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SCORES: Web-Based Rocket Propulsion Analysis for Space Transportation System Design

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ABSTRACT

SCORES (SpaceCraft Object-oriented Rocket Engine Simulation) is a web-based rocket engine analysis tool suitable for use in conceptual design. New features and improvements have significantly increased the utility of the program. The most notable improvement is the addition of hydrocarbon combustion through improvements in chemical equilibrium calculations. Other improvements include rocket sizing capability, conical and aerospike nozzle options, SI units, and thrust-to-weight estimation.

SCORES supports the spacecraft and launch vehicle design team by providing rocket thrust, specific impulse, and thrust-to-weight. The input parameters required by SCORES are mixture ratio, chamber pressure, throat area, and expansion ratio. SCORES provides a quick-look trade study capability by maintaining the appropriate level of fidelity and computational time. This allows SCORES to be used effectively in a Multidisciplinary Design Optimization environment.

This paper describes the current status in the development of SCORES, details recent improvements, and provides comparisons with industry standard codes and historical engine data.

NOMENCLATURE

ε	nozzle area ratio (A_e/A_t)
γ	ratio of specific heats
η	efficiency
θ	cone 1/2 angle
A	area (in^2)
A*	sonic throat area (in^2)
g	specific Gibbs free energy (J/kg-K)
h	specific enthalpy (J/kg-K)
Isp	specific impulse (sec)
Lox	liquid oxygen
LH_2	liquid hydrogen
M	Mach number
$\dot{m}$	mass flow rate (lb./sec)
MW	molecular weight (kg/kg-mole)
O/F	oxidizer to fuel ratio
p	pressure (psia)
P	power (MW)
P/W	power-to-weight
RBCC	Rocket Based Combined Cycle
SSDL	Space Systems Design Lab
T	thrust (lbs)
T/W	thrust-to-weight
X_i	mole fraction of species *i*
Y_i	mass fraction of species *i*

Subscripts

c	combustion chamber
e	nozzle exit
mix	perfect gas mixture
t	nozzle throat

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INTRODUCTION

The Space Systems Design Lab (SSDL) at the Georgia Institute of Technology required a liquid rocket engine analysis tool for advanced launch vehicle design. In fulfillment of this need, Way developed a design tool called SCORES (SpaceCraft Object-oriented Rocket Engine Simulation)[1]. SCORES, as shown in Figure 1, is a web-based tool suitable for use in conceptual design. However, new features and analysis capabilities were required in order to improve its utility.

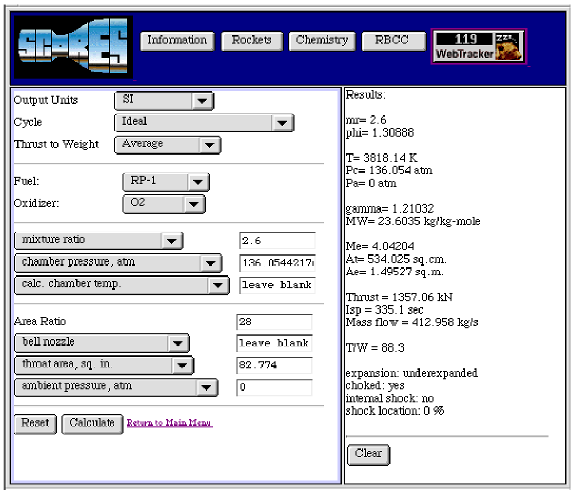

Figure 1 - SCORES 2.0 Web Page

SCORES supports the design team by providing propulsion parametrics such as thrust and specific impulse (Isp.) The design input parameters required by SCORES are top-level propulsion parameters that affect the overall vehicle design. These parameters include cycle type, mixture ratio, chamber pressure, throat area, and expansion ratio.

The primary motivation for developing this tool was to provide the spacecraft or launch vehicle designer with "quick-look" answers to propulsion system trade studies. Of importance in performing such trade studies is maintaining the appropriate level of fidelity and computational time. Maintaining a fidelity consistent with rapid run times allows the designer to use SCORES effectively in an Multidisciplinary Design Optimization (MDO) environment.

A secondary use for SCORES has been found in academia. It has been used effectively in the classroom to provide rocket engine instruction. The web interface and rapid calculations assist students in developing a feel for the significance of engine parameters and how they impact the overall rocket performance.

This paper describes the current status in the development of SCORES. First, a brief background on the SCORES system will be presented. Second, the details of recent improvements and comparisons with industry standard codes will be discussed. Finally, SCORES simulations will be compared with historical engine data.

BACKGROUND

The SCORES web site is public and can be accessed at the Uniform Resource Locator (URL) address listed below:

http://titan.cad.gatech.edu/~dwway/SCORES

Three programming languages, in addition to the C++ source code, are used to bring SCORES to the World Wide Web. These languages are Hyper Text Mark-up Language (HTML), Practical Extraction Report Language (Perl), and Java. Figure 2 shows the flow of information within the SCORES system. SCORES may be run in three ways: from the web (represented by the upper flowpath in Figure 2), interactively from the UNIX operating system, or autonomously using custom scripts (the lower flowpath.) Each of the elements in these flowpaths will be discussed next.

SCORES uses three HTML frames to organize multiple web pages (see Figure 1.) The top frame is a control frame that contains four buttons. These buttons access the "information" page, the "rockets" engine performance page, or the "chemistry" equilibrium calculation page. The "RBCC" button links the user to the SCCREAM RBCC analysis tool, also being developed by SSDL[2]. The left hand frame is the input frame and the right hand frame is the output frame. This arrangement allows the simultaneous, side-by-side display of both inputs and outputs.

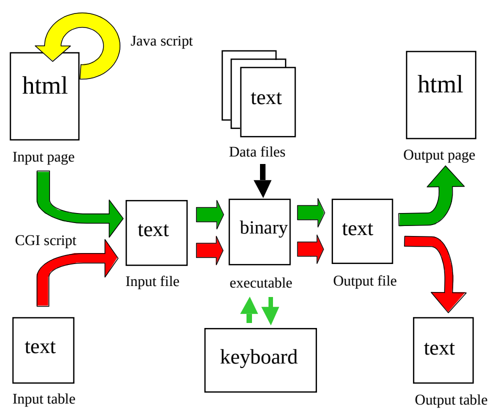

Figure 2 - Flowpaths

Java scripts, indicated in the top left corner of figure 2, perform dynamic range checking and unit conversion. If the user inputs a value which is out of range, a warning message will appear, showing the allowable limits. The Java scripts also dynamically change the default settings based on the user's selections. The final function performed by the Java scripts is to preprocess all of the inputs into SCORES default English units. These Java scripts enhance the flexibility of the code and make the system more user-friendly.

When the user is satisfied with the inputs and presses the "calculate" button, the HTML form "posts" the data to a Common Gateway Interface (CGI) script. The "post" method of transferring data is generally preferred over the "get" method when the form contains more than one piece of information. Each HTML input page posts data to a unique CGI script.

The CGI scripts are written in Perl. Their function is to accept input from the HTML forms, create the appropriate input files, pipe the input file through the executable application, and then parse the output file for the desired information. The final task for the scripts is to generate the output HTML page and display that page in the right hand frame on the user's browser. Each CGI script runs a unique executable.

As shown in Figure 2, several text data files are required by the SCORES executables. These data files contain chemical species thermodynamic data as well as combustion system definitions. Providing this information in data files allows for dynamically altering the chemical system without recompiling the source code.

SCORES is not intended to be a high-fidelity propulsion tool. It was created to be a conceptual design tool capable of quickly generating reasonably accurate engine performance data in support of early launch vehicle design studies. The level of detail in SCORES will be expanded on in the following section.

ANALYSIS PROCESS

SCORES models a rocket engine in two parts. First, the chemical processes occurring in the combustion chamber are analyzed. Second, the expansion of hot gasses in the convergent-divergent nozzle is analyzed.

The combustion process is assumed to occur adiabatically and at constant pressure. Additionally, all of the molecular species involved in the combustion are assumed to be thermally perfect gasses. Finally, the initial velocity of the reactants are taken to be zero, thus assuming an infinite-area combustor. Therefore, the temperature and pressure in the combustion chamber are taken to be total values. The initial temperature of all the reactants is assumed to be 500K. The composition of the product gasses is then determined through chemical equilibrium calculations. These calculations are discussed in more detail later.

For the convergent-divergent nozzle, the flow is assumed frozen at the equilibrium conditions calculated for the combustion chamber. The expansion process is then modeled as a steady, inviscid, quasi-1D, isentropic flow. Because of the quasi-1D assumption, cross-sectional area and expansion ratio are the only geometry variables. A detailed description of the nozzle contour is not necessary. The combustion products are assumed to be a mixture of calorically perfect gasses.

Thrust and Isp are calculated from the determined nozzle exit conditions. These estimates typically over-predict the thrust and Isp. This over-prediction is due to the ideal nature of the assumptions. Statistically based efficiencies are then used to simulate losses by correcting the thrust and Isp values. A pull-down menu allows the user to choose a cycle type. The chosen cycle type determines the values of efficiency applied. A detailed description of the analysis procedure can be found in the previous paper[1].

NEW FEATURES & IMPROVEMENTS

The following list identifies specific improvements and new features recently added to SCORES 2.0. Each is discussed in detail.

1. Hydrocarbon fuels
2. New oxidizers
3. Faster calculations
4. SI system of units
5. Sizing capability
6. Geometry options
7. Shock location
8. Nozzle types
9. Thrust-to-weight
10. Equivalence ratio
11. Mass fractions
12. Improved iterations
13. Download link

Hydrocarbon Fuels

The previous version of SCORES lacked the capability to analyze hydrocarbon combustion. The restriction to only hydrogen-fueled rockets severely limited the usefulness of the previous code, eliminating many engines of interest. The FASTRAC engine, being developed at the NASA Marshall Space Flight Center, and the Russian NK-33, being modified by Aerojet for the Kistler K-1 launch vehicle, are prime examples of previously excluded engines. The extension to hydrocarbon fuels is attributable to a change in the method used in calculating chemical equilibrium.

Two basic methods exist for determining chemical equilibrium compositions. These methods are the equilibrium-constant method and Gibbs free energy minimization.

The first method, the equilibrium-constant method, is taught in most thermodynamic and combustion textbooks. This method was used exclusively prior to 1958[3]. The FORTRAN subroutine WIEN is an example of this method applied to hydrocarbon-air combustion[4]. While the equilibrium-constant method lends itself nicely to analytical solutions, it requires the specification of independent chemical reactions. This requirement prevents the equilibrium-constant method from being implemented in a general computer code which is applicable to many different systems.

The second method directly minimizes the Gibbs free energy (for constant pressure processes) subject to mass conservation constraints. The composition with the minimum Gibbs free energy corresponds to the equilibrium state of the system. Within this method there are multiple ways to perform the minimization. Two methods are discussed.

STANJAN is a set of computer programs developed at Stanford University for analysis of chemical equilibrium problems[5]. This code uses the method of element potentials to perform the Gibbs free energy minimization. In contrast to the equilibrium-constant method, this method is very general and may be applied to any system, within the limits of the ideal gas assumption. Any system may be analyzed for which the appropriate thermodynamic properties of the species are known.

The first version of SCORES also used the method of element potentials with very good success[1]. However, a robust optimizer is required for this very challenging, non-linear, constrained optimization. An accurate solution to this problem requires small tolerances on the mass conservation constraints. SCORES used several optimization techniques, including sequential linear programming (SLP) and sequential quadratic programming (SQP), before abandoning this method in favor of the one described next. These methods all had difficulty determining the numerical optimum while enforcing small tolerances.

Chemical Equilibrium and Applications (CEA), developed at the NASA John H. Glenn Research Center at Lewis field, also uses a Gibbs free energy minimization procedure[6]. However, in CEA the minimization is performed differently than discussed above. In this scheme, Gibbs free energy is minimized by first following the method of Lagrange. This method transforms the problem into a set of non-linear equations. The resulting equations are solved through a steepest-descent Newton-Raphson iteration. Details of this proceedure can be found in the CEA report[6].

The new version of SCORES adopts this iterative method, which is both versatile and rapid. Each iteration requires the inversion of a Jacobian matrix. SCORES 2.0 performs this inversion by a Piviting, Lower, Upper (PLU) matrix decomposition procedure[7].

Convergence of the Newton-Raphson method usually occurs in less than 20 iterations. Gordon and McBride point out that two conditions can lead to large corrections and singular matrix inversions: poor initial guesses and species that are present in very small amounts[6]. The second condition may occur in SCORES 2.0 when analyzing adiabatic combustion at stoichiometric conditions. If this situation occurs, the user may specify a combustion temperature.

Implementation of this equilibrium scheme requires the following information:

1. Specification of the molecular species present at equilibrium.
2. Thermodynamic properties of the species present at equilibrium.
3. The initial concentrations of each atomic element present in the system.
4. The initial enthalpy of the reactants (for adiabatic temperature calculations only.)

The following paragraphs describe each of these conditions and their implementation in detail.

Molecular Species specification:

Note that the first condition above does not include the specification of the reactant species initially present. Therefore, a database with all of the possible reactants for each system is not needed. SCORES currently maintains a database of 11 product species: H_2O, H_2, O_2, H, O, OH, CO, CO_2, N_2, NO, and Ar. These species are sufficient to describe the 18 different combinations of fuels and oxidizers currently available.

Text data files define the species present for the particular propellant combination chosen. These data files allow the species specification to be performed dynamically, without recompiling the source code. This dynamic specification can be seen easily on the SCORES 2.0 chemistry web page, where the species listed in the equilibrium output change with the propellant combination selected. Because of SCORES' object-oriented format, additional species and propellant combinations are easily included.

Thermodynamic properties:

Thermodynamic properties of the 11 product species are provided by curve-fits to the Joint Army Navy Air Force (JANAF) thermochemical database[8]. The required properties are specific heat at constant pressure (c_p), specific Gibbs free energy (g), and specific enthalpy (h). Each property is needed as a function of temperature over the range of possible combustion chamber temperatures. The curve-fit process is described in detail in the previous paper[1].

Initial element concentrations:

Because only the atomic element concentrations are needed, a full set of thermodynamic properties for each of the reactants is not required. Instead, the user must only specify the atomic make-up of the reactants and the mixture ratio. In the current application therefore, a propellant is completely described by the following: number of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and argon (Ar) atoms in the molecule. Additionally, the molecular weight of the reactant is needed for equivalence ratio calculations and the initial enthalpy is needed for adiabatic calculations.

The current fuels available are:

1. Hydrogen, H_2
2. Methane, CH_4
3. Jet fuel, JP-4
4. Jet fuel, JP-5
5. Jet fuel, JP-10
6. Kerosene, RP-1

Initial enthalpy:

As mentioned above, the initial enthalpy of the reactants entering the combustion chamber is also needed for adiabatic flame temperature calculations. Enthalpy is not needed if the combustion temperature is known or specified. For simplicity, the enthalpies used in the current version of SCORES 2.0 assume that all propellants are initially at a 500 K temperature.

By fixing the initial temperature, the specification of only a single enthalpy is required for each propellant. The enthalpy of the mixture is then calculated as a weighted average of the reactant enthalpies for the specified mixture ratio. For the range of conditions found in most combustion chambers, the initial temperature does not appreciably alter flame temperature.

An improved combustion model would allow the specification of initial temperature, or enthalpy, of each of the propellants. Specifying the temperature in this manner would require knowledge of reactant enthalpy as a function of temperature. This is easily incorporated in the source code. However, because it is often difficult to find thermodynamic properties of many of the propellants of interest, such an improved model is not currently available in SCORES 2.0.

In order to validate the accuracy of the new equilibrium calculations, several comparisons are made to industry standard codes. In the previous paper, comparisons of mole fractions and temperature were made with STANJAN and CEA[1]. These comparisons showed excellent agreement between all of the codes. The same comparison is repeated here in order to benchmark the new results with those previously obtained.

Equilibrium compositions and temperature were determined for 25 Lox/LH_2 combustion chamber conditions. These conditions consisted of a full-factorial combination of 5 mixture ratios (4.0, 4.5, 5.0, 5.5, 6.0) and 5 chamber pressures (1000, 1500, 2000, 2500, 3000 psi).

Figure 3 shows the major species for a representative case. The case shown is for a mixture ratio of 6 and a chamber pressure of 1000 psi. Figure 4 shows the minor species for the same case. The calculated adiabatic flame temperatures for a full sweep of mixture ratios at a chamber pressure of 1000 psi. is shown in Figure 5.

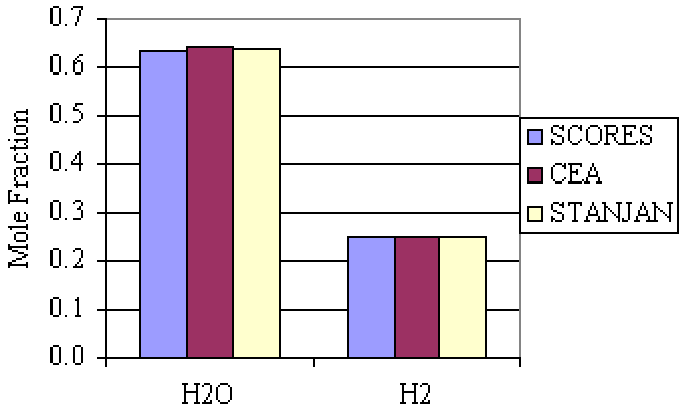

Figure 3 - Major Product Species

Lox/LH2 Combustion

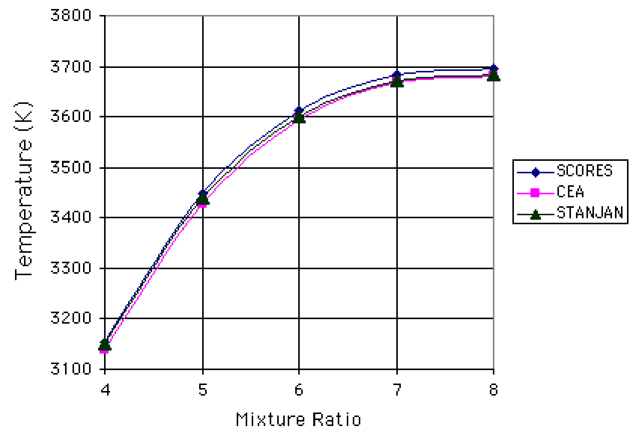

Figure 5 - Flame Temperature

Lox/LH2 Combustion

All three codes showed excellent agreement in all the 25 cases, thus validating the new LH_2 chemical equilibrium calculations.

In order to validate the hydrocarbon chemistry, equilibrium compositions were also compared to CEA for Lox/CH-4 combustion at 6 mixture ratios (4.0, 4.4, 4.8, 5.2, 5.6, 6.0) and 5 chamber pressures (500, 1500, 2500, 3500, 4500 psi). Figure 6 shows excellent agreement between the two codes, in both magnitude and trends, for all species. The chamber pressure in Figure 6 is 500 psi. Similar results were obtained for all other chamber pressures.

Finally, equilibrium results were again compared to CEA for Lox/JP-5 chemistry at 6 mixture ratios (3.4, 3.6, 3.8, 4.0, 4.2, 4.4) and 5 chamber pressures (500, 1500, 2500, 3500, 4500 psi). Figure 7, at 500 psi chamber pressure, again shows excellent agreement between the two codes, validating the hydrocarbon chemistry.

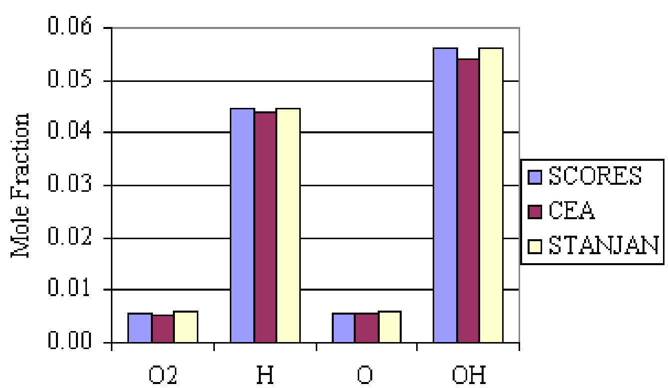

Figure 4 - Minor Product Species

Lox/LH2 Combustion

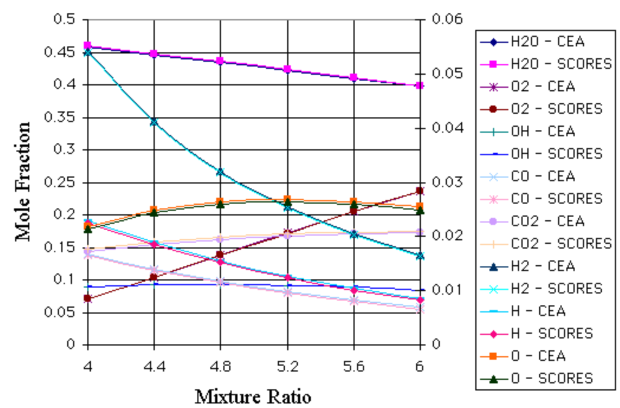

Figure 6 – Product Mole Fractions

Lox/CH-4 Combustion

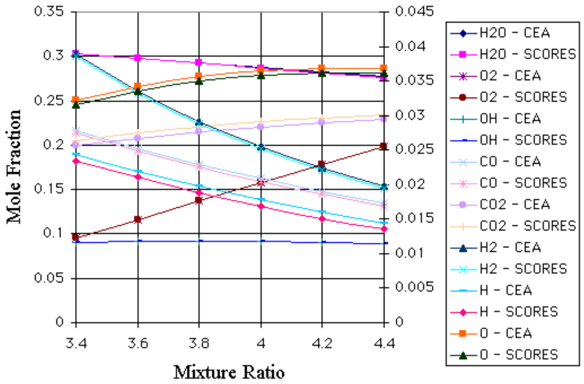

Figure 7 – Product Mole Fractions

Lox/JP-5 Combustion

New Oxidizers

The improved equilibrium calculations, discussed above, also allowed the specification of new oxidizers. As mentioned, the chemical equilibrium calculations are sufficiently general to handle any system. The oxidizers are specified identically to the fuels (by chemical make-up, molecular weight, and initial enthalpy). The constituents of the oxidizer "air" are N_2, O_2, CO_2, and Ar.

The current oxidizers available are:

1. Oxygen, O_2
2. Air
3. Hydrogen peroxide, H_2O_2

Faster Calculations

The addition of multiple fuels and oxidizers to SCORES 2.0 is undoubtedly the most significant and important improvement made. The new equilibrium routines are computationally more efficient. Therefore, the improved capability derived from the additional fuels does not come at the cost of slower run times. To the contrary, this capability has been accompanied by faster run times. Typical run time on an SGI Octane is 0.16 seconds.

Systeme International Units

Though most of the historical engineering data available is expressed in English units, many of today's designs are being expressed in Systeme International (SI) units. The previous version of SCORES allowed only English units for input and output. Any unit conversions needed were performed off-line by the user. The current version of SCORES is very versatile, allowing a variety of input units: English, SI, or both. Additionally, a pull-down menu allows the selection of either English or SI output units.

The versatility in input units is a result of the embedded Java scripting in the web pages. The Java scripts perform all of the unit conversions dynamically. All units are converted automatically to SCORES default English units prior to running the executable.

Rocket Engine Sizing

The previous version of SCORES required the specification of nozzle throat area and expansion ratio for the thrust calculation. Because of this, the user had to perform a manual iteration on throat area if the design required a certain thrust.

The current version of SCORES is more amenable to the design process. SCORES 2.0 now provides an option to size the nozzle throat area to match a required thrust. Because the thrust is linear with throat area, the required throat area is simply the guessed value, 1 sq.in. by default, multiplied by the ratio of required thrust to calculated thrust. Therefore, no iteration is required, making the sizing option just as rapid as the analysis option.

Geometry options

As mentioned, the previous version of SCORES required specification of the throat area. In the new version, either the throat area or the exit area may be specified along with expansion ratio.

Additionally, many trajectory optimization codes, such as the Program to Optimize Simulated Trajectories (POST), require the exit area to properly model thrust and Isp over varying altitudes[9]. For this reason, both throat area and exit area are displayed in the output section.

Shock Location

If the pressure ratio across the nozzle (chamber pressure over ambient pressure) is low enough, a normal shock will form in the divergent section of the nozzle. The previous version of SCORES included a flag to warn the user when this condition occurred. However, the location of the shock was not known.

The new version of SCORES now includes a golden section iteration routine to solve for the location of the shock within the nozzle. The golden section method, described in Vanderplaats[10], is an interval reduction procedure with a known convergence rate.

The shock routine guesses the shock location and calculates the exit pressure using quasi-1D adiabatic flow and normal shock relations. The exit pressure is then compared to the ambient pressure and the iteration continues for a specified number of iterations. The shock location (area ratio at the shock) is then presented as a percentage of the nozzle expansion ratio. For example, suppose the shock location is reported at 25% for a nozzle with an expansion ratio of 40. In this example, the shock would be located at the position in the nozzle where the area ratio was 10.

Nozzle Types

SCORES thrust calculations assume a bell nozzle with an exit angle of zero, exhausting a perfectly uniform flow. SCORES 2.0 now includes options for conical nozzles and aerospikes.

The conical nozzle is modeled by applying an efficiency to the ideal nozzle calculations to account for spreading. The form of this efficiency is shown in equation (1) where θ is the cone half angle. This angle must be specified for conical nozzles.

$$\eta = \frac{1}{2}(1+\cos\theta) \tag{1}$$

The aerospike nozzle is modeled as an adjustable area ratio, bell nozzle at ideal expansion. Implementation is easily performed through bypassing the usual iteration for exit Mach number. Instead, the exit Mach number is calculated from the isentropic flow relation for total pressure, equation (2). In this equation, the exit pressure is set equal to the known ambient pressure.

$$\frac{P_e}{P_c} = \left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{-\gamma}{\gamma-1}} \tag{2}$$

Once the exit Mach number is known, the area ratio is calculated from the Area-Mach number relation, equation (3).

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \tag{3}$$

This procedure would, however, predict an infinite area ratio, and therefore and infinite thrust, at vacuum conditions. To prevent this, a minimum exit pressure of .05 atmospheres is used in SCORES 2.0. This limit corresponds to a maximum expansion ratio of slightly over 220. Cases for which this limit are used will show an under-expansion.

Thrust-to-Weight

SCORES 2.0 now includes a low-fidelity estimation of thrust-to-weight (T/W). This estimation is not intended to provide absolute values of engine weight. Such an estimation would depend heavily on technology level and manufacturing techniques and would require a much higher level of fidelity than is provided here. Instead, the calculated T/W should be viewed as a first estimation, which could be useful in predicting T/W trends. The actual values of T/W may vary somewhat from those predicted.

The T/W estimation in SCORES 2.0 is based on the premise that the engine will develop a constant power-to-weight (P/W), where power, defined in equation (4), is based on the chamber and exit enthalpies.

$$P = \dot{m}\left(h_c - h_e\right) \tag{4}$$

The validity of this assumption will be discussed later in this section.

Power is easily calculated within the same routines that predict thrust and Isp. If the P/W is known, then the T/W is found easily from the thrust and power by equation (5).

$$\frac{T}{W} = \left(\frac{P}{W}\right)\frac{T}{P} \tag{5}$$

To allow for differences in technology levels, SCORES 2.0 provides a user input to select the T/W relative to other engines. The user may select "high", "average", or "low" from a pull-down menu. A selection of "average" uses a P/W of 0.017 MW/lb, while a selection of "high" or "low" uses a P/W of 0.023 or 0.015 MW/lb respectively.

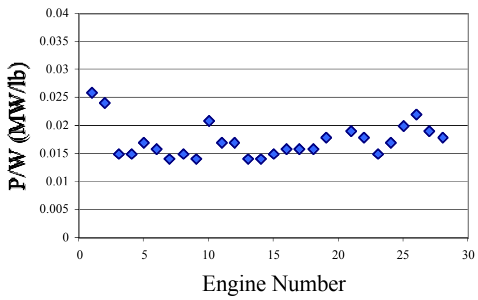

Figure 8 - Power to Weight

Figure 8 shows a plot of the P/W calculated by SCORES 2.0 for 28 rocket engines for which T/W was known. These engines ranged in thrust from 50,000 lbs. to 1,500,000 lbs and provided a representative cross-section of fuel types and engine cycles. Note the relative invariance of the P/W. The values for P/W vary only slightly from 0.015 to 0.025 and therefore support the premise of constant P/W. The range of P/W shown in Figure 8 determined the "high" and "low" T/W options available to the user. The "average" T/W selection was determined by taking the statistical mean from the 28 engines analyzed.

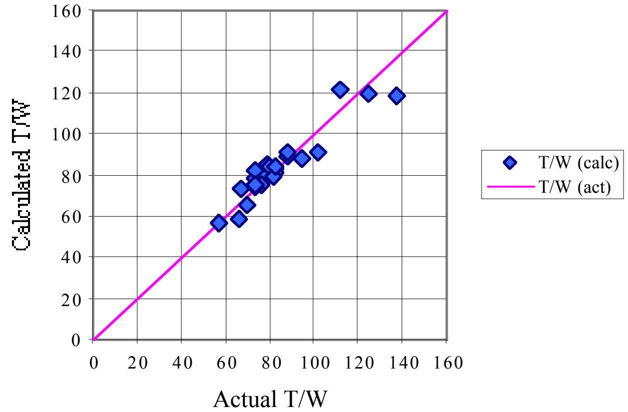

Figure 9 – Vacuum Thrust to Weight

Figure 9 compares the actual vs. calculated T/W. In each case, the most appropriate P/W rating ("high", "average", or "low") was used. This plot further supports the premise of constant P/W. The results show a T/W correlation within +/-15%. While this error may not be acceptable for weight estimation, it may be within allowable tolerances for early conceptual design and trade studies.

Equivalence Ratio

In addition to O/F mixture ratio based on weight, SCORES 2.0 now allows the mixture specification by equivalence ratio. Both the mixture ratio and the equivalence ratio are calculated for the given propellant combination and displayed in the output section for reference.

Mass Fractions

SCORES 2.0 chemistry calculations now display the equilibrium concentrations in both mole fractions and mass fractions. Mass fractions are related to the mole fractions through the molecular weights of the species and mixture, as shown in equation (6).

$$Y_i = X_i \frac{MW_i}{MW_{mix}} \tag{6}$$

Improved Iterations

Determining the exit Mach numbers requires iteratively solving the Area-Mach number relation, equation (3), until the calculated area ratio matches the actual expansion ratio. The previous version of SCORES used a secant method iteration. This iteration procedure was not bounded and therefore, the solution could, under the correct conditions, converge on the subsonic solution when a supersonic solution should exist in the nozzle.

The new version of SCORES corrects this potential problem by using a golden section iteration to solve for the exit Mach number. The new routine is bounded by Mach 1.0 and therefore ensures that the supersonic solution is found.

Download Link

Users may now download SCORES 2.0 from the World Wide Web. A compressed file containing the SCORES 2.0 executables, web pages, CGI scripts, and data text files can be found by following the "download" button on the SCORES 2.0 main menu. The executable files have been compiled for an SGI workstation. Versions for other computer platforms are not available at this time. The download option is provided as a convenience only. The preferred method for running SCORES is from the web page.

Engine Performance

The foregoing comparisons validated only the chemical equilibrium calculations or supported the T/W estimation. It is also desired to validate SCORES' performance calculations. Therefore, SCORES 2.0 performance predictions are compared to historical rocket engine data.

Table 1 - Engine Data

Engine	ε	A_t (in^2)	O/F	P_c (psia)
J-2 (200K)	27.5	169.6	5	670
M-1	40	803.24	5	1100
RL10A-3-3	57	20.75	5	400
J-2 (225K)	27.5	169.8	5.5	670
J-2 (230K)	27.5	169.6	5.5	691
J-2S	40	116.9	5.5	1246
SSME	77.5	83.16	6.011	3277
RL10A-3-3A	61	19.2	5	475
RL10A-4	84	19.3	5.5	568

A similar comparison was performed in the previous paper[1]. That study compared nine existing Lox/LH_2 rocket engines. These engines were: 200K J-2, M-1, RL10A-3-3, 225K J-2, 230K J-2, J-2S, SSME, RL10A-3-3A, and RL10A-4. Data for these engines, presented in Table 1, was taken from The CPIA/M5 Liquid Propellant Engine Manual[11]. These engines were again analyzed along with another 40 engines from various sources. Of the 49 rocket engines analyzed 27 were Lox/LH_2, 21 were Lox/Kerosene, and 1 was Lox/CH-4 (see Appendix A.)

In each case, SCORES 2.0 was run at vacuum conditions using the engine data provided. The calculated results for thrust and specific impulse were then compared with the advertised values. The ratio of the actual values to the predicted values determined the efficiencies. These efficiencies were compared and a sample mean and variance were calculated.

The mean thrust efficiency was .9633, with a variance of .2413. The mean Isp efficiency was .9550, with a variance of .0920. The efficiency correction is always applied to the vacuum conditions. In this way, SCORES maintains the proper relation between vacuum and sea-level conditions.

Table 2 - Thrust Comparison (lb.)

Engine	Actual	Ideal	Corrected
RD-107	56,000	56,400	55,300
RD-108	52,900	53,600	52,600
RD-111	91,500	93,200	91,500
RD-170	444,200	452,800	444,500
RD-171	444,200	452,900	444,700
RD-180	466,500	473,200	464,500
SSME	512,400	525,200	515,600
RL10A-4	20,800	21,300	20,900
RD-701	178,500	184,000	180,600

Table 3 - Isp Comparison (sec)

Engine	Actual	Ideal	Corrected
RD-107	313.0	325.2	314.6
RD-108	315.0	325.0	314.5
RD-111	317.0	326.3	315.7
RD-170	337.0	342.5	331.4
RD-171	337.0	342.2	331.1
RD-180	337.2	342.6	331.5
SSME	454.4	476.7	461.3
RL10A-4	449.0	473.5	458.1
RD-701	460.0	477.7	462.2

Figure 10 is a plot of Isp efficiency vs. Thrust efficiency for all 49 engines. This plot shows a grouping of points with good agreement near the target value of (1,1). Several points lay outside the area designated as “good agreement”. For these points, the engine data used may be in error. In many cases, the throat area was not known and had to be calculated based on reported vacuum and sea-level thrust or installed engine envelope. Such calculations introduce uncertainty in the “actual” data.

The data with good agreement in Figure 10 has a mean thrust efficiency of 0.9817 and a variance of 0.0224. These points have a mean Isp efficiency was 0.9676, with a variance of .0308. These mean efficiencies were then used to correct the predicted values of vacuum thrust

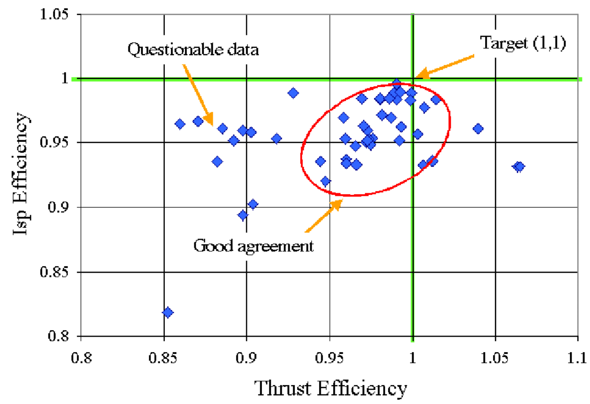

Figure 10 - Efficiencies

and Isp. Table 2 shows the actual, ideal, and predicted thrust for nine of the engines analyzed. Table 3 also shows the actual, ideal, and predicted Isp. The corrected thrust values have a maximum relative error of 3.2%. The maximum relative error for Isp was 3.6%. This error is acceptable for conceptual-level design.

Appendix A lists the data used for the 49 rocket engines. The authors make no claims to the accuracy of the reported engine parameters. This data was used only for comparative purposes.

CONCLUSIONS

1. The new features and improvements recently added to SCORES 2.0 have significantly increased the utility of the program. The most notable improvement is the addition of hydrocarbon combustion.

2. SCORES 2.0 provides propulsion performance parametrics within an accuracy suitable for conceptual-level design. This accuracy has been demonstrated through comparisons with historical engine data.

3. Through a web-based format, SCORES 2.0 provides a rocket engine analysis tool which is suitable for multidisciplinary or geographically dispersed design environments.

4. SCORES 2.0 provides a complete rocket engine analysis package. The rapid analysis and user-friendly interface allow SCORES 2.0 to function as a valuable instructional tool.

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REFERENCES

1. Way, D.W. and J.R. Olds. “SCORES: Developing an Object-Oriented rocket Propulsion Analysis Tool.” AIAA-98-3227. Conference Proceeding of the 34th AIAA/ASME/SAE Joint Propulsion Conference in Seattle, WA. 1998.

2. Bradford, J.E. and J.R. Olds. “Enhancements to SCCREAM, A Conceptual RBCC Engine Analysis Tool.” AIAA-98-3775. Conference Proceeding of the 34th AIAA/ASME/SAE Joint Propulsion Conference in Seattle, WA. 1988.

3. Kuo, K.K., *Principles of Combustion*, John Wiley & Sons, Inc., New York, NY. 1986.

4. Glassman, I., *Combustion*, Second Edition, Academic Press, Orlando, FL. 1987.

5. Reynolds, W. C. “The Element Potential Method for Chemical Equilibrium Analysis Implementation in the Interactive Program STANJAN,” Department of Mechanical Engineering Stanford University. 1986.

6. Gordon, S. and McBride B., “Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications”, NASA Reference Publication 1311.

7. Atkinson, K.E., *An Introduction to Numerical Analysis*, Second Ed., John Wiley & Sons, Inc., Ney York, NY. 1989

8. Chase, M.W. et al., *JANAF Thermochemical Tables*, 3rd Ed., American Chemical Society, Washington, DC. 1986.

9. ”Brauer, G. L., et al. “Program to Optimize Simulated Trajectories (POST).” Final report for NASA contract NAS1-18147, Martin-Marietta Corp., September 1989.

10. Vanderplaats, Garett N., *Numerical Optimization Techniques for Engineering Design with Applications*, McGraw-Hill Inc., New York, NY. 1984.

11. Chemical Propulsion Information Agency *CPIA/M5 Liquid Propellant Engine Manual*, Johns Hopkins University, Columbia, MD. 1998.

Table A1 – Lox/LH2 Rocket Engines

Engine	O/F	Pc (atm)	ε	At (in^2)	Tvac (lbs)	Thrust SCORES	Isp (sec)	Isp SCORES
J-2	5.5	52	27.5	185.08	230,000	260,849	425.0	454.47
J-2	5.5	53	27.16	169.70	230,000	243,634	424.9	454.33
J-2 (200K)	5	46	27.5	169.60	200,000	211,102	426.0	462.75
J-2 (225K)	5.5	46	27.5	169.80	225,000	211,642	422.6	453.57
J-2 (230K)	5.5	47	27.5	169.60	230,000	215,999	422.7	453.73
J-2S	5.5	82	40	115.65	265,000	261,788	436.0	465.74
J-2S	5.5	85	40	116.90	265,000	274,323	435.0	466.00
M-1	5	75	40	803.24	1,500,000	1,659,930	428.0	474.12
RD-0120	6	215	85.7	73.85	440,850	453,422	455.0	478.14
RD-701	6.1	122	123.4	52.24	178,500	183,957	460.0	477.73
RL10A-3-3	5	27	57	20.75	15,000	15,621	444.0	473.49
RL10A-3-3A	5	32	61	19.20	16,500	17,182	444.4	475.99
RL10A-4	5.5	39	84	19.30	20,800	21,339	449.0	473.46
RS-53	6	204	77.5	83.19	470,000	482,817	453.5	476.03
SSME	6.011	223	77.5	83.16	512,845	527,746	452.9	476.50
SSME	6.034	206	77.5	83.40	469,000	488,841	453.3	475.51
SSME	6	223	77.5	82.76	512,410	525,192	454.4	476.70
SSME	6	222	77.5	90.89	512,300	574,190	453.5	476.66
STME	6.993	153	45.02	146.60	650,000	625,154	429.2	446.72
STME	6	136	62.5	112.77	435,000	432,329	437.5	469.14
Vulcain	5.25	109	45	93.09	252,685	281,482	424.4	474.59

Table A2 – Lox/Kerosene Rocket Engines

Engine	O/F	Pc (atm)	ε	At (in^2)	Tvac (lbs)	Thrust SCORES	Isp (sec)	Isp SCORES
F-1	2.27	67	16	1017.88	1,522,000	1,786,540	265.0	323.77
MA-5A_btr	2.25	49	8	226.19	238,350	277,297	297.1	308.08
MA-5A_btr	2.25	43	8	226.19	215,350	243,307	295.6	307.53
MA-5A_btr	2.25	49	8	226.19	241,350	277,297	297.8	308.08
MA-5A_str	2.27	50	25	72.38	87,100	97,012	316.7	330.10
NK-33	2.8	144	27	95.33	368,237	371,701	331.0	332.42
NK-33	2.6	143	27	87.73	339,000	339,292	331.0	334.78
RD-105	2.7	58	14.2	94.03	141,090	142,241	302.0	317.32
RD-106	2.7	58	20.4	93.66	145,069	144,634	310.0	323.93
RD-107	2.47	58	18.9	37.28	55,696	57,257	312.0	325.16
RD-107	2.47	58	18.9	36.70	55,977	56,366	313.0	325.16
RD-108	2.39	50	18.9	40.14	51,256	53,099	308.0	325.00
RD-108	2.39	50	18.9	41.53	52,661	54,938	315.0	325.00
RD-108	2.39	50	18.9	40.50	52,886	53,575	315.0	325.00
RD-111	2.39	77	18	45.83	91,497	93,186	317.0	326.28
RD-120	2.6	161	106	43.93	187,400	201,963	350.0	354.05
RD-170	2.6	242	36.87	68.11	444,166	452,822	337.0	342.53
RD-170	2.6	242	36.4	68.98	444,250	458,345	337.0	342.33
RD-171	2.63	242	36.87	68.11	444,166	452,932	337.0	342.24
RD-172	2.6	256	36.87	66.85	469,513	470,219	337.0	342.83
RD-172	2.6	255	36.4	67.70	469,500	474,063	337.0	342.61
RD-173	2.63	252	36.87	65.47	459,790	453,411	337.0	342.46
RD-180	2.72	254	36.87	67.57	466,703	471,983	337.8	341.54
RD-180	2.72	253	36.87	67.57	466,700	470,120	337.8	341.51
RD-180	2.6	254	36.4	67.84	466,500	473,176	337.2	342.59
RS-27	2.25	48	8	213.72	231,700	256,656	295.0	307.99
RS-27A	2.245	48	12	209.09	237,000	258,213	302.0	316.74

Table A3 – Lox/CH-4 Rocket engines

Engine	O/F	Pc (atm)	ε	At (in^2)	Tvac (lbs)	Thrust SCORES	Isp (sec)	Isp SCORES
STBE	2.7	204	48	124.88	713,115	708,101	348.0	356.08