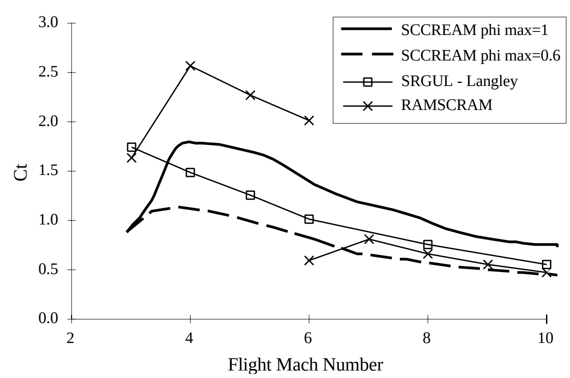

Figure 19 - C_t Comparison Data (group 2)

SCCREAM and RAMSCRAM at Mach 3 and for RAMSCRAM's supersonic flow result at Mach 6. Recall that there is no pinch point in the SRGUL data and there is no downturn of C_t at Mach 2.

The higher thrust coefficient predicted by RAMSCRAM in ramjet mode is almost certainly causing the higher I_{sp} also seen in figure 18. Work is continuing to identify the cause of this discrepancy, but it is likely due to differences in the combustor model between SCCREAM and RAMSCRAM.

CONCLUSIONS

An analysis tool for predicting RBCC engine performance has been developed and is well suited for use in the conceptual launch vehicle design environment. SCCREAM uses a quasi-1D engine analysis method to predict engine I_{sp} and thrust over a wide range of flight conditions. The code outputs a properly formatted engine table for use in an industry standard trajectory optimization code, POST. Among the conclusions drawn in this paper are the following:

1. Written in C++ and running operating on a UNIX workstation, SCCREAM is a significant improvement over it's spreadsheet-based predecessors in terms of speed, stability, and flexibility.

2. SCCREAM was easily integrated into the conceptual design process for a reference RBCC SSTO launch vehicle. SCCREAM generated engine performance tables were used to identify an optimum flight path trajectory.

3. For the reference engine geometry and flight profile tested, the results from SCCREAM compare favorably with previously published RBCC engine performance data as well as data produced by other engine analysis tools.

FUTURE WORK

SCCREAM will continue to be improved to increase it's accuracy and capabilities without sacrificing speed, ease of use, and flexibility. Among the near-term improvements being considered are the following:

1. The ability to analyze scramjet mode performance directly within SCCREAM. While the basic flow equations are in place, improvements to the combustion model, the inlet model, and modification of the iteration flow property iteration schemes will be required. This will eliminate the dependence on NASA scramjet data.

2. An improved method of calculating specific heat capacity, C_p, for the flow at various stations. The current very limited table look-up mechanism will be replaced with a more detailed table or curve fit.

3. An improved inlet pressure recovery model. A new pressure recovery model will be created that includes information about the actual inlet geometry in the calculation of pressure recovery.

4. Demonstrate that SCCREAM can be included in an automated launch vehicle design framework or computing architecture. From the beginning, SCCREAM was created to be a design-oriented code. It can operate as a standalone code, but can also be included as a subroutine or contributing analysis in a larger multidisciplinary design optimization framework. This capability will allow the system-level designer to optimize the entire vehicle (propulsion, trajectory, configuration, material, etc.) for an overall objective function (e.g. return on investment).

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