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SCCREAM: A Conceptual Rocket-Based Combined-Cycle Engine Performance Analysis Tool

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A new computer analysis tool capable of predicting rocket-based combined-cycle engine performance data (thrust and I_{sp}) over a wide range of flight conditions and engine operating modes is presented. The tool is called SCCREAM, which stands for simulated combined-cycle rocket engine analysis module. SCCREAM is an object-oriented workstation-level code written in C++ that can be remotely executed through a web-based user interface. It uses quasi-one-dimensional flow analysis techniques, 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 subsequent trajectory optimization. An overview of SCCREAM and the program logic is presented. Results from SCCREAM are compared with published rocket-based combined-cycle engine performance data and with data generated by other engine analysis tools for a representative reference vehicle configuration.

Nomenclature

A_i	=	engine cross-sectional area at station i, ft^2
C_p	=	specific heat at constant pressure, BTU/slug · °R
C_t	=	thrust coefficient, thrust/$q - A_1$
I_{sp}	=	specific impulse, s
LH2	=	liquid hydrogen
LOX	=	liquid oxygen
P_t	=	total pressure, lb/ft^2
q	=	freestream dynamic pressure, lb/ft^2
γ	=	ratio of specific heats
ϕ	=	combustor equivalence ratio

RBCC Background

ROCKET-BASED combined-cycle (RBCC) engines (formerly known as composite engines[1]) are a class of propulsion systems that combine traditional rocket elements and traditional air-breathing elements into a single physically and thermally integrated propulsion system. RBCC engines are capable of operating in several different modes, including high thrust ejector mode (air-augmented rocket), high I_{sp} ramjet and scramjet modes, and a traditional rocket mode that can provide high altitude and vacuum thrust.[2] Preliminary concept studies have shown that a launch vehicle powered by RBCC engines can optimally transition through its various operating modes during ascent to produce a high trajectory-averaged I_{sp} relative to a traditional rocket.[2,3] High trajectory-averaged I_{sp} typically results in lower propellant mass fractions and lighter gross weight vehicles for a given payload-delivery mission. Studies to quantify any operational cost savings, economic return on investment improvements (improved business case), and mission flexibility advantages of next-generation reusable launch vehicles powered by RBCC engines are currently underway.[4–6]

Project Motivation

To support advanced RBCC vehicle studies, engineers in a conceptual launch vehicle design environment need to be able to assess candidate engine performance at each point in the ascent trajectory. That is, at a given flight velocity and altitude, what are the thrust and I_{sp} produced by the engine? These data are typically used in a trajectory optimization code to determine a minimum propellant flight path to orbit. Published *experimental* performance data for RBCC engines are sparse and limited to only a few flight conditions for a limited number of RBCC engine configurations and propellant combinations. Flexible and parametric *analytical* engine predictions are necessary to support the conceptual design effort.

For a typical conceptual RBCC vehicle investigation, designers might require engine data beginning at takeoff to in-space rocket mode operation. Depending on the fidelity of the investigation and the number of operating modes of the RBCC engine, thrust and I_{sp} data at as many as 250–500 flight conditions might be required. Because of computing-speed limitations, the required engine data are commonly generated off line (i.e., a priori) by a computational propulsion analysis tool for the range of expected altitudes, flight speeds, and operating modes. The resultant engine performance database is formatted into a tabular form that can subsequently be interpolated from as needed by the trajectory optimization code. Computational propulsion analysis tools capable of parametrically addressing a full range of RBCC variants in all operating modes are currently rare, if not nonexistent, in the open literature. SCCREAM is introduced as a new tool capable of meeting these requirements.

Simulated Combined-Cycle Rocket Engine Analysis Module

Development Background

The subject engine analysis tool, SCCREAM (for simulated combined-cycle rocket engine analysis module), has evolved from tools generated under earlier research efforts. Original tool-building steps in 1993 resulted in a simple spreadsheet model that was capable of predicting RBCC engine performance at a range of altitudes and velocities, but only in the ejector mode.[7] The original model could also incorporate a supercharging fan if required. The spreadsheet consisted of approximately 2500 iterative calculation cells to perform the requisite internal engine flow calculations (pressures, temperatures, mass flow rates, etc., throughout the engine). This original spreadsheet generated properly formatted tabular data that could be electronically transferred to a workstation-class computer and imported into a widely used trajectory optimization program, POST.[8]

Subsequent research extended the original spreadsheet model to include fan-ramjet and ramjet modes of operation.[9] The number of

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iterative spreadsheet cells increased to approximately 10,000. As in the original tool, this new 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 process was often unstable. That is, the internal pressures, velocity, and Mach number iteration could easily diverge for certain flight conditions. For this situation to be remedied; a new stand-alone RBCC engine analysis tool was developed.

This new tool, SCCREAM, is an object-oriented code written in C++. The code runs on a UNIX workstation, provides data for a full range of flight conditions and engine modes in under 90 s of computing time, has more stable internal iteration schemes, and retains the ability to output properly formatted POST engine tables.[10,11] 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 initial, conceptual-level launch vehicle design studies.

Current SCCREAM Tool—SCCREAM v5.5

SCCREAM v5.5 has the capability to model the performance of many different classes of RBCC engines, as well as conventional ramjet and scramjet engines. Current RBCC classes that can be analyzed include the supercharged ejector ramjet (SERJ), the (nonsupercharged) ejector ramjet (ERJ), the ejector scramjet (ESJ), the supercharged ejector scramjet (SESJ), the ejector scram-rocket (ESR), and the supercharged ejector scram-rocket (SESR). Each of these variants includes an ejector (air-augmented rocket) mode, a ramjet mode, and an in-space rocket mode (pure rocket mode). Optional supercharged ejector, fan-ramjet, scramjet, and scram-rocket modes are included in some cases. SCCREAM is capable of analyzing bipropellant rocket primaries with a LOX or hydrogen peroxide oxidizer and LH2, methane, propane, or JP-5 fuel. Monopropellant hydrogen peroxide primaries can also be analyzed. Secondary or afterburner fuels include LH2, methane, propane, JP-5, and JP-10. Axisymmetric and two-dimensional (underslung) engine configurations can be analyzed. The latter typically includes forebody precompression effects modeled as a multiple ramp wedge or a cone. High-speed and high-altitude aftbody expansion effects can be simulated by means of a user-defined external engine exit area ratio. Users can select to view results in a vehicle tip-to-tail thrust accounting system or cowl-to-tail thrust accounting system. The latter option assumes that forebody drag is included in a separate aerodynamic drag account by the vehicle designer.

Executing SCCREAM

SCCREAM operates either as a stand-alone executable code or as a contributing analysis in a larger multidisciplinary conceptual design process. The preferred interface is via the World Wide Web, using standard web-browser software.[12] This interface allows remote users to access a "novice" or "expert" version of the code, set up custom engine configurations and geometries for analysis, and view the performance results on line. For various reasons, users may also wish to download an executable version of SCCREAM to their local Silicon Graphics workstation.

After each engine mode has been analyzed for the range of desired flight conditions, several tabular and graphical output formats are available. First, a properly formatted POST engine text file (Fig. 1) is created for use in a subsequent trajectory analysis. SCCREAM automatically generates plots of engine performance in JPEG and Postscript formats for quickly assessing an engine's capabilities. A detailed list of flow properties at each engine station for every flight condition is also available as a text file. SCCREAM execution time is very quick. Over 350 different flight conditions in various operating modes, with accompanying performance plots, can be analyzed in ~90 s on a Silicon Graphics Octane[2] workstation.

```
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 $
```

Fig. 1 Sample output (POST engine file).

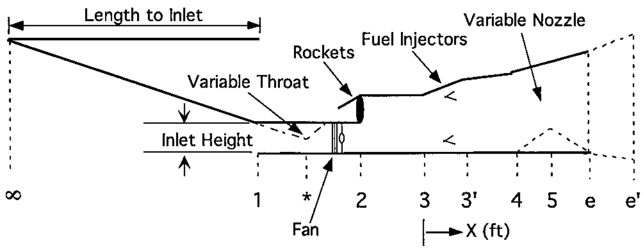

Fig. 2 SCCREAM station locations.

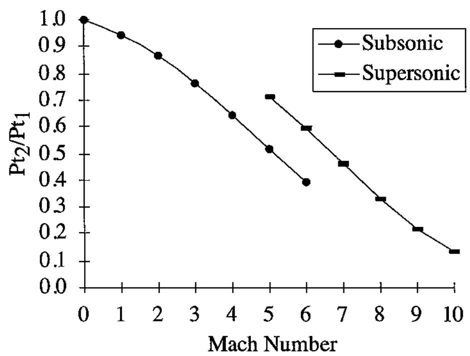

Fig. 3 Inlet pressure recovery.

SCCREAM Flowpath Modeling Technique

SCCREAM operates by solving for the engine internal fluid flow properties (velocity, temperature, pressure, mass flow rate, gamma, specific heat) through the various engine flowpath stations for each of the engine operating modes (Fig. 2). Equations for conservation of mass, momentum, and energy are used. Fluid heat capacities are determined as a function of temperature and local constituent mole fractions. The solution process is often iterative at a given engine station or between a given downstream and upstream station. The engine flowpath cross-sectional area is the only geometry variable along the stream direction (uniform flow with no crosswise components). The flow properties are calculated by using quasi-one-dimensional inviscid flow equations. Component efficiencies are used to simulate viscous losses throughout, losses of total pressure in the mixer and nozzle, and reduced enthalpy in both the rocket primary and main combustor. The internal inlet (starting at the cowl plane) is simulated by simple total pressure recovery schedules for representative inlets with subsonic and supersonic flows (Fig. 3). External compression caused by a vehicle forebody or compression spike can be simulated by a user-defined cone angle or multiple wedge ramp angles. External aftbody exhaust expansion can be simulated with a user-defined external nozzle area ratio. The engine net thrust and I_{sp} are determined by using a control volume analysis of the entering and exiting fluid momentum and the static pressures at the inlet and exit planes.

As a way to allow users to parametrically consider a variety of engine scales and internal geometry configurations, most internal areas in SCCREAM are determined based on ratios to the maximum inlet/cowl cross-sectional area. Default area ratios are supplied, so typically a user enters only the reference inlet area (A_1). The size (blockage area) of the rocket primary unit is calculated 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 (air-to-rocket propellant) 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. Depending on the value of ϕ in the engine afterburning combustor (related to the air-breathing mode fuel flow rate and engine throttle setting), scaling the engine inlet area down or the rocket primary up might result in a choked flow condition in the combustor. In this case, internal logic in SCCREAM will automatically reduce the fuel flow rate until the choked condition is removed. By default, SCCREAM uses a value of $\phi = 1.0$ in the afterburning combustor if possible. Users may also specify a different maximum throttle value, if desired.

In order to generate a POST engine table, a candidate engine's performance is evaluated at multiple flight conditions over a user's specified altitude and Mach number ranges. For example, a ramjet's operational Mach numbers might be set from 2 to 6, with altitude ranges from 30,000 to 150,000 ft. Overlapping Mach numbers and altitudes between various RBCC operating modes allows a trajectory analyst to subsequently select optimum engine mode transition points if desired. Default Mach number and altitude ranges are provided for each mode, as well as default grid resolutions within each range. Users may override these defaults as desired.

Performance in the rocket mode (no airflow) is determined by using flow equations for a high nozzle 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 vehicle aftbody. Thus, the engine's internal geometry can compromise nozzle efficiencies relative to optimally contoured conventional rocket nozzles.

The following section provides additional detail regarding the internal modeling techniques and thermodynamic assumptions used at each cross-sectional station in the current SCCREAM code.

Station Calculation Details

Forebody/Inlet/Rocket Primary

Figure 2 shows the station numbers and reference engine locations used by SCCREAM for a generic RBCC. Station 1 is at the inlet plane of the engine. Freestream flow conditions at station "infinity" are modified by a bow shock to simulate the flow precompression effect of a vehicle forebody or inlet spike on the engine. For conical forebodies, the Taylor and Maccoll equations[13] are solved to obtain the flow gradients at the inlet plane. The forebody shape (wedge or cone) and the forebody angles are entered by the user. Therefore, the flow conditions at station 1 are typically not the same as the freestream flight conditions. After the forebody precompression effects are analyzed; the static flow properties are determined at the inlet face. For conical flows, the entering momentum and mass flow rate are obtained by integrating the radial flow properties between the vehicle surface and cowl lip. Area averaged values are used for the static properties.

From station 1 to station 2, the total pressure recovery through the inlet is determined by using a standard Mil-Spec recovery schedule for an inlet terminating with a normal shock in the case of the inlet providing subsonic flow (Fig. 3). For the case of the inlet providing supersonic flow, a total pressure curve fit for an inlet with supersonic flow is used. Pressure recovery is defined as the "total" or stagnation pressure at station 2 divided by the total pressure at station 1. The recovery schedules can be changed by the user to match specific inlet performance if desired. 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,

$$A_2 = A_3 - A_p \tag{1}$$

where A_p is a function of the size of the rocket primaries; A_2 can be a "pinch point" in the engine and will affect when an inlet will start if the blockage caused by the rocket primary is excessive. This will depend upon the user's specific engine geometry design.

In the 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 (A_*). The flow is assumed to be choked at this point. Should the combination of rocket exhaust from the primaries and secondary airflow 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 a user-specified maximum Mach number, typically 0.8–0.9, is obtained. If the flow at station 1 is supersonic and the mass flow rate exceeds the value that can be compressed through the inlet throat, the inlet is assumed to be "unstarted" and a normal shock is located just upstream of station 1. A total pressure loss is taken across the normal shock, and the inlet pressure recovery schedule is not used because the flow is subsonic. A choked flow calculation based upon the reduced total pressure and subsonic flow conditions is then used to determine the new secondary mass flow rate.

In fan-ramjet and ramjet modes, the default maximum inlet throat area is assumed to be equal to the smaller of A_1 or A_2. In this case, the secondary airflow through the engine is either the maximum mass flow rate that can be passed through the inlet throat at sonic conditions or the mass flow rate projected directly upstream of the inlet, whichever is less. At flight Mach numbers up to 3 or 4, the secondary mass flow often tends to be limited by the maximum throat area for typical designs and the inlet is unstarted. At higher Mach numbers, the secondary mass flow is generally limited by the maximum inlet area and is more typical of standard ramjet analysis. An engine designer might choose to increase the mixer area (and thus the inlet throat) to start the inlet sooner at the cost of additional engine size and weight.

When total pressure, total enthalpy, secondary mass flow, and area are known, 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 uses the temperature and Mach number (i.e., the definition of Mach number), and the other uses 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-ramjet, and ramjet modes, the subsonic solution for Mach number is always selected.

Mixer/Diffuser

Between stations 2 and 3, the primary rocket exhaust (if the primary is operating) is mixed with the secondary air from the inlet. The user has seven different propellant combinations for the rocket primary subsystem from which to select. These propellants include both oxygen and hydrogen peroxide oxidizers, as well as hydrogen, propane, methane, and JP fuels. Parametric response surface equations (RSEs) as functions of oxidizer-to-fuel mixture ratio and chamber pressure have been generated, based on results from the industry-standard chemical equilibrium code, CEA,[14] to approximate the detailed chemical composition in the primary exhaust for each propellant combination. The user is required to enter a mixture ratio, chamber pressure, and area ratio for the primary. Even though fuel-rich rocket primaries can be modeled, SCCREAM assumes that no combustion occurs in the mixer, thus a diffusion-then-afterburning

(DAB) cycle. Again, the equations for conservation of mass, momentum, and energy are used to solve iteratively for the static pressure, temperature, and velocity at station 3, using the Mach number as an iteration variable. A new specific heat (C_p), ratio of specific heats (γ), and molecular weight based on the combined rocket exhaust and secondary flow are calculated at station 3 during the iteration process. Mass averaging techniques are used for C_p and molecular weight. Parametric JANNAF (Joint Army–Navy–NASA–Air Force) curve fits for individual species C_p have been created as functions of temperature. The primary rocket mass flow rate (either set by the user or automatically varied to match a required sea-level static thrust), 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 the ejector mode is too large to be passed through station 3, the inlet throat area is reduced to limit the secondary mass flow rate. At supersonic flight conditions, this can result in an inlet unstart.

Combustor

The combustor geometry is defined by the user by means of area ratios based on the mixer area as $(A_{3'}/A_3)$, and $(A_4/A_{3'})$; see Fig. 2. The length of the forward and aft combustor sections are also required as inputs. The combustor nominally operates at a user-defined maximum equivalence ratio, ϕ. ϕ is the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. A ϕ of 1.0 indicates stoichiometric combustor operation. The user can specify the fuel injection angle, velocity, temperature, and location. Additionally, a linear heat release profile for the reacting fuel is also required. Default values are provided. For a given ϕ, SCCREAM marches through the combustor by solving flow equations based on the method of influence coefficients.[15] A fourth-order Runge–Kutta solver is used at each step. After each step analysis is complete, fluid flow properties are updated by assuming a thermally perfect gas. The amount of fuel reacted with the atmospheric oxygen, and any additional oxygen from the rocket primary at each step, is based on the heat release profile entered. For the combustion chemistry, a simple mass balance with an efficiency factor is used for hydrogen and fuel-lean hydrocarbons. For fuel-rich hydrocarbons, a major species equilibrium analysis is used to determine the correct ratio of carbon monoxide to carbon dioxide. Minor species mass flow rates (O, H, OH) generated by the rocket primary are held constant in the combustor.

If the user-input maximum ϕ results in a thermal choke before reaching the combustor exit, SCCREAM automatically reduces ϕ at that flight condition until the flow is just choked at station 4. This typically occurs at the lower Mach numbers in ramjet modes (Mach 2–3) and scramjet modes (Mach 5–7). Note that the actual ϕ used by the program at each flight condition is tabulated in the output files, should the user desire to increase the combustor area to produce a more desirable fuel flow rate in ramjet and scramjet modes (again at the expense of additional engine weight).

Nozzle

The chemistry of the nozzle is assumed to be frozen at the composition existing the combustor. For subsonic combustion modes, the variable geometry nozzle is a simple converging-diverging nozzle that expands the flow to supersonic speeds. For supersonic combustion, the nozzle is a simple divergent nozzle. At lower altitudes, the internal 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 external vehicle aftbody expansion by including a maximum theoretical expansion area that increases with altitude. The rate at which the theoretical exit area increases and its maximum value are user inputs.

For the overall net engine thrust, thrust coefficient (C_t), and I_{sp} to be determined, the exit pressure, exit velocity, and exit mass flow rate are used in a control volume equation along with the appropriate inlet conditions (for either cowl-to-tail or tip-to-tail force accounting systems). The thrust coefficient in the nonejector airbreathing modes is defined as

$$C_t = \text{thrust}/q_\infty A_1 \tag{2}$$

where A_1 is a fixed constant area. The default nondimensionalizing area is the inlet area at station 1, but users may select other areas if preferred (e.g., the stream tube area at shock-on-lip conditions). C_t is a common way to nondimensionalize engine thrust to enable parametric scaling by inlet size and flight conditions.

Benchmarking SCCREAM Results

Hyperion Reference Vehicle

As a way to compare and benchmark the RBCC engine performance data generated by SCCREAM to data available from other sources, a test case vehicle was adopted. Figure 4 shows an artist's rendering of the *Hyperion* launch vehicle. *Hyperion* is a single-stage-to-orbit (SSTO) concept for a third-generation reusable launch vehicle currently being investigated by the Space Systems Design Laboratory (SSDL) at the Georgia Institute of Technology.[6] The unpiloted vehicle is fully reusable and takes off and lands horizontally. It uses five LOX/LH2 ejector scramjet RBCC engines for primary propulsion. Orbital maneuvering system (OMS) engines on the top of the aftbody can assist in trim during vehicle ascent. The forebody has a conical lower surface with a 10 deg cone half-angle and a shallow elliptical upper surface. *Hyperion*'s structural and subsystem technologies are consistent with an expected 2025 initial operational capability.

Hyperion is capable of powered landing and self-ferry by using two small, hydrogen ducted fans mounted under the wings. These engines are protected by a retractable inlet cover during ascent and entry. *Hyperion* is designed to deliver 11,100 lb of payload to the International Space Station (220 n mile × 220 n mile × 51.6 deg) from Kennedy Space Center. In ramjet and scramjet modes, the vehicle flies a constant dynamic pressure boundary trajectory of 2000 psf (Fig. 5). The transition from scramjet mode to pure rocket mode begins at Mach 9 and is complete by Mach 10.

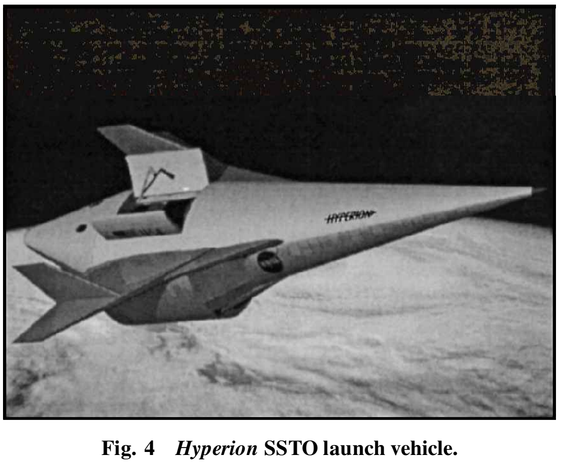

Fig. 4 ***Hyperion* SSTO launch vehicle.**

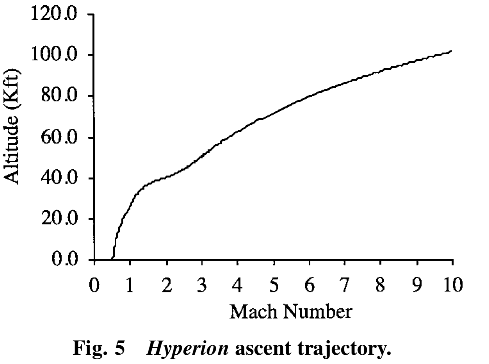

Fig. 5 ***Hyperion* ascent trajectory.**

Table 1 *Hyperion* ESJ engine data

Characteristic	Measurement
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 ϕ	1.0

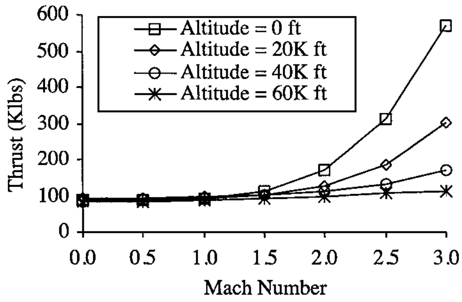

Fig. 6 Ejector mode thrust results.

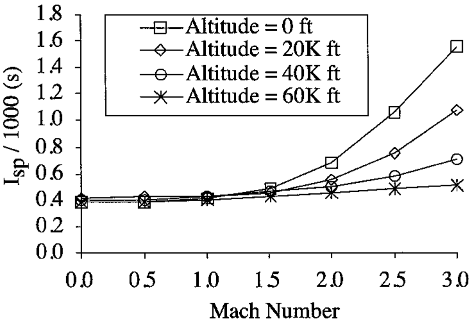

Fig. 7 Ejector mode I_{sp} results.

Table 1 summarizes the per engine ESJ engine characteristics for each of the five RBCC engines on *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 per engine. A rocket mode vacuum expansion area of 180 was assumed, which yields a vacuum I_{sp} of 462 s.

SCCREAM was run to generate full engine performance data sets in the ejector mode (from Mach 0 to Mach 3), ramjet mode (from Mach 2 to Mach 6), and scramjet mode (from Mach 6 to Mach 10) over a range of altitudes for the reference engine. Figures 6 and 7 show a sample of the data set generated by SCCREAM for the ejector mode. Note the expected improvement in ejector I_{sp} and thrust as the vehicle accelerates and increases the secondary flow rate (mass capture). However, this thrust and I_{sp} augmentation effect is reduced at higher altitudes.

SCCREAM-generated data for ramjet mode C_t and I_{sp} for a range of altitudes is shown in Figs. 8 and 9. Note the unusual behavior in C_t near Mach 3. As expected, the C_t rises between Mach 2 and Mach 3 as the thrust increases as a result of increased total pressure and secondary mass flow rate through the engine. However, near Mach 3, the C_t begins to rapidly increase. A more detailed investigation of the results indicated that this increase is a result of the inlet's starting (ingesting the normal shock standing off the inlet face).

Between Mach 3 and 4, the inlet is started, but the combustor chokes at the user-input ϕ of 1.0. SCCREAM automatically throttled ϕ in this range. The result is a temporary increase in I_{sp} near Mach 3.5. I_{sp} and C_t behavior beyond Mach 4.0 is more typical of a ramjet with a ϕ of 1.0. 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.

Table 2 Sample ejector mode station results

Flight $M = 0.5$, Phi $= 1.0$	S_1	S_2	S_4	S_e
Area (ft^2)	27.0	8.24	22.5	16.5
Local Mach number	0.50	0.47	0.35	1.63
Velocity (fps)	548.7	516.3	1507.8	6179
Total press. (lb/in.^{2})	14.5	14.2	50.5	50.5
Total temp. (°R)	526.3	526.3	6077.7	6077.7

Table 3 Sample ramjet mode station results

Flight $M = 3.5$, Phi $= 1.0$	S_1	S_2	S_4	S_e'
Area (ft^2)	27.0	8.24	22.5	78.9
Local Mach number	2.96	0.46	0.60	2.75
Velocity (fps)	3130.9	769.2	1976.0	6631.6
Total press. (lb/in.^{2})	59.2	45.3	28.8	28.8
Total temp. (°R)	1258.2	1258.2	4514.2	4514.2

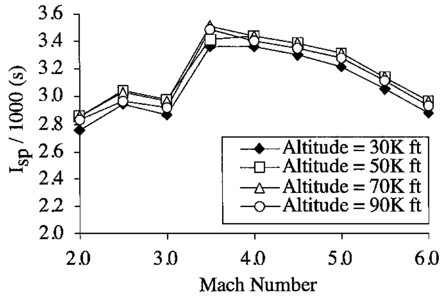

Fig. 8 Ramjet mode I_{sp} results.

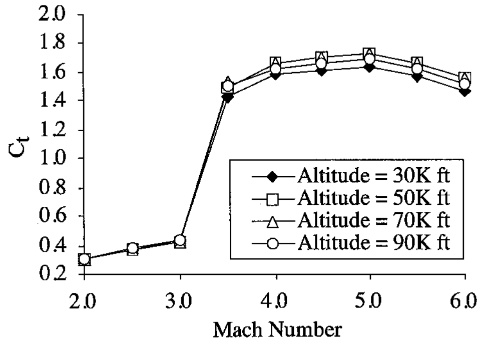

Fig. 9 Ramjet mode C_t results.

With the use of the SCCREAM data set, an optimized reference trajectory for *Hyperion* was determined (Fig. 5). Engine thrust and I_{sp} were determined at each altitude and flight velocity by interpolating from data tables provided by SCCREAM. Typical engine station (S_i) flow values at two selected points along the reference trajectory are shown in Tables 2 and 3 (the ejector and ramjet modes, respectively). It is important to note that a SCCREAM *data set* is not associated with a particular flight path but rather is a table of thrust and I_{sp} versus a range of Mach numbers, altitudes, and operating modes. Flying an optimum trajectory through the full SCCREAM data set results in a specific history of I_{sp} and C_t (or thrust) versus Mach number. In this case, the engine performance data set generated by SCCREAM in properly formatted tabular form was easily transferred to POST to determine an optimum flight path for *Hyperion*.

Comparison with Published Engine Performance Data

For the thrust, C_t, and I_{sp} values generated by SCCREAM to be validated, the results have been compared with open-literature RBCC engine data from historical sources. A seminal work published by Escher and Flornes[1] in 1967 (referred to as "NAS7-377" in the following figures) contains extensive RBCC engine performance data, including the ERJ and ESJ mode net thrust and I_{sp} for a vehicle flying along a 1500-psf dynamic pressure boundary. The NAS7-377 data used in this paper are for an external precompression flowfield generated by an 8-deg half-angle wedge forebody. Appropriate cone data were not available for comparison. The ERJ thrust data were nondimensionalized to C_t values by using an 82-ft^2 reference inlet area (A_1) and $q_\infty = 1500$ psf. The ESJ data used a 100-ft^2 reference inlet area (A_1).

A study of RBCC engines performed by Foster et al.[3] in 1988 contains C_t data for a scramjet and complete I_{sp} data for an ESJ engine over a 1500-psf trajectory. In the reference (referred to as "Astronautics" in the following figures), C_t data are tabulated directly and do not have to be calculated from a known thrust. Although the vehicle studied in Ref. 3 used a 10-deg half-angle conical forebody, the only available tabulated I_{sp} data in the reference are for a 6-deg half-angle wedge.

The effect of differences in external forebody precompression on an RBCC engine is not insignificant. At high speed, 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, in spite of possible sources of difference, the data from NAS7-377 and the Astronautics study are thought to provide a reasonable comparison set for SCCREAM applied to the reference *Hyperion* trajectory.

Figure 10 shows the engine C_t for the SCCREAM case, the NAS7-377 ERJ and ESJ data, and the Astronautics study data for an ESJ. C_t provides a better comparison in airbreathing modes than overall thrust as a result of the differences in reference vehicle size and freestream dynamic pressure among the data sets. Figure 11 shows comparison data for I_{sp} in the ramjet and scramjet modes.

The SCCREAM thrust coefficient data in Fig. 10 are 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. A comparison of I_{sp} in Fig. 11 indicates good agreement in the ejector mode and ramjet modes. However, SCCREAM yields a somewhat lower I_{sp} in the scramjet mode than the comparison data. Scramjet mode I_{sp} is known to be extremely sensitive to inlet pressure recovery and combustor efficiency assumptions, and this is the likely cause of the differences observed.

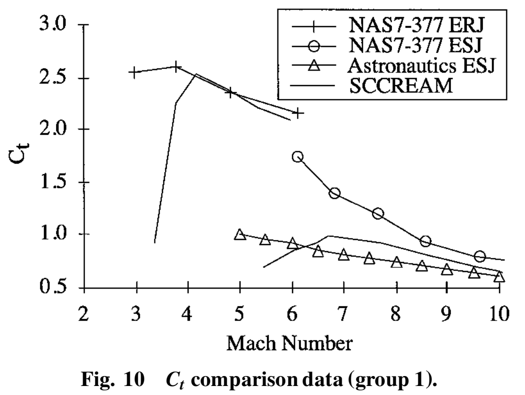

Fig. 10 C_t comparison data (group 1).

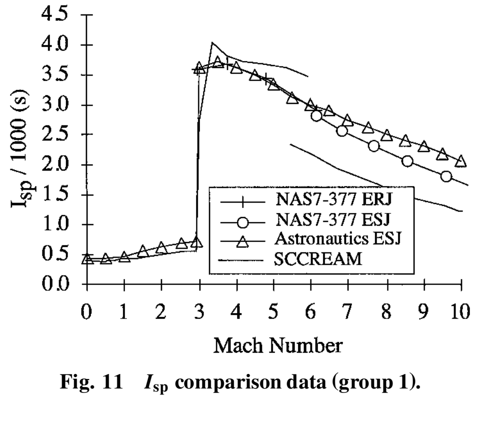

Fig. 11 I_{sp} comparison data (group 1).

Comparison with Other Engine Analysis Codes

Although SCCREAM offers a unique, multimode analysis customized for RBCC engine design, comparative analysis tools exist for analyzing high-speed airbreathing engine performance (ramjets and scramjets). Three contemporary airbreathing engine analysis codes were selected to serve as a validation set for SCCREAM in ramjet and scramjet modes. A comparative RAMSCRAM[16] data set has been generated for the reference *Hyperion* engine geometry and flight path. RAMSCRAM was developed and is maintained by NASA–Glenn Research Center. SRGULL is a preliminary ramjet/scramjet engine design tool developed and maintained by NASA–Langley Research Center. SRGULL is a restricted access code, but Shaughnessey et al. used SRGULL to generate ramjet and scramjet performance for an airbreathing launch vehicle with a 5-deg half-cone and published the engine performance results in the open literature.[17] These results are for a non-RBCC engine with a different engine geometry and inlet efficiency. The ramjet performance analysis code,[18] RJPA, developed at The Johns Hopkins University in the mid-1960s, was also used to generate scramjet mode engine performance data for an engine configuration similar to that of the *Hyperion* vehicle. RJPA is a FORTRAN-based code that uses a one-dimensional integral analysis approach and is applicable to a wide variety of airbreathing and rocket propulsion concepts. The combustor uses the NOTS equilibrium code for determining the chemical composition of the flow. Frozen and equilibrium flow analysis options can be selected. Consistent inlet performance, engine geometry, component efficiencies, and mass capture assumptions were used when comparison data were generated among the SCCREAM, RAMSCRAM, and RJPA cases.

Figure 12 shows the thrust coefficient comparisons for the four codes, SCCREAM, RJPA, RAMSCRAM, and SRGULL, for ramjet and scramjet operating modes. It can be seen that SCCREAM and RAMSCRAM match very well for the ramjet portion of the trajectory where the inlet is started. SCCREAM appears to accurately predict an equivalent drop in thrust from transitioning from subsonic to supersonic combustion. Note that an instantaneous switch from subsonic to supersonic flow is modeled here, but a real engine would likely have a much smoother and gradual transition between the two modes. In the scramjet mode, RJPA and SCCREAM agree very well, as previously shown. RAMSCRAM appears to have less thrust than SCCREAM and RJPA in the scramjet mode, but it still displays similar trends.

The SRGULL scramjet data fit very well with all three codes at Mach numbers greater than 7. However, as the Mach number decreases from Mach 7 to Mach 5.5, SRGULL's thrust coefficient continues to increase, whereas those of the rest exhibit a decrease. SCCREAM, RJPA, and RAMSCRAM have lower thrust coefficients at these Mach numbers as a result of throttling of the equivalence ratio to prevent choking of the *Hyperion* reference engine. The need to throttle ϕ to prevent choking the flow is largely dependent on the engine geometry and inlet efficiency. Shaughnessey's engine accommodates a ϕ of 1.0 at these Mach numbers, which accounts for the increasing thrust level. (Unfortunately, the internal geometry of the SRGULL engine was not published in Ref. 17.) However, optimizing an engine configuration for scramjet performance often

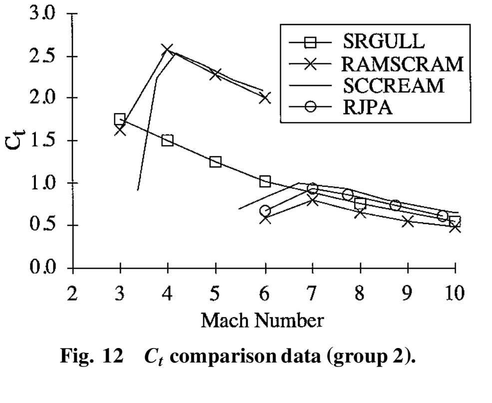

Fig. 12 C_t comparison data (group 2).

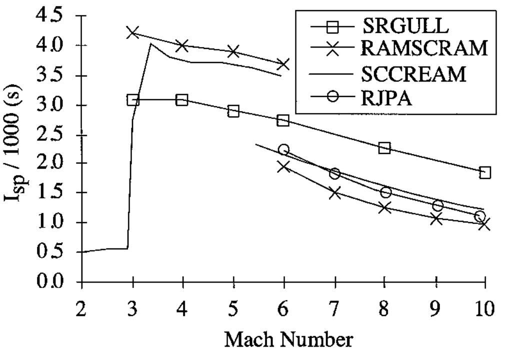

Fig. 13 I_{sp} comparison data (group 2).

results in compromises in the performance in ramjet and ejector modes, as seen by the lower ramjet mode thrust coefficients from the SRGULL engine in Fig. 12.

Figure 13 shows the I_{sp} profiles for the four codes. Once again, SCCREAM and RAMSCRAM match well for ramjet mode performance. SCCREAM and RJPA match almost exactly in the scramjet mode, and RAMSCRAM is displaying similar trends again. The SRGULL I_{sp} profile does not coincide well with any of the other codes. It should be reiterated that SRGULL was not available to the authors to be run on the reference *Hyperion* engine geometry, and therefore it represents a different internal flowpath. However, the SRGULL data do provide an interesting reference for comparing RBCC performance with an engine designed for only ramjet/scramjet operation.

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-one-dimension 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 a popular trajectory optimization code. Among the conclusions drawn in this paper are the following:

1) Written in C++ and executed on a UNIX workstation by means of a remote World Wide Web interface, SCCREAM is a fast and flexible conceptual engine performance analysis tool capable of analyzing a variety of RBCC engine configurations and propellant combinations.

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 high-speed airbreathing engine analysis tools.

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