

SCORES-II Design Tool for Liquid Rocket Engine Analysis
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Tool Description

- ▶ SCORES-II is a liquid rocket engine performance prediction tool for use in the conceptual design process
- ▶ Developed by SpaceWorks Engineering, Inc.
- ▶ Very fast execution times (on order of a few seconds)
- ▶ Minimal number of user inputs
- ▶ Provides high degree of accuracy
- ▶ Written in object-oriented C++ language
- ▶ Executes on Unix, PC, and Mac OS X platforms



- ▶ **Original version of tool, SCORES, developed by Dr. David Way at Georgia Tech (1998)**
- ▶ **Highlights**
 - Written in C++
 - Had web-based use interface
 - Very fast execution speeds
 - Computed preliminary engine T/W based on a power-to-weight ratio parameter
- ▶ **Drawbacks**
 - Chemical equilibrium model lacked necessary methods for accurate performance predictions
 - ▶ No method for solving the entropy problem, $T=f(s,P)$
 - Used CPG derivations for performance predictions
 - Nozzle flow was always frozen at chamber composition
 - Efficiency factors still failed to obtain desired accuracy, when compared to existing engines
 - Only available on Unix platform





SCORES-II Tool Capabilities



Propellant Combinations

- ▶ SCORES-II supports a number of common rocket propellant combinations

Fuel Options

Built-in

- ▶ Types:
 - Hydrogen (H_2)
 - Hydrogen-Peroxide (H_2O_2)
 - Kerosene/RP-1 ($C_{11}H_{1.9423}$)
 - Methane (CH_4)
 - Propane (C_3H_8)
 - MMH ($C_1H_6N_2$)
 - UDMH ($C_2H_8N_2$)
- ▶ User specifies temperature

Generic

- ▶ Types:
 - $C_xH_yN_z$
 - User specifies x, y, and z
- ▶ User specifies initial enthalpy

Oxidizer Options

Built-in

- ▶ Types:
 - Oxygen (O_2)
 - Hydrogen-Peroxide (H_2O_2)
 - Nitrogen Tetra-Oxide (N_2O_4)
- ▶ User specifies temperature

Generic

- ▶ Types:
 - $N_xO_yH_z$
 - User specifies x, y and z
- ▶ User specifies initial enthalpy



- ▶ **SCORES-II capable of 3 different engine design options**
 - 1) Match a specified total mass flowrate
 - 2) Required thrust at select ambient condition
 - 3) Match throat area

- **Throttled engine analysis can also be performed**
 - ▶ **User specifies minimum, maximum and number of throttle settings**
i.e. 30%, 110%, and 5 steps would generate analysis at: 30%, 50%, 70%, 90%, and 110%
 - ▶ **Throttle is defined as percentage of reference engine mass flowrate**
 - ▶ **Engine P_c is then varied to match throat area from reference engine**



SCORES-II Engine Efficiencies

- ▶ Overall engine efficiency (η_{overall}) is composed of 4 component efficiencies:

- 1) Cycle - open vs. closed cycle losses
- 2) Combustor - chamber and injector losses
- 3) Reaction - non-equilibrium effects
- 4) Nozzle - divergence and friction losses

$$\eta_{\text{overall}} = \eta_{\text{cycle}} * \eta_{\text{combustor}} * \eta_{\text{reaction}} * \eta_{\text{nozzle}}$$

- ▶ Two options for using efficiencies

- 1) User sets specific values for 4 components ('override' mode)
- 2) User can employ the 'expert system' efficiency routine

- ▶ Based on an analysis of 20+ modern engines with varying thrust classes, cycles and operating conditions
- ▶ All efficiencies are either constants or linear functions based on engine design values
i.e. η_{cycle} is 1.0 for staged-combustion engines, η_{nozzle} is function of area ratio

- ▶ Overall efficiency factor is then applied to ideal, vacuum Isp value

$$\text{actual } I_{sp_{\text{vac}}} = \eta_{\text{overall}} * \text{ideal } I_{sp_{\text{vac}}}$$

$$\begin{aligned} \text{Thrust}_{\text{vac}} &= I_{sp_{\text{vac}}} * \text{mdot} \\ \text{Thrust}_{\text{sls}} &= \text{Thrust}_{\text{vac}} - P_a * A_e \\ I_{sp_{\text{sls}}} &= \text{Thrust}_{\text{sls}} / \text{mdot} \end{aligned}$$



- ▶ **Frozen or equilibrium nozzle analysis**
- ▶ **User can specify number of output parameters significant digits**
- **Automatic generation of POST trajectory code performance deck**
 - **File format is either single entry values for non-throttled cases or 1-D table for for throttled engine cases**
 - **Include thrust, Isp, and exit area**
 - **User can specify POST specific multipliers like throttle parameter and engine ID number**





Analysis Methods



- ▶ Utilizes minimization of Gibbs free energy method
 - ▶ Based on work by Gordon and McBride
 - ▶ Reduced set of equations assuming only gaseous products
 - ▶ Uses Newton-Raphson technique with LU-decomp for solving series of simultaneous, non-linear equations
 - ▶ Can solve (T,p) and (s,P) problems
 - ▶ Can currently handle 5 different atoms: C, H, N, O, and Ar with 14 different species considered

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

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

For specified T and P

- ▶ Chemical properties database features:
 - ▶ H₂, O₂, N₂, H₂O, CO₂, CO, H, OH, O, NO, N, C, CH₄, Ar
 - ▶ Cp, hs, and s values curve-fit as exponentials, high-order polynomials, or linear models
 - ▶ Formation enthalpy and latent heat of vaporization also included





Equilibrium Model Verification



Equilibrium Test Cases

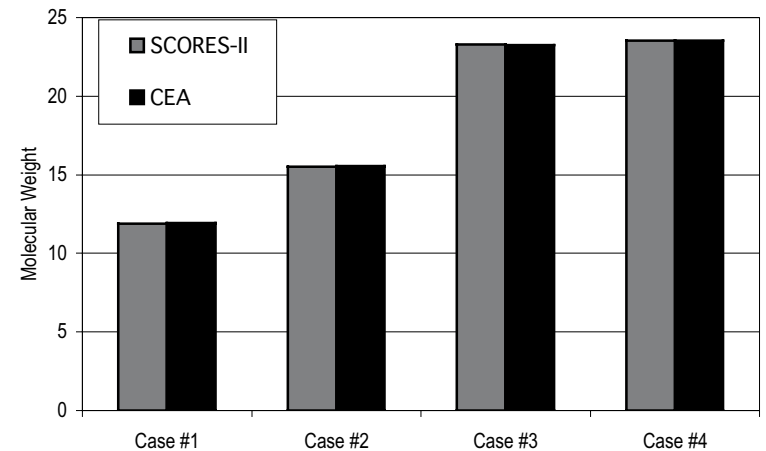
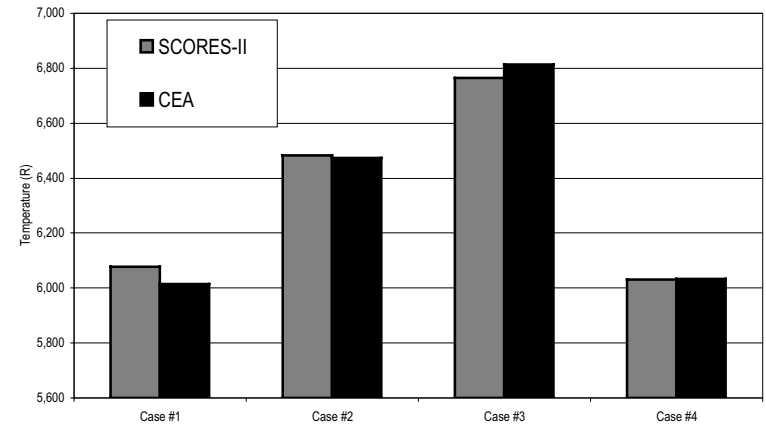
- ▶ SCORES-II EQ model compared with results from CEA – Chemical Equilibrium and Applications
- ▶ Variety of propellant combinations, o/f ratios, and Pc's examined
- ▶ 4 case results to be presented

Parameter	Case #1	Case #2	Case #3	Case #4
o/f	5.0	7.5	2.5	2.5
Pc (psia)	3,000	1,000	2,000	500
Fuel	LH2	LH2	RP-1	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



Equilibrium Verification – Temperature and *MW*

- ▶ Overall, excellent agreement is obtained for both equilibrium temperature and *MW*
- ▶ Maximum temperature difference of 61° R occurs for Case #1
- ▶ No notable differences appear in mixture *MW*
 - 0.34% maximum error
- ▶ Differences can most likely be attributed to:
 - Trace elements occurring in CEA, not present in SCORES-II database
 - Any differences in chemical property databases (e.g. initial mixture enthalpy)



Equilibrium Verification – Mole Fractions

- Species mole fractions also showed good agreement for all cases
- For Cases 2-4, some trace species appeared in CEA equilibrium solution. These species were not in the SCORES-II chemical properties database and thus were not considered
 - H_2O_2 , HO_2 , HCOOH , HCO , COOH , HNO , NO_2 , and NH

	Case #1		Case #4	
	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





Real Engine Performance Comparisons



Real Engine Comparisons

- ▶ **SCORES-II performance model compared with results from a number of existing engines**
- ▶ **'Expert System' efficiency routine was employed**
- ▶ **Utilized 'required thrust' sizing option with Pa=0 (vacuum conditions)**
- ▶ **Results from 5 different engine designs will be presented**

	SSME	RS-27A	Aestus	RD-120	RL10B-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



Real Engine Comparison Results

- ▶ Vacuum Isp predictions from SCORES-II compared with known values from selected engine cases
- ▶ Maximum difference observed was <1 second
- ▶ Additional parameters from SCORES-II also provided for reference

Performance Predictions

Units: seconds	SSME	RS-27A	Aestus	RD-120	RL10B-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

Engine Sizing Results

mdot, lbm/s	1,127.5	809.23	18.95	532.95	53.359
Exit Area, ft ²	43.89	17.68	12.06	30.77	39.006
Throat Area, ft ²	0.566	1.474	0.145	0.290	0.137



Throttle Engine Example

- ▶ Performed throttled engine analysis for notional staged-combustion engine
- ▶ Results indicate thrust, mass flowrate, and Pc track almost exactly with throttle %
- ▶ Isp decreases by almost 2 seconds from high to low throttle settings
 - Result of Pc impact on chamber temperature, entropy, and *MCU*

Reference Engine Specifications

Cycle	SC
Fuel	LH2
Oxidizer	LOX
Pc, psia	3,500
<i>o/f</i>	6.5
Epsilon	50
Tvac, lbf	500K

Performance Predictions

	30%	70%	110%
T_{vac} , lbf	149,441	349,654	550,130
Isp _{vac} , seconds	442.65	443.9	444.4
Pc, psia	1034.7	2438.6	3852.1

Throat Area: 0.524 ft²

Exit Area: 26.2 ft²

100% throttle mdot: 1,125.4 lbf/s





User-Interface Methods



- ▶ **SCORES-II primarily supports 2 different user-interfaces**

- ▶ **Text-Based**

- ▶ **Unix Command line or as a PC console application**
- ▶ **User manually edits formatted text input file, executes tool, then parses output**

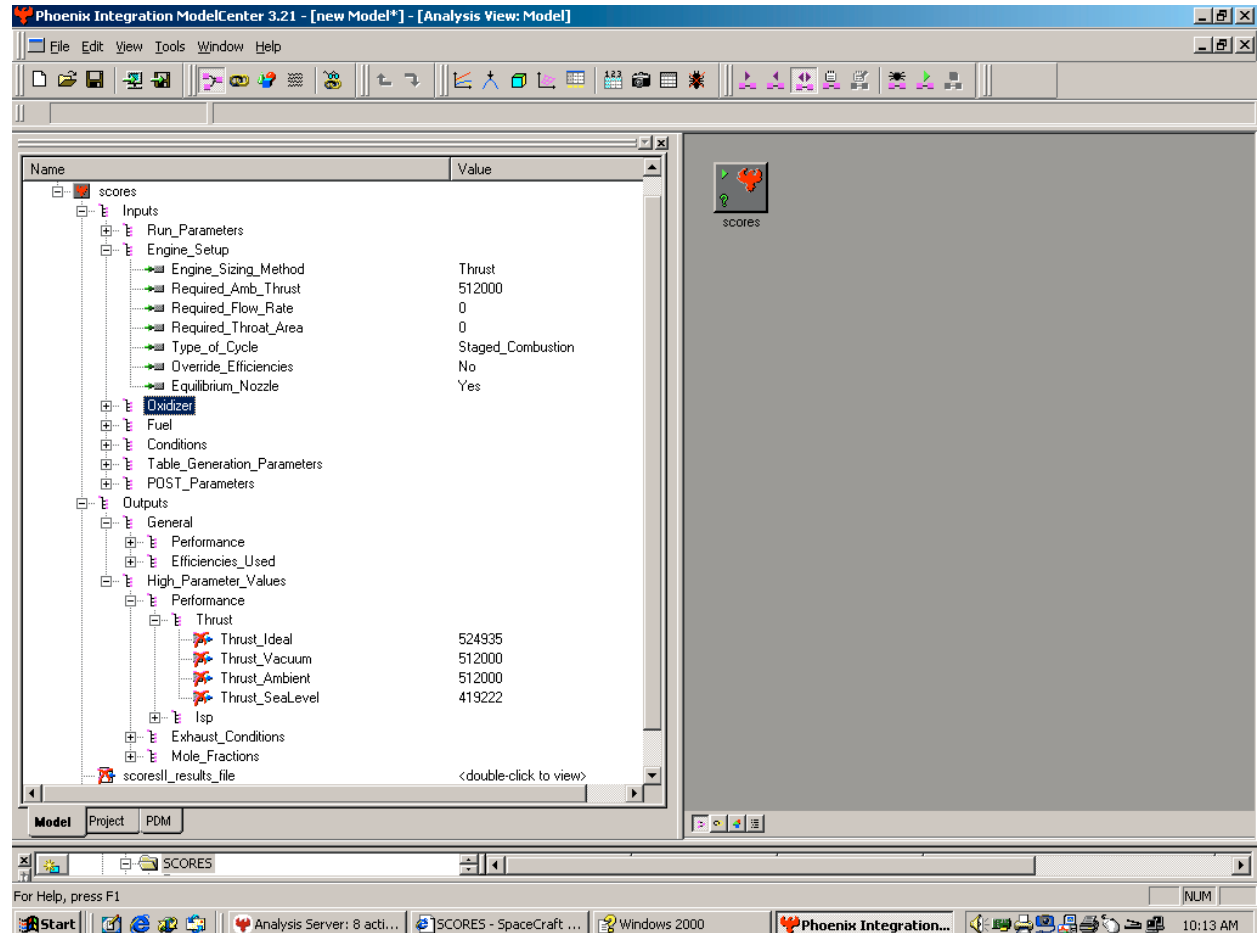
SCORES-II Sample Input File (partial)

Match	THRUST
Thrust_Required(lbf)	500000.0
MP_Required_100%(lbf/s)	0.0
Throat_Area_Required(ft2)	0.0
Oxidizer_Type	O2
O_Oxid_x	0.0
H_Oxid_y	0.0
N_Oxid_z	0.0
Oxidizer_Temperature(R)	163.0
Oxidizer_Enthalpy(BTU/lbm)	0.0
Fuel_Type	H2
C_Fuel_x	0.0
H_Fuel_y	0.0
N_Fuel_z	0.0
Fuel_Temperature(R)	39.0
Fuel_Enthalpy(BTU/lbm)	0.0
Equilibrium_Nozzle	YES
Expansion_Ratio	50.0
Mixture_Ratio	6.5
Chamber_Pressure(psi)	3000.0
Ambient_Pressure(psi)	0.0



Interface Options (2)

- ▶ **Filewrapped version of SCORES-II in Analysis Server© with access through ModelCenter©**
 - ▶ Supports automated execution of SCORES-II and easy integration with other tools
 - ▶ Filewrapper can drive either PC, Mac, or Unix version
 - ▶ Filewrap provides error/range checking on user variables, as well as provide quick references in variable description tags
 - ▶ Wrap features pull-down boxes and direct access to all input and output files





Conclusions



Conclusions and Summary

- ▶ A liquid rocket engine performance prediction tool written in C++ has been created
- ▶ SCORES-II offers a number of engine design options:
 - Supports number of fuel/ox combinations (built-in) or user can specify own as $C_xH_yN_z$ and $H_xO_yN_z$
 - Can size engine for required thrust, throat area, or mass flowrate specification
 - Any number of throttle settings can be analyzed
- ▶ Equilibrium model compared very well with results from CEA for variety of propellants and conditions
- ▶ 'Expert efficiency' routine provides very accurate performance predictions in comparison with existing engines
- ▶ Automatic POST deck generation allows for easy integration with trajectory tools
- ▶ ModelCenter® filewrapper allows for automated execution and integration into design environment

SCORES-II is commercially available from SpaceWorks Engineering

- Full package includes source code, documentation, PC and Unix executables, and MC filewrapper



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