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ABSTRACT

The SCORES-II program is a conceptual-level engineering design and analysis tool for the performance prediction of liquid propellant rocket engines. The tool is written in the C++ programming language and can be compiled and executed on all major computing platforms (e.g. UNIX, PC, Mac). SCORES-II can be executed through a command line/console application or via the ModelCenter© environment with its filewrapper. The Analysis Server© filewrap allows for automated execution and integration with other disciplinary analysis tools.

SCORES-II can support a wide variety of engine configurations. In addition to the built-in propellant options, the chemical equilibrium routine is capable of handling any generic fuel and oxidizer combination. Numerous options exist for sizing an engine, including thrust and throat area matching. An 'expert system' of engine efficiencies is also included, allowing for cycle, chemical reaction, injector/combustor, and nozzle influences on performance.

The equations used for the performance calculations, equilibrium chemistry model, and engine sizing will be presented and discussed. Chemical equilibrium results obtained from implementing these equations will then be compared with results from another equilibrium code widely used in industry. Performance predictions from SCORES-II will be compared with known performance values for a number of existing engines. Sample results demonstrating SCORES-II's throttled engine analysis will be presented for a notional engine design. The tool's user-interface options will also be discussed.

Finally, the paper will include a future work section detailing additional improvements and capabilities planned for future incarnations of SCORES.

NOMENCLATURE

A_t	*throat area, ft²*
A_e	*exit area, ft²*
*C**	*characteristic exhaust velocity, ft/s*
Cp	*mixture specific heat, BTU/(lbm-R)*
EX	*expander*
GG	*gas-generator*
H_t	*mixture total enthalpy, BTU/lbm*
Isp	*specific impulse, seconds*
LOX	*liquid oxygen*
LH2	*liquid hydrogen*
MMH	*monomethyl hydrazine*
MW	*mixture molecular weight*
NTO	*nitrogen tetra-oxide*
Pa	*ambient pressure, psia*
Pc	*chamber pressure, psia*
PF	*pressure fed*
R	*universal gas constant*
SC	*staged-combustion*
T	*thrust, lbf*
T_{ad}	*adiabatic flame temperature, R*
TO	*tap-off*
UDMH	*unsymmetrical dimethyl hydrazine*
Xi	*mole fraction of species i*
h_s	*mixture static enthalpy, BTU/lbm*
s	*mixture specific entropy, BTU/(lbm-R)*
o/f	*mixture ratio, oxidizer-to-fuel by weight*
ε	*nozzle expansion area ratio*

BACKGROUND

The first incarnation of SCORES, which stands for SpaceCraft Object-oriented Rocket Engine Simulation, was developed by David Way at the Georgia Institute

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of Technology in 1998[1,2]. The intent of the tool development was to create a liquid rocket engine code for usage in the conceptual design environment. This tool needed to be fast and require a minimal number of user inputs, while still providing a high degree of accuracy.

This 'proof of concept' version was written in object-oriented C++ language and featured a unique web-based user interface. Initially, the code only handled hydrogen and oxygen propellants, but this was later expanded to include a number of hydrocarbon fuels. The positive attributes of this code were its quick execution time, built-in efficiency database, and thrust-to-weight estimation based on an engine power density calculation.

While the overall SCORES design tool concept was demonstrated, the degree of accuracy provided by the tool was insufficient. While some engines performance would match fairly well with existing engines, others did not[2].

The source of the error primarily resided in the tool's chemistry model limitations. While the equilibrium mole fractions would compare fairly well with other equilibrium codes, the adiabatic flame temperature calculation (Tad) often did not. This discrepancy was often in the range of a few hundred degrees Rankine. Another drawback was that the equilibrium routine only performed a temperature [T=*f*(h,P)] analysis. There was no capability for solving the entropy problem [T=*f*(s,P)] which is critical for obtaining accurate performance predictions. The lack of the entropy solution meant that the performance equations had to be based on a calorically perfect gas (CPG) model with isentropic derivations. These assumptions lead to correction factors being applied to the engine which could not be consistently applied over different engine designs. This factor and the frozen flow nozzle assumption inevitably lead to the performance prediction deficits.

SCORES-II is the commercial version and incarnation of the original SCORES tool. Developed solely by SpaceWorks Engineering, Inc., the tool has been coded independent of the original, with only the original stated goals and capabilities retained. All of the issues associated with the first version have been virtually eliminated and the tool's capabilities have been greatly expanded.

MODELING CAPABILITIES

SCORES-II is a fairly versatile and flexible tool. With its numerous design capabilities, the tool can be used in a variety of design scenarios. Projects to date have used the code for main propulsion system sizing, mixture ratio trades with full vehicle closure, uncertainty analysis, and OMS/RCS thruster performance prediction. While not an all inclusive list, some of the main code capabilities and functionality will be presented next.

Propellant Types

Chemical properties for a number of fuel types have been built into SCORES-II. These fuel types include hydrogen (H_2), propane (C_3H_8), methane (CH_4), RP-1 ($C_1H_{1.942}$), monomethyl hydrazine (MMH, $C_1H_6N_2$), and unsymmetrical dimethyl hydrazine (UDMH, $C_2H_8N_2$). Any generic fuel type in the C-H-N system can also be specified by the user by providing the proper molecular coefficients corresponding to $C_xH_yN_z$. As an example, for octane fuel the user would specify x=8, y=18, and z=0.

Similarly, chemical properties for a number of oxidizer combinations have been included. These oxidizer types are oxygen (O_2), hydrogen peroxide (H_2O_2), and nitrogen tetra-oxide (N_2O_4). Any generic oxidizer type in the H-N-O system can also be specified by providing the molecular coefficients corresponding to $O_xH_yN_z$.

When using any of the propellant types with built-in chemical properties, the user is only required to specify the initial temperature of the propellant. For cases using generic fuels or oxidizers, the user must specify the initial enthalpy of each generic propellant. As an example, for octane the user would specify an enthalpy of 3812.6 BTU/lbm, corresponding to an initial temperature of 536.67 R.

Engine Sizing

For engine sizing and design, the user has three options. The first of these is to specify the actual mass flowrate through the nozzle throat. This value is typically known when modeling an existing engine and the thrust values and engine areas are output parameters. For new engine designs, the user can specify a 'required thrust' at a selected ambient condition or a 'required throat area'. In the case of the thrust-matching, SCORES-II will determine the mass

flowrate required and necessary nozzle throat and exit area to achieve this thrust value. The user specifies the ambient condition at which the necessary thrust value is met (e.g. Pa=0 corresponds to vacuum conditions sizing). This method is especially useful in the design environment when attempting to 'close' a vehicle configuration. In the case of area-matching, SCORES-II will determine the corresponding mass flowrate that yields the desired throat area. Both the flowrate and thrust are output values in this case.

SCORES-II can also compute the performance of a throttled engine. The user is required to specify the desired maximum and minimum throttle settings as well as the number of throttle steps between the maximum and minimum values. There is no limit on the number of cases that can be analyzed. As an example, throttle settings of 110%, 50%, and 4 steps will yield throttled engine performance analysis at 110%, 90%, 70% and 50%.

Efficiency Factors

SCORES-II includes an 'expert system' efficiency factor routine. This routine includes four efficiency factors, which are: cycle, reaction, combustor, and nozzle. These factors are all affected by the engine's cycle type, propellant combination, and operating conditions. The incorporation of this system into SCORES-II either removes the need for the user to guess what the efficiency will be or provides the user with a departure point based on 'historical' performance trends for real engines. The performance corrections are applied by default based on the user's input parameters. Optionally, users can override this routine and specify their own efficiency factors.

Nozzle Flow

An engine's propellant combination (and, to a lesser extent, mixture ratio and chamber pressure) chiefly determines the degree of chemical reactions occurring downstream of the combustion chamber. Some engine flows remain nearly frozen at the composition obtained in the combustion chamber, while others continue to react and reach approximate chemical equilibrium at each temperature and pressure condition along the nozzle. In order to simulate this effect, the user can select either a 'frozen' nozzle flow composition or an 'equilibrium' nozzle flow composition.

Output Options and Formats

The main output file from SCORES-II contains all of the thermodynamic properties (T, P, V, h, s, etc.) in the engine. The four engine efficiencies used, as well as the overall efficiency factor is provided. Thrust and Isp at ideal, vacuum, ambient, and sea-level conditions are always generated, where the user determines what the ambient condition corresponds to by specifying Pa. Additionally, mole fractions for each species are provided in a tabular format.

One of the more unique aspects of SCORES-II is that it will automatically generate a file containing the engine performance results formatted for use with the Program to Optimize Simulated Trajectories (POST) trajectory code[3]. The table contains either a single performance point or multiple points in a 1-D table, for the case of throttled engine analyses. The points consist of the engine thrust and Isp at vacuum conditions. The engine exit area is also provided for back pressure calculations by POST. Additionally, the user has the ability to change POST-specific nomenclature like the engine identification number and throttle variable name (e.g. 5hgenv5, 4hetal). Figure 1 provides a sample of this output file.

```
c engine throat area: 0.611 ft2
c
c engine exit area (ft2)
I$tab table=4hae1t,0,30.546 $
c
c engine vacuum specific impulse (seconds) versus throttle setting
I$tab table=5hisp1t,1,4hetal,4,3*1,
  0.500, 443.154,
  0.700, 443.660,
  0.900, 443.996,
  1.100, 444.239,
 $
```

Figure 1. Sample POST Engine Deck

When linking analysis tools to an optimizer, it is often necessary to have a significantly higher number of digits for the output values. The higher fidelity numbers are often necessary to support gradient or sensitivity analysis calculations. To generate meaningful higher fidelity output digits requires tighter convergence tolerances on internal code iterations. Therefore, the user has the ability to set both the desired number of significant output digits for all variables, as well as the convergence tolerances. But, higher convergence tolerances increase code runtime, thus for general, non-optimization runs, lower values

for both these parameters can be used to speed execution without any significant loss in overall accuracy.

Units

While the input parameters must be specified in English Engineering(EE) units, the user has the option of selecting EE or SI output units. Table 1 contains the unit type options for various output parameters.

Table 1. Output Unit Options

Length	ft or m
Area	ft^2 or m^2
Speed	ft/s or m/s
Mass Flowrate	lbm/s or kg/s
Pressure	lbs/in^2 or Pa
Temperature	R or K
Thrust	lbf or N
Energy Density	BTU/lbm or KJ/kg
Specific Heat and Entropy	BTU/lbm-R or KJ/kg-K

ANALYSIS METHODS

Equilibrium Chemistry

SCORES-II equilibrium chemistry model is based on the work done by Gordon and McBride[4]. The method used for determining equilibrium compositions is the minimization of Gibbs energy. This technique can be implemented very generically and can handle additional species without any significant increase in execution time (additional atom types will however).

For a specified temperature and pressure, the following equation set must be solved:

$$\sum_{i=1}^{5}\sum_{j=1}^{14} a_{kj}a_{ij}n_j\pi_i + \left(\sum_{j=1}^{14} a_{kj}n_j\right)\Delta\ln n = b_k^o - b_k + \sum_{j=1}^{14}\frac{a_{kj}n_j\mu_j}{RT} \quad (1)$$

for k=1 to 5

$$\sum_{i=1}^{5}\sum_{j=1}^{14} a_{ij}n_j\pi_i + \left(\sum_{j=1}^{14} n_j - n\right)\Delta\ln n = n - \sum_{j=1}^{14} n_J + \sum_{j=1}^{14}\frac{n_j\mu_j}{RT} \quad (2)$$

The first summation in both sets is for the 5 different atoms types: C, H, N, O, and Ar. The second summation is for the 14 different species being considered in the analysis: H_2, O_2, N_2, O, H, N, H_2O, OH, CO, CO_2, C, CH_4, NO, and Ar. The variable a_{ij} is a 5-by-14 matrix mapping each atom '*i*' to species '*j*'. The number of moles for each species is represented by 'n_j', with '*n*' being the total moles in the mixture. The universal gas constant is represented as '*R*', with '*T*' being the specified temperature. The specified pressure influences the chemical potential '$\mu_{i,j}$' as:

$$\mu_{i,j} = g^o{}_{i,T} + RT\ln\left(\frac{n_i}{n}\right) + RT\ln P \quad (3)$$

where $g^o{}_{i,T}$ is the Gibbs function of the pure species (*i*) at 1 atm[5].

Note that when these equations are expanded they form a system of six simultaneous, non-linear equations. The solution to this problem formulation is best obtained through a Newton-Rhapson (N-R) root-finder. The N-R routine is fairly simple to program but does require initial guesses to be made.

The solutions proceeds by incrementally updating the number of moles for each species *j* and the total moles until the update values to all species are within a specified tolerance ($\sim 10^{-5}$). At each iteration, the updated matrix is solved using a Lower-Upper (LU) matrix decomposition algorithm with complete pivoting[6]. The LU algorithm requires about the same number of mathematical operations as a traditional Gaussian Elimination method, but the addition of the 'complete pivoting' step reduces truncation and round-off errors by reducing the chance of division operations with small numbers. Each solution of the matrix system results in correction terms for the number of moles for each species in the system, as well as the total number of moles present. An initial guess for each of the product moles equal to 1/14 is made, as suggested by Gordon and McBride.

For the solution of the entropy problem, i.e specified pressure and entropy, the equilibrium temperature will become an output value in addition to the composition. Due to the similarity of the equations, they will not be repeated for brevity. The reader is referred to Reference 4 for more details on this subject.

Chemical Properties

To eliminate time-consuming property table lookups, curve fit data for the formation enthalpy, sensible enthalpy, latent heat of vaporization, Gibbs free

energy, and constant-pressure specific heats from the JANNAF tables have been generated for a number of molecules[7]. Included in the database are the previously mentioned 14 species considered as potential products in the equilibrium analysis as well as: H_2O_2, C_3H_8, $C_1H_{1.942}$, and N_2O_2. Enthalpy of formation values for $C_1H_6N_2$ and $C_2H_8N_2$ are also included, but the variation with temperature for these molecules is not available. The general form of these models are as constants, piecewise-continuous polynomials or exponentials with temperature as the independent variable.

Engine Efficiencies

From a collection of about 20 modern engine designs, the vacuum specific impulse for these real engines has been compared to the ideal engine performance (at their respective ε, o/f, and Pc). A required overall efficiency factor was then computed based on the real-to-ideal Isp ratio. This overall efficiency is assumed to be comprised of four specific efficiency factors (i.e. cycle, reaction, combustor, and nozzle), whose values were determined from the results of a regression analysis on the modern engines. The cycle efficiency (η_{cycle}) accounts for open system losses. The reaction efficiency ($\eta_{reaction}$) accounts for the non-equilibrium state of the flow. The combustor efficiency ($\eta_{combustor}$) accounts for losses due to the combustion process and injection losses. The nozzle efficiency (η_{nozzle}) accounts for divergence and friction losses. The equation for the overall efficiency is:

$$\eta_{Overall} = \eta_{cycle} * \eta_{reaction} * \eta_{combustor} * \eta_{nozzle} \quad (3)$$

The nozzle efficiency is influenced by the ε and propellant type of the user's engine. The combustor efficiency is dependent on the o/f and propellant type. Both the cycle and reaction efficiency are constant values that only depend on the cycle and propellant type, respectively. For example, the η_{cycle} for staged-combustion engines is always 1.

Rocket Performance

The engine is divided into three main stations or components: an infinite area chamber, the throat, and the nozzle exit plane. Assessing the overall engine performance metrics of thrust and Isp requires multiple iterative equation solvers, each building on the analysis results from the upstream station.

To start the analysis process, the total enthalpy of the propellant (H_t), chamber pressure (Pc), and mass flowrate (*mdot*) must be known. The *mdot* value can be either from a user-specified value or a 'guess' from SCORES-II (thrust or area matching option).
The chamber analysis is conducted by iterating on the chamber temperature (T_{ad}) until the required H_t value is obtained. Each guessed value for Tad will have a different equilibrium composition (X_i's), for a given Pc. Both the composition and Tad will effect the H_t value. This process is solved through a simple bi-section algorithm with appropriate maximum and minimum starting values for T_{ad}.

Once the value for T_{ad} is determined and an equilibrium composition obtained, the entropy (*s*) of the system can be determined using Equation 4, The specific heat (Cp) and specific heat ratio (γ) for the chamber can also be determined. Calculation of the flow velocity and Mach number in the chamber is unnecessary.

$$s = \sum_{j=1}^{14} n_j \left(s^o{}_j + R \ln\left(\frac{n_i}{n}\right) + R \ln P \right) \quad (4)$$

With the chamber conditions established, the analysis proceeds to the next component, the engine throat. It is necessary to solve for the throat conditions so that the throat area (A_t) can be determined. Once the throat area is found, the exit area (A_e) can also be computed.

At the throat, the flow will be at sonic conditions (Mach 1). To solve for the sonic conditions, an iterative procedure of guessing the throat static pressure is conducted. A bi-section routine can again be employed, with a maximum value for the static pressure set equal to Pc and a minimum value of zero. It is assumed that the flow progresses from the chamber to the throat section isentropically, therefore the throat entropy is equal to the chamber entropy previously determined. With a specified static pressure and entropy, the equilibrium routine can be utilized to determine the new flow composition and static temperature (i.e. T=*f*(s,P) problem). Using this static temperature value, it is then possible to compute the Cp, γ, and h_s at the throat. From the Energy equation, the flow velocity can be determined next, followed by the Mach number. If the resultant Mach number is not unity, then the assumed static pressure value can be adjusted and the process repeated until the user specified convergence tolerance is met.

Once all the sonic flow conditions have been determined at the throat, A_t can be calculated using the continuity equation. Additionally, the engine characteristic exhaust velocity (C*) can also be found using Equation 5.

$$C^* = \frac{PcA_t}{\dot{m}} \tag{5}$$

Following completion of the throat section analysis, SCORES-II advances to the nozzle exit plane. Depending on the user selected option, two analysis can occur: an equilibrium flow analysis and a frozen flow analysis. Each will be discussed next, as their analysis process are significantly different.

For the equilibrium nozzle flow solution, a method nearly identical to that used for the throat is used. The difference for this component analysis lies in the final calculations. Instead of trying to converge on a Mach number requirement, as before, the A_e becomes the target. Thus, the assumed static pressure will be adjusted until the resultant A_e matches the area defined by ε and A_t.

For the frozen nozzle flow solution, while an iterative process is required, the flow composition will not be update and will be fixed at the values obtained at the engine's throat. The solution process entails guessing the static temperature at the nozzle exit. From an assumed temperature, the Cp, γ, and h_s can be determined. Using the energy equation, the exit velocity can then be computed. Using Equation 6a-d, the exit static pressure can be found. With all the known thermodynamic properties (T, P, $\mathcal{MW}$, and V), the corresponding A_e can be found using the continuity equation. If this exit area does not match that defined from A_t and ε, the assumed static temperature is adjusted and the process repeated until convergence is obtained.

$$z_1 = \sum_{i=1}^{14} \frac{\dot{m}_i}{MW_i \dot{m}} \tag{6a}$$

$$z_2 = \sum_{i=1}^{14} \frac{\dot{m}_i}{MW_i \dot{m}} \ln(n_i) \tag{6b}$$

$$z_3 = \sum_{i=1}^{14} \frac{\dot{m}_i}{MW_i \dot{m}} s_i \tag{6c}$$

$$P_e = e^{((-s - Rz_2 + z_3)/(Rz_1))} \tag{6d}$$

Once all the thermodynamic properties have been determined at the exit station, the engine performance can be assessed using Equations 7 and 8. Equation 7 provides the thrust coefficient and 8 provides the ideal vacuum Isp. Using either the user specified efficiencies or results from the expert system, the overall efficiency can be computed and applied to the ideal vacuum Isp, as shown in Equation 9. Once the actual engine vacuum Isp has been determined, the vacuum thrust, sea-level thrust, and sea-level Isp can be determined using Equations 10, 11, and 12. For the sea-level calculations, an ambient pressure (Pa) value of 14.69 psia is used. The Pa value can also be substituted with a value corresponding to a specific altitude to determine the respective engine performance at that condition.

$$C_f = \frac{V_e}{C^*} \tag{7}$$

$$Isp_{vac,ideal} = \frac{V_e}{g} + \frac{P_e A_e}{\dot{m}} \tag{8}$$

$$Isp_{vac,actual} = \eta_{overall} Isp_{vac,ideal} \tag{9}$$

$$T_{vac} = Isp_{vac,actual} \dot{m} \tag{10}$$

$$T_{sls} = T_{vac} - P_a A_e \tag{11}$$

$$Isp_{sls} = \frac{T_{sls}}{\dot{m}} \tag{12}$$

Throttled Engine Analysis

Once the reference engine conditions have been established, the throttled engine performance results can be computed. The throttle setting is defined as a percentage of reference engine's *mdot*. The A_t is fixed

at the reference engines value, thus the Pc must be adjusted to ensure that the flow chokes at the throat. This involves an iterative process of guessing a Pc, solving the chamber and throat components, then verifying if the assumed Pc yielded the necessary A_t. Once the correct Pc is determined, the nozzle analysis follows the same procedure outlined previously.

VERIFICATION

Equilibrium Properties

SCORES-II's equilibrium model will be compared with a commonly used industry equilibrium code called CEA – Chemical Equilibrium and Applications. This code was developed by Gordon and McBride at the NASA Glenn Research Center. The code has an extensive chemical property database and numerous options for solving equilibrium problems (e.g. T&P, H&P, S&P, etc.) with gaseous, condensed, and ionized species. While the code will predict engine performance numbers, it only determines the ideal performance values and will not 'size' an engine, throttle an engine, nor generate a POST deck.

To verify the SCORES-II model, four different equilibrium cases were selected, of various propellant combinations, pressures, and mixture ratios. Table 2 provides the conditions used for these four cases.

Table 2. Equilibrium Verification Cases Settings

	Case #1	Case #2	Case #3	Case #4
o/f	5	7.5	2.5	2.5
Pc, psia	3,000	1,000	2,000	500
Fuel	LH2	LH2	JP-4	NTO
Oxidizer	LOX	LOX	LOX	MMH
T_{fuel}, R	39.0	39.0	536.67	536.67
T_{ox}, R	163.0	163.0	163.0	536.67

For each of the four cases, SCORES-II and CEA were executed with identical input parameters. The output parameters extracted for comparison consisted of the equilibrium temperature, mixture molecular weight, and mole fractions. Note that due to the more extensive chemical database, some trace species were generated from CEA that do not appear in the available SCORES-II chemical database. While the equilibrium solution containing these species is probably mathematically correct (minimum Gibbs), the complex collisions necessary to actually create these trace particles are unlikely to occur.

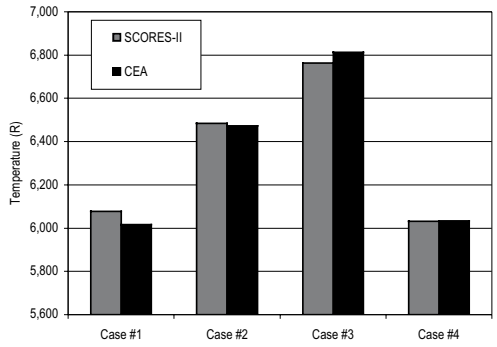

Figure 3. Equilibrium Temperature Comparisons

Figure 3 provides the comparative charts for the equilibrium temperature for the four cases examined. Excellent agreement is obtained between the two codes, with a maximum difference of 61° R occurring for Case #1. The differences can most likely be attributed to the trace elements being formed in CEA and any differences in the total enthalpy due to differences in the chemical property data.

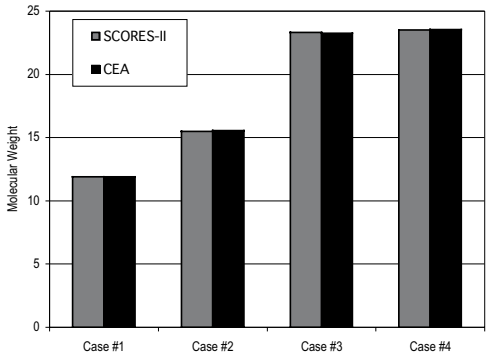

Figure 4. Equilibrium Molecular Weight Comparisons

The molecular weight comparisons for all cases are shown in Figure 4. Note again that excellent agreement is obtained between the codes. Any differences in values are in the second decimal place and are negligible. The maximum relative difference is 0.34%.

Table 3 contains the mole fractions for Cases 1 and 4 (Cases 2 and 3 have been left out for brevity). Note that only species values who were present in both codes are presented. For Case #1, no additional species were present. The following species were omitted for Case #4: NO_2, H_2O_2, HNO, COOH, HO_2, and NH. Because of this, the mole fractions from CEA presented in the table for Case #4 do not sum to unity. The maximum mole fraction from these trace species was 0.00006 for NH.

Table 3. Mole Fraction Comparisons for Cases 1 and 4

	Case #1		Case#4	
Species	SCORES-II	CEA	SCORES-II	CEA
H_2O	0.604105	0.60778	0.359114	0.37781
H_2	0.362325	0.36268	0.043985	0.03779
O_2	0.00027	0.00022	0.033739	0.03204
OH	0.014101	0.01196	0.053601	0.0442
O	0.000431	0.00033	0.010793	0.00819
H	0.018775	0.01703	0.015274	0.01169
CO_2	0	0	0.074983	0.08329
CO	0	0	0.070859	0.06457
CH_4	0	0	0	0
C	0	0	0	0
N	0	0	0.00001	0.00001
NO	0	0	0.018476	0.01478
N_2	0	0	0.319171	0.32555
Total	1.0	1.0	1.0	0.9992

Engine Performance

SCORES-II was executed with settings for a number of existing rocket engines. These engines considered and their design parameters are presented in Table 4. Note that the engines represent a wide variety of cycle types, thrust classes, propellant combinations, and operating conditions.

Table 4. Engine Verification Run Cases

	SSME	RS-27A	Aestus	RD-120	RL10 B-2
Cycle	SC	GG	PF	SC	EX
Fuel	LH2	RP-1	MMH	RP-1	LH2
Oxidizer	LOX	LOX	NTO	LOX	LOX
Pc, psia	3,280	702	145	2,360	640
o/f	6.034	2.24	2.05	2.6	5.85
Epsilon	77.5	12.0	83.0	106.0	285.0
Tvac, lbf	512K	244K	6,140	187K	24,750

Table 5 contains the vacuum specific impulse results from the SCORES-II analysis of these engines. Notable is that for all cases, the engine specific impulse difference is always less than 1 second, with 4 of the 5 cases providing nearly identical results. Although the comparative information is not available for the existing engines, Table 6 contains some additional output parameters from the analysis. It should be pointed out that for all cases ran, SCORES-II's 'expert efficiency' routine was employed.

Table 5. Verification Case Results

Units:seconds	SSME	RS-27A	Aestus	RD-120	RL10 B-2
Actual Isp,vac	454.4	301.7	324	350	464
SCORES-II Isp,vac	454.38	301.64	324.01	350.88	463.84
Difference	0.02	0.06	0.01	0.88	0.16

Table 6. Additional Computed Engine Parameters

	SSME	RS-27A	Aestus	RD-120	RL10 B-2
mdot, lbm/s	1,127	809.23	18.95	532.95	53.36
Exit Area, ft^2	43.89	17.68	12.06	30.77	39.01
Throat Area, ft^2	0.566	1.474	0.145	0.290	0.137

Throttled Engine

While a comparative case is not available, a demonstration of SCORES-II's throttled engine analysis was conducted for a notional engine design. For this analysis, a LOX/LH2 staged-combustion cycle engine (100% throttle) was sized to provide 500Klbf of thrust at vacuum conditions. The Pc was set to 3,500 psia and the o/f was set to 6.5. The nozzle area ratio was selected to be 50, which yielded a A_t of 0.524 ft^2. The total mass flowrate for the engine at 100% throttle was determined to be 1125.4 lbm/s. This engine was then examined at throttle settings of 110%, 70%, and 30%. Table 7 summarizes the results of this analysis. Of interest is the fact that the engine Isp is not constant and varies by up to 1.75 seconds between the minimum and maximum throttle settings. The effect is due to the variation in T_{ad}, s, and $\dot{m}$ caused by the changes in Pc. Also note that while the throttle setting is assumed to be a percentage of the mass flowrate for the reference engine, the resultant

engine thrust and chamber pressure values track almost exactly with the throttle setting.

Table 7. Throttled Engine Results

	30%	70%	110%
Tvac, lbf	149,441	349,654	550,130
Isp,vac, sec	442.65	443.9	444.4
Pc, psia	1034.7	2438.6	3852.1

USER INTERFACE MODES

SCORES-II offers two different ways for the user to interact and execute the code, they are: a text-based mode and through the ModelCenter© environment.

The text-based mode offers user's direct access and manipulation of the SCORES-II input file. The program is executed via a UNIX command line or as a console application on a PC. Results are generated and stored in text files that can be easily accessed and read by the user.

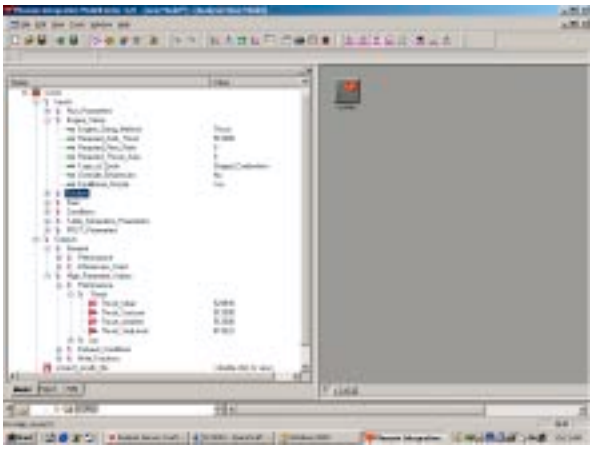

Figure 6. SCORES-II in ModelCenter© Environment

Using Phoenix Integration's ModelCenter© and AnalysisServer© environment, SCORES-II has been 'wrapped' to be easily included in any propulsion or vehicle simulation. This wrapper allows fast 'in-the-loop' analysis and easy updates to a vehicle's rocket propulsion system(s). This is especially useful for performing parametric and multi-disciplinary optimization studies. The filewrapper contains descriptions for each input parameter to SCORES-II as well as upper and lower bounds for most parameters. Propellant types, nozzle analysis options, and efficiency options are implemented as pull-down boxes. Figure 6 provides a snapshot of SCORES-II in ModelCenter. An additional feature of this interface (not unique to the SCORES-II file wrap) is that the tool can be hosted from a single machine running AnalysisServer. This allows for an unlimited number of users to access the code without the need to distribute the source/executable and eliminates the need for local host compilation/installation.

CONCLUSIONS

A tool suitable for use in conceptual design studies for the prediction of liquid rocket engine performance has been established. This tool features a number of engine sizing options (e.g. thrust, throat area) and thus it can be utilized in a number of different scenarios. The 'expert system' efficiency routine accounts for a number of performance loss mechanisms, based on results from existing engines.

The 14-species chemical equilibrium routine was shown to perform very well when compared with the industry-standard Chemical Equilibrium and Applications (CEA) code. In addition to excellent agreement between species mole fractions, the adiabatic flame temperature and mixture molecular weight also compared very well with CEA's results.

SCORES-II successfully predicted the vacuum specific impulse for a number of existing, modern engines. The engines varied in cycle, propellant combination, expansion ratio, and operating mixture ratio. Typical relative errors between SCORES-II and the real engine specifications were generally much less than 1 second of Isp. Results from a throttled engine analysis case were presented and the throttle setting was shown to produce Isp differences of almost 2 seconds.

FUTURE WORK

A roadmap for the future development of the SCORES tool has already been established. Among the planned improvements are:

1) A preliminary power balance model will be implemented. Analysis of the turbopumps, turbine(s), and preburner(s)/gas generator components will be performed. The user will be able to select from a number of different engine cycles. In addition to providing additional details of the engine design, it is planned that the impact of open cycles (GG, TO) on the specific impulse will be better accounted for with the possible elimination of the current cycle efficiency parameter.

2) The engine weight is a difficult but very important parameter necessary for accurately performing trades on the engine design. Using a combination of physics-based methods and empirical data, the weight of the major engine components can be determined. This analysis requires many of the more detailed engine results that will be obtained from the new power balance capability.

3) Using the weight and power balance results, it is then possible to perform a cost analysis for the engine. A number of development and manufacturing cost models already exist and incorporating these into SCORES should be a relatively easy task.

The future development plans for SCORES-II are currently being implemented and have been 'proof of concept' tested as an Excel spreadsheet in another SEI developed tool called Liquid Rocket Engine (LRE) Designer.

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