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REDTOP-2: Rocket Engine Design Tool Featuring Engine Performance, Weight, Cost, and Reliability

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The Rocket Engine Design Tool for Optimal Performance-2 (REDTOP-2) is a newly created engineering design tool for use in the conceptual and preliminary design of space transportation systems utilizing liquid propulsion rocket engines. REDTOP-2, one of many unique engineering tools commercially available from SpaceWorks Engineering, Inc. (SEI), represents a novel entry into the current suite of propulsion modeling tools. REDTOP-2 is capable of analyzing the flowpath characteristics of numerous engine configurations to perform a power balance of the turbomachinery hardware (pumps and turbines) to achieve a user specified main chamber combustion pressure. The engine performance, in terms of thrust and specific impulse (Isp), is then determined based on the results of this power balance and the flow conditions (pressure, temperature, flowrate, etc.) in the chamber(s) and nozzle(s). Engine weight is assessed at the main component level using a combination of empirical and physics based analysis methods to provide vacuum, ambient, and sea-level thrust-to-weight (T/W) values. A cost model capable of predicting engine development, first unit, and production costs has been incorporated. Additionally, REDTOP-2 features a top-down modeling approach for computing engine safety and reliability metrics. REDTOP-2 is written in the modern, object-oriented C++ programming language and will execute on PC, Mac, and SGI platforms. Execution times are on the order of 30 seconds to 5 minutes, depending on the computing platform, engine configuration and design option selected by the user. User interface options currently include a command-line execution with ASCII file manipulation, filewrappers for use in Phoenix Integration's ModelCenter© environment, and a PC-based graphical user interface (GUI). This paper will describe the REDTOP-2 tool and its capabilities. Sample results obtained from exercising the tool for a number of different existing engine designs will be presented. Results from a multi-variable sensitivity study on a LOX/LH2 fuel-rich, single preburner staged-combustion engine will be highlighted. Two sample applications involving vehicle designs will be discussed. The first involves probabilistic/uncertainty analysis for an all-rocket vehicle design and the second the rocket main propulsion system analysis of an airbreathing, two-stage RLV concept with first stage tail-rockets and all-rocket second stage propulsion. Finally, future directions in the development of REDTOP-2 will be discussed.

Nomenclature

A_t	=	throat area, ft^2
A_e	=	exit area, ft^2
ARWB	=	all-rocket winged body
EX	=	expander cycle
GG	=	gas-generator cycle
Isp	=	specific impulse, seconds
LOX	=	liquid oxygen

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LH2	=	liquid hydrogen
Pa	=	ambient pressure, psia
Pc	=	chamber pressure, psia
SC	=	staged-combustion cycle
splitEX	=	split-expander cycle
T	=	thrust, lbf
TO	=	tap-off
o/f	=	mixture ratio, oxidizer-to-fuel by weight

I. REDTOP-2 Background

The Rocket Engine Design Tool for Optimal Performance-2 (REDTOP-2) is a newly created engineering design tool for use in the conceptual and preliminary design of space transportation systems utilizing liquid propulsion rocket engines. REDTOP-2, one of many unique engineering tools created by SpaceWorks Engineering, Inc. (SEI), represents a novel entry into the current suite of propulsion modeling tools. The code, a commercial product from SEI, offers a fast, end-to-end engine assessment capability at a fidelity level not typically exercised in early design phases.

REDTOP-2 represents an evolution of prior propulsion tools created by SEI. The performance analysis portion of REDTOP-2 has heritage with SEI's commercially available REDTOP code. This tool, which is capable of predicting the thrust, Isp, and nozzle geometry for liquid rocket engines, was intended primarily for early estimates and conceptual design studies. This tool is limited in that is does not detail the engine flowpath, size components, nor provide an engine T/W estimate.

An initial investigation by SEI into the feasibility of developing a tool for the initial sizing and power balance of an engine's primary components resulted in a spreadsheet based design tool called Liquid Rocket Engine Designer (LREDesigner). This tool, implemented in Excel, featured VB macros that would 'balance' the engine by varying turbine pressure ratios, preburner/gas-generator flowrates, and pump discharge pressures to achieve the desired chamber pressure. A weight model was developed for estimating the turbomachinery, nozzle, and main chamber component masses. This spreadsheet tool was provided to NASA-MSFC's engine system's group in 2002 and has subsequently been incorporated and expanded upon. Additionally, this tool has been utilized in NASA's Advanced Engineering Environment (AEE) Program to support a number of vehicle studies under the SLI/NGLT RLV program.

REDTOP-2 extends the capabilities demonstrated in these earlier tools by combining their functionality into a single, integrated tool operating at a significantly higher fidelity level. This tool eliminates inconsistencies in performance predictions caused by the use of the disparate tools. Furthermore, the overall capabilities in this area have been extended through implementing additional engine cycle options/configurations (e.g. series vs parallel flow, single vs dual preburner, etc.), finer component level modeling (secondary valves, injectors, etc.), and an expanded engine weight breakout structure.

II. Modeling Capabilities

REDTOP-2 analyzes the flowpath characteristics to perform a power balance of the turbomachinery hardware (pumps and turbines) to achieve the specified chamber pressure, for a user selected engine cycle, configuration and propellant combination. The engine performance, in terms of thrust and specific impulse (Isp), is then assessed based on the results of this power balance. Engine weight is assessed at the primary component level using a combination of empirical and physics based analysis methods to provide vacuum, ambient, and sea-level thrust-to-weight (T/W) values. A number of cost models exist for predicting engine development, first unit, and production costs. Additionally, REDTOP-2 features a top-down modeling approach for computing engine safety and reliability metrics.

REDTOP-2 is written in the modern, object-oriented C++ programming language and will execute on PC (Windows 2000/NT/XP), Mac OS X, and SGI platforms. Execution times are on the order of 30 seconds to 5 minutes, depending on the computing platform, engine configuration and design option selected by the user. User interface options currently include a command-line execution with ASCII file manipulation, filewrappers for use in Phoenix Integration's ModelCenter© environment, and a PC-based graphical user interface (GUI).

For engine sizing and design, the user has three options. The first of these is to specify the actual mass flowrate provided from the propellant tanks. 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, REDTOP-2 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 psi 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, REDTOP-2 will determine the corresponding mass flowrate that yields the desired throat area. Both the flowrate and thrust are output values in this case.

A. Cycle Models

REDTOP-2 features a number of predefined engine cycles from which the user can select from. These cycles include: staged-combustion (SC), expander (EX), split expander (splitEX), gas-generator (GG), and tap-off (TO). Each of these cycles are implemented with various configuration arrangements and flowpath routing options. In some cases of identical cycle and flowpath descriptions, the engine arrangement is also given a flowpath design number. Table 1 illustrates the various engine cycles and configuration options. The addition of new engine cycles, configurations, and components is a relatively easy process that is enabled through the use of object-oriented coding.

The SC cycles feature dual and single preburner configurations, as well as a catalyst pack option, with either parallel or series turbine flows (when applicable). Additionally, the SC cycles contain a number of flowpath options that include different methods for powering the low-pressure pump's turbines (e.g. chamber coolant gases, high-pressure pump discharge flow, etc.). The user may elect not to have low-pressure pumps, depending upon propellant properties and tank supply pressures.

Both the EX and splitEX cycles feature series or parallel turbine flow options. The GG cycle currently features only a single burner configuration and along with the TO cycle, either series or parallel turbine flow options. All cycles with preburners or gas-generators can support fuel and oxidizer rich chamber conditions. All configurations can support a regenerative nozzle and analysis of the associated fuel cooling flow. Additionally, a film-cooling option is provided for most configurations.

For open engine cycles (TO and GG), REDTOP-2 will determine the required turbine gas flowrate, subject to a maximum turbine pressure ratio. Propellant flows that are not passed through the main chamber are presumed dumped overboard via a secondary nozzle(s). The thrust contribution of this nozzle is also assessed by REDTOP-2. For closed engine cycles (SC, EX, and splitEX), the turbine drive gas flowrate is dictated by the specific flowpath selected and the preburner(s) mixture ratio (if present). All cycles feature fuel and oxidizer tank repressurization lines. The user is simply required to specify the fraction of the flow being circulated back to the tanks.

Table 1. REDTOP-2 Engine Cycle and Configuration Options.

Parameter	User Options
Cycle Type	SC, GG, TO, EX, or splitEX
Configuration	Dual Preburner, Single Preburner/GG, Catalyst Pack, or None
Turbine Flow Sequence	Series, Parallel, Separate
Flowpath Design #	1, 2, or 3

B. Input Parameters

Model specification parameters have been designed to support rapid engine scaling, resizing, and parametric studies. Almost all input parameters are specified in terms of a fraction, ratio, or efficiency percentage. Any dimensional parameters are specified with English Engineering (EE) units. In addition to the cycle and configuration selection, typical top-level inputs common to almost all cycles include:

1) Required Thrust, Mass Flowrate, or Throat Area
2) Chamber and Preburner/Gas-Generator Mixture Ratio(s)
3) Desired Chamber Pressure
4) Turbomachinery (pump and turbine) Efficiencies
5) Valve, Injector, and Heat Exchanger Pressure Drops
6) Regenerative, Radiative, and Ablative Nozzle Area Ratios
7) Chamber/Throat and Nozzle Heat Fluxes
8) Nozzle shape, half-angle, equilibrium flow fraction, and length fraction (% of conical nozzle)

Numerous second-order parameters exist which vary by engine type. These include input parameters specific to each component of the cycle such as average material densities and yield strength, burst pressures, safety factors, and unit weights.

C. Component Models

The REDTOP-2 code is comprised of a number of fundamental component or part models that are utilized to construct a specific cycle configuration model. In general, each component features a standardized input and output interface with a flow composition object that varies dynamically based on the fluid property database contents. Each component analysis consists of a performance/flow modeling segment, followed by a weight analysis. The specific components available for constructing an engine include: Chamber, Pump, Turbine, Valve, Flow Splitter, Flow Divider, Injector, Heat Exchanger, and Nozzle. These model components have the following characteristics:

1) The "Chamber" component is used for the main chamber, preburner, or gas-generator analysis and can support multiple inflow streams. The chamber model extends from the injector face to the throat and performs an equilibrium flow calculation with heat loss, in the case of regenerative cooling, at these two locations. The chamber geometry is determined based on a characteristic length, set by the user, and the calculated flow Mach number. These parameters allow for computation of the chamber aspect ratio, diameter at injection plane, volume, and surface area. With a known geometry, the chamber weight can be assessed, based on user specified material properties, safety factors, burst pressure, etc.
2) The "Pump" and "Turbine" components are used for any boost, low pressure, high pressure, or split pump turbomachinery analysis. The user specifies the pump and turbine efficiencies and can modify the default database parameter values of pump operating parameters (propellant vapor pressure, head coefficient, suction specific speed, etc.) that vary with the propellant type. Shaft speeds, which can be limited by the user, are computed by the pump and based on cavitation and/or stage-specific speed limitations. Based on the maximum stage pressure rise, an estimate for the number of stages in the pump is calculated. A few pump geometric parameters in the form of impeller exit and inlet diameter are also calculated. The turbine model obtains shaft speed and horsepower requirements from its associated pump. The part can then either be analyzed with a specified pressure ratio and variable propellant flowrate or fixed flowrate and variable pressure ratio.
3) The "Valve" component is used for any main, secondary, inlet, bypass, or control valve modeling. The user is required to specify the pressure drop through the valve for determining the exit flow conditions. Valve weight is based on the flow pressure and diameter at the maximum flowrate condition. The "Flow Splitter" and "Flow Divider" components are used to split and combine flows at various junctures in the engine. When splitting a flow, the user must specify the flow fractions to each path. For flow mergers, an effective outflow is computed based on an averaging of the inflow conditions. Example cases utilizing these components are coolant flow mergers (nozzle heat-exchanger outflow combining with CCV flows) and tank repressurization flow splits. For both components, up to five split or merge paths can be considered.
4) The "Injector" component is utilized for the main chamber flow injection and any preburner/gas-generator flow injection. The user must specify the pressure drop across the injector. The weight of this part is included in the 'Chamber' component, thus only a fluid flow analysis is performed.
5) The "Heat Exchanger" is typically used for regenerative cooling in the main chamber, throat, and nozzle sections. In this model, a total heat load is applied (added or subtracted) to the entering propellant flow. The total heat load is based on a calculated heat flux rate and transfer area. The heat flux rate is based on a user specified reference heat flux rate with an associated pressure. User control of a scaling parameter allows for correlation of the heat flux with actual test or other detailed analysis and adjustment of the heat flux value at different engine operating conditions. The heat transfer area is based on regenerative nozzle and chamber surface area calculations. While a detailed analysis of the flow through the heat exchanger channels or tubes is not currently performed, an equilibrium analysis is performed at the exit conditions to assess any disassociation of the propellant.
6) The "Nozzle" component is used for the main engine nozzle analysis and any 'secondary nozzles' for open-cycle configurations. The user specifies area ratio regions of the nozzle that are either regenerative, radiative, or ablatively cooled. The associated weight for these disparate regions is then computed based on the nozzle geometry. Both cone and bell shaped designs are supported. For bell shapes, a Rao-method contour analysis is performed. Both shape options allow for equilibrium and frozen flow calculations with a user defined equilibrium-to-frozen fraction used to account for finite rate chemical kinetics. In addition to the reaction losses, defined by the equilibrium-to-frozen flow fraction, the divergence angle of the nozzle is also utilized in correcting the performance predictions. A file containing a 2-D contour map of the nozzle geometry is also generated.

D. Fluid Properties and Equilibrium Chemistry

REDTOP-2 features a flexible fluid property database tied to a dynamic equilibrium chemistry model. Species can be added or removed from any REDTOP-2 analysis by simply altering the species database file list. Thermodynamic properties for any species considered in the system are stored in an ASCII text file containing density, entropy, and enthalpy values versus temperature and pressure. These tables are required to be uniform, but the user has control of the data resolution (pressure and temperature increments). Species properties in both liquid and gaseous forms are contained in the same table.

Execution time is increased due to the use of table lookups and interpolation instead of curve fits for property values. This method was implemented for improved accuracy and due to the ease in constructing tables versus trying to develop an acceptable polynomial function for each property.

The equilibrium chemistry model is based on the work done by Gordon and McBride[1]. 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 affect execution time). New species and atom types added to the species database are automatically included in the equilibrium solution. The default fluid properties database contains species data for: hydrogen (H2), oxygen (O2), water/steam (H2O), hydrogen-peroxide (H2O2), methane (CH4), propane (C3H8), hydroxyl (OH), monatomic oxygen (O), monatomic hydrogen (H), carbon dioxide (CO2), carbon monoxide (CO), nitrogen (N2), helium (He), ethane (C2H6), ethene (C2H4), and kerosene/RP-1 (represented as C12H24). The species properties have been compiled from a number of resources, including JANAF[2].

E. Additional Modeling Options

REDTOP-2 can also compute the performance of a throttled engine. The user is required to specify both the maximum throttle condition (e.g. 100%) and the actual operating throttle (e.g. 90%). The maximum throttle will size the engine flowpath geometry (valves, chamber throat, nozzle, etc.) and determine the total weight of the engine. Once the engine weight has been assessed, the throttled engine performance is evaluated. Additional features supported include:

1) Ability to model configurations with multiple chambers/nozzles (e.g. RD-170)
2) Controller weight estimation with desired redundancy level
3) Bypass of low pressure/boost pumps when appropriate for configuration and fluids
4) Impure propellants specified as weight fractions (e.g. 95% hydrogen-peroxide and 5% water)
5) Scale factor input parameter for ease in sizing from a reference engine design
6) Weight estimation for engine health monitoring (EHM), gimbals, and a nacelle

F. Cost Modeling

There are two cost models currently implemented in the REDTOP-2. For internal SEI studies, a NASA/Air Force Cost Model (NAFCOM) derived simulation has been linked to the core REDTOP-2 performance outputs. Additionally, SEI has developed its own rocket engine cost model, referred to as the Rocket Cost Model (RCM). This second model is included in commercial sales of the product.

Several high level inputs for REDTOP-2 generally apply to all of the cost models. These inputs include: inflation rate, fiscal year of outputs, production rate per year, production quantity, and program contingency, support, and profit factors. Nominally values for both the first unit cost and average cost (with learning/rate effects) are calculated.

The goal of the RCM is to provide a more detailed component level cost model that attempts to utilize the detailed weight breakdown provided by the performance algorithms within REDTOP-2. Additional enhancements are also provided in the SEI RCM to include user specified learning curves, inflation adjustment factors, cost skewing factors, systems integration costs, etc.

The cost algorithms in the RCM component of the REDTOP-2 model use historically-based relationships to determine development (Design, Development, Testing, and Evaluation-DDT&E) and engine acquisition costs (Theoretical First Unit-TFU and average production cost). Adjustment factors are incorporated to account for various technology levels. Specific regression equations are used to determine the level of testing and tooling required for an engine system based upon specific quantitative performance data such as engine thrust, weight, chamber pressure, etc.

Unique features implemented in REDTOP-2's RCM include:

1) Variety of options for learning and rate effect adjustments
2) Adjustment factors for both performance (weight, thrust level, etc.) and non-performance related engine characteristics (tooling level, prototype level, etc.)

3) Cost skewing factor for development cost
4) Addition of systems integration costs along with hardware based costs, including: integration, assembly and checkout (IACO), system test operations (STO), ground support equipment (GSE), systems engineering and integration (SE&I), and program management
5) Inflation adjustment factor based on the NASA New Start Inflation Index or the Consumer Price Index (CPI)

G. Reliability Analysis

REDTOP-2 uses a top-level safety and reliability model based upon general engine characteristics. Inputs to the model include: number of valves, number of combustion devices, number of turbopumps (low and high pressure), fuel and oxidizer turbine temperatures, throttle condition (operating pressure/design pressure), and whether the engine incorporates or has: health monitoring system (EHMS), self-limiting cycle, double containment for turbopumps, double-containment hot-gas system, oxygen rich combustion, inter-propellant seal package, nacelle, etc.

The inputs are used to calculate a number of different reliability metrics. The reliability chain proceeds with a metric for mission success being calculated. A "premature shutdown or failure" occurrence is the chance of an engine shutting down due to a sensor reading or outright failure. The quantity of one minus this value is the probability that the engine completes its mission. This value is subsequently reported as the reliability of the engine. Various other reliability chain events are calculated including: premature shutdown, control redlines, and true cut / false cut given the previous two conditions. The characteristics defined by the inputs (as described in the previous paragraph) are coupled multiplier factors to determine the safety metric. In this case the safety metric represents the amount of damage done to the system in the case of a failure.

Future versions of REDTOP-2 will incorporate a detailed engine reliability and safety analysis based on a bottom-up assessment of individual engine components and system layout redundancy.

H. User Interface Options

REDTOP-2 offers three options for the user to interact with and execute the code. These include a text based command line mode, running the code through Phoenix Integration's ModelCenter© environment or via a graphical user interface (GUI) for the PC.

1) Command Line: The ASCII file manipulation-based mode offers users direct access and manipulation of the REDTOP-2 input files. The program is executed via the command line on Unix-based systems (Max OS X or SGI) or as a DOS console application on a PC (Windows NT/2000/XP). Results are generated and stored in ASCII files that can be easily accessed and read by the user. Adjustment factors for both performance (weight, thrust level, etc.) and non-performance related engine characteristics (tooling level, prototype level, etc.)
2) ModelCenter: Using Phoenix Integration's ModelCenter© and Analysis Server© environment, REDTOP-2 has been 'wrapped' to be easily included in any propulsion or vehicle simulation. This wrapper allows fast 'in-the-loop' analysis and easy updates of the vehicle's rocket propulsion system(s). This is especially useful for performing parametric and multi-disciplinary optimization studies. Each engine cycle/configuration option also has a unique fileWrapper, which can be effortlessly imported into any ModelCenter© *.pxc model file. The fileWrapper's contains descriptions of each input parameter to REDTOP-2 for the particular cycle/configuration being examined. Some error checking is achieved with upper and lower bound limits imposed on variables. Engine cycles, configurations, propellant types, etc. are implemented as drop-down boxes. Usage of REDTOP-2 within ModelCenter© will be illustrated in the sample cases section of this paper.Addition of systems integration costs along with hardware based costs, including: integration, assembly and checkout (IACO), system test operations (STO), ground support equipment (GSE), systems engineering and integration (SE&I), and program management
3) PC GUI: The graphical user interface option, as shown in Fig. 1, is available on Windows XP/2000/NT based platforms. A GUI version that will operate under Mac OS X platforms is anticipated. The GUI consists of 7 primary sheets or tabs, each containing variables divided into the following categories: General Parameters, Oxidizer, Fuel, Cycle Specific, Cost, Reliability, and Preferences. The Cycle Specific and Cost tabs have multiple sub-tabs to further organize the variables into additional categories. The General Parameters tab features the engine cycle and configuration options as well as variables that are associated with every engine cycle, like the thrust-sizing, chamber pressure, mixture ratio, nozzle expansion ratio, throttle setting, and engine accessory options. Selection of a specific engine cycle and

configuration on this sheet will dynamically adjust the necessary input parameters on subsequent sheets in the GUI.

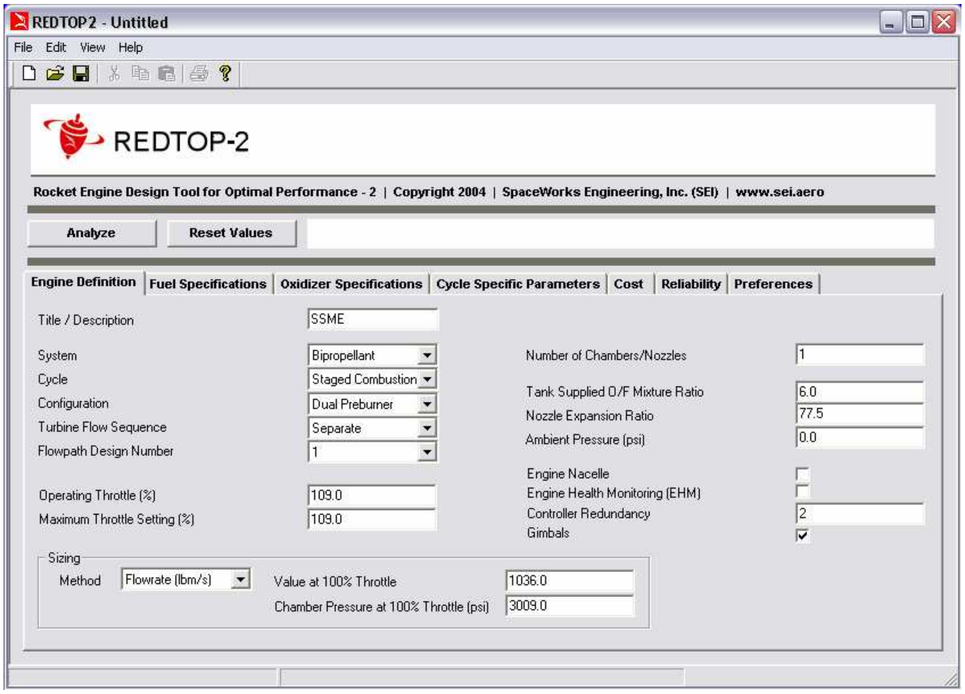

Figure 1. REDTOP-2 GUI-General Parameter Input Sheet.

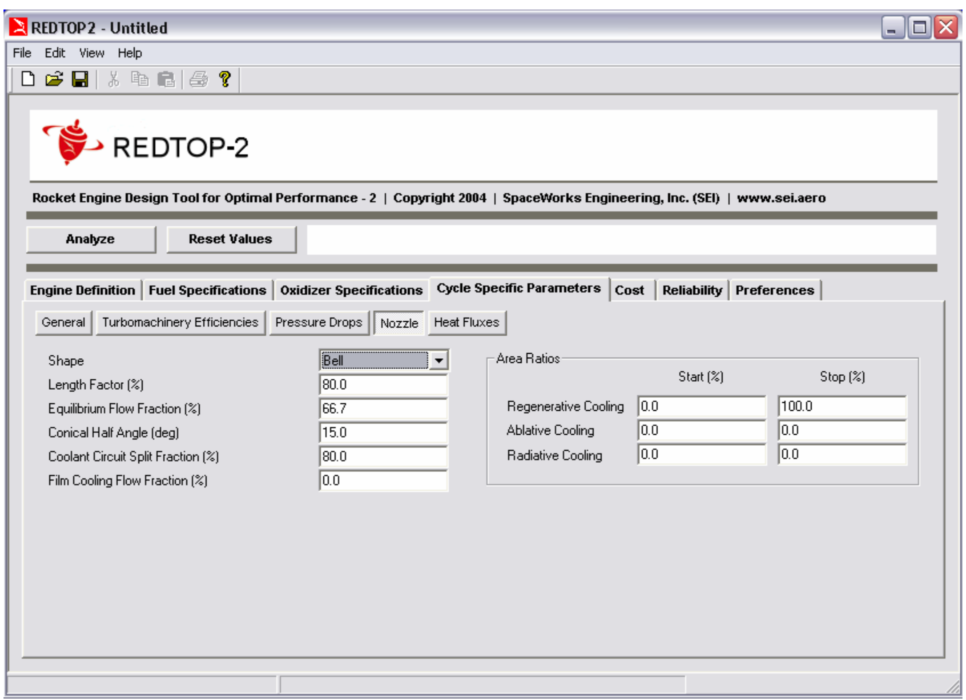

Figure 2. REDTOP-2 GUI-Cycle Specific Input Sheet.

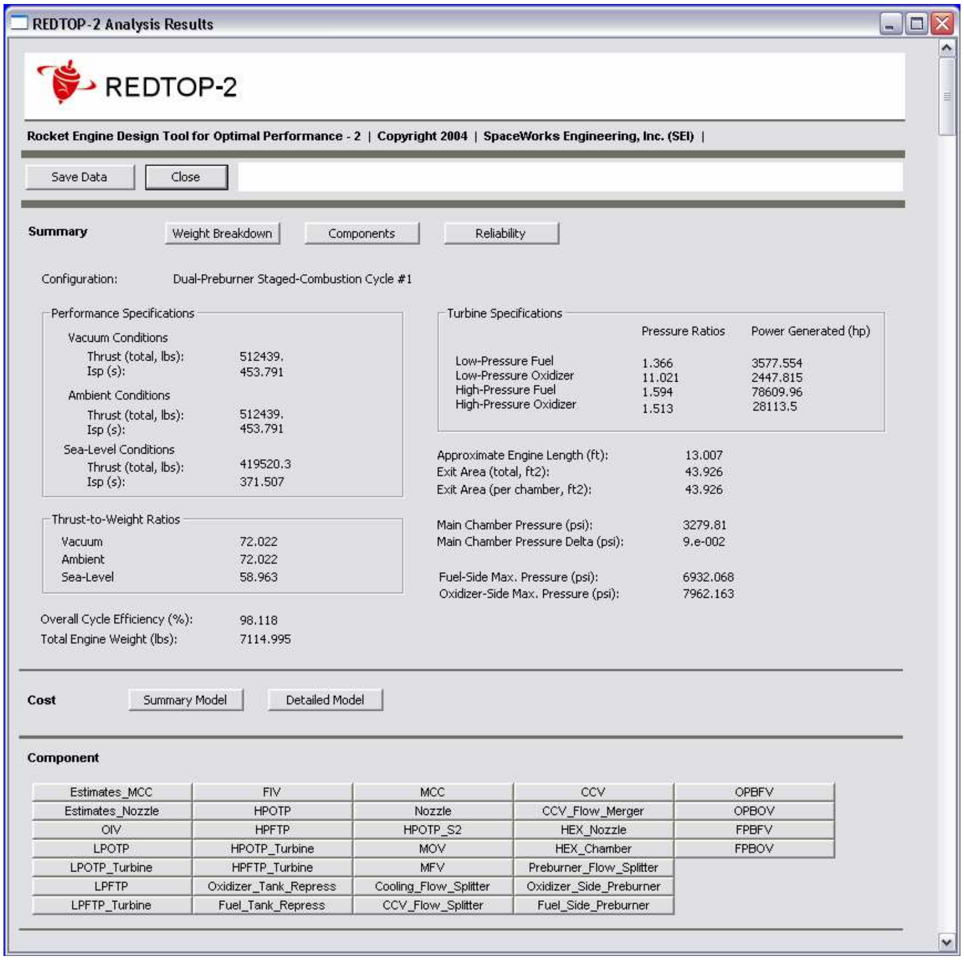

Figure 3. REDTOP-2 GUI-Results Dialog Window.

III. Test Cases

REDTOP-2 models have been constructed and executed for a number of actual liquid rocket engines. Engines to be presented here include the: Space Shuttle's SSME, the RL10A-3-3A, the J-2S, and the RS-68. Note that with the exception of the SSME, detailed engine specifications are not readily available from public sources. Additionally, there are differences in the flowpath design. For all cases, the flowpath configuration that best matches the known engine design is utilized.

A. Space Shuttle Main Engine (SSME)

The SSME, designed and constructed in the 1970s to power the Space Shuttle, is a dual-preburner fuel-rich staged-combustion (SC) cycle engine. It features a fully regenerative nozzle, a low-pressure fuel pump driven by chamber coolant gases, a high-pressure fuel, a split high pressure oxidizer pump, and a low-pressure oxidizer pump driven by the first split discharge flow from the high-pressure oxidizer pump.

A flowpath schematic of this engine is provided in Fig. 3[3]. Based on data obtained from this reference, the pump/turbine efficiencies, pressure drops through valves and injectors, and preburner mixture ratios were supplied to REDTOP-2. Table 2 summarizes the values for a number of key input parameters for the SSME.

After model setup, REDTOP-2 was executed for the SSME configuration. The sizing mode selected was to target a specified propellant flowrate of 1,129.68 lbm/s and a Pc 2,995 psi. at a 100% throttle setting. The maximum and operating throttle was then set at 109%. Execution time was approximately 25 seconds on a dual 1.8Ghz G5 PowerPC with 1.5GB of RAM. Table 3 summarizes the key output parameters from REDTOP-2 for this engine and compares them with the results obtained for similar input parameters values.

Excellent agreement is obtained in terms of the thrust and Isp achieved at vacuum conditions. Similar agreement is shown at sea-level operating conditions. Some of the discrepancies in the pump discharge pressure as well as turbine pressure ratios are likely attributable to differences in the fuel and oxidizer property data.

Unlike most other industry power balance codes, REDTOP-2 also predicts engine weight and geometry. For this analysis, the engine was identified to have gimbals, no nacelle or advanced EHM, and a double-redundant controller. A 100% regeneratively-cooled nozzle was specified. Table 4 provides a summary of the engine weight, T/W, and length predictions from REDTOP-2 versus the actual SSME specifications.

Table 2. Key SSME Input Parameters.

Parameter	Value
Propellants	LOX/LH2
Tank Supplied Mixture Ratio (MR)	6.0
Chamber Pressure at 100% (Pc)	2,995 psi
Fuel-Side Preburner Mixture Ratio	0.976
Ox-Side Preburner Mixture Ratio	0.68
HPOTP Eta	67 %
HPOTP-S2 Eta	80 %
HPFTP Eta	73 %
HPFTP Turbine Eta	78 %
HPOTP Turbine Eta	78 %
MOV delta-P	16.3 %
MFV delta-P	5 %
Nozzle Area Ratio (100% regen. cooled)	77.5 : 1

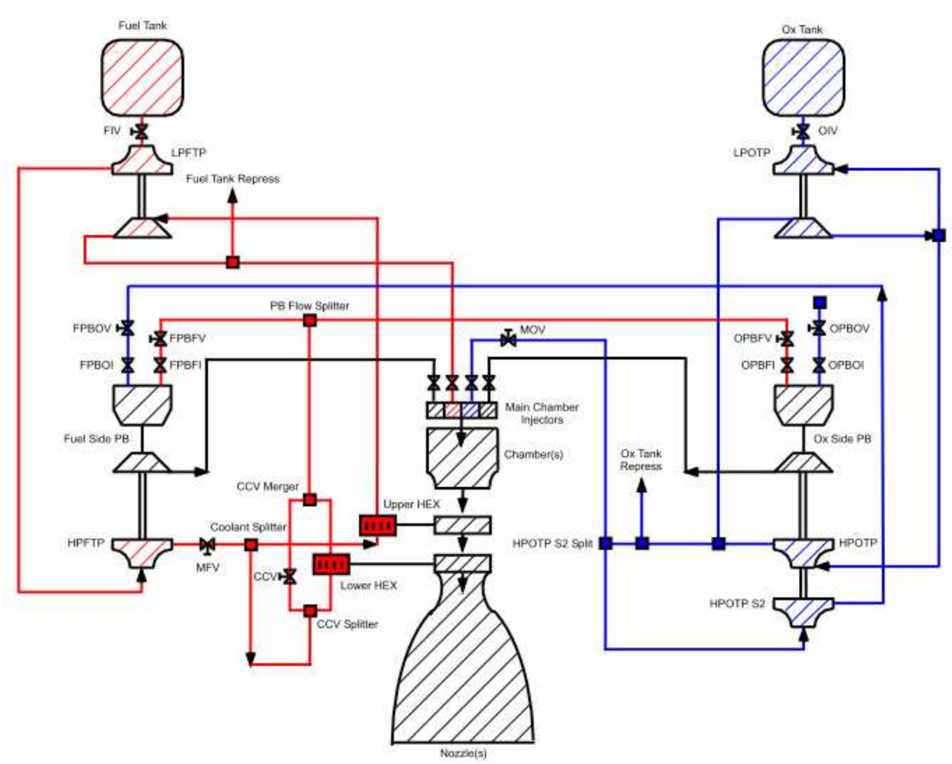

Figure 4. SSME Staged-Combustion Flowpath Schematic.

Table 3. Key SSME Output Parameters.

Parameter	REDTOP-2 Value	Ref. Value
Vacuum Thrust (lbs)	511,052	512,350
Vacuum Isp (s)	453.36	453.5
SLS Thrust (lbs)	417,944	419,404
SLS Isp (s)	370.76	371.9
Throat Area (ft^2)	0.5679	0.568
Nozzle Exit Area (ft^2)	44.01	44.02
HPFTP Turbine Pressure Ratio	1.602	1.577
HPOTP Turbine Pressure Ratio	1.516	1.54
HPFTP Pressure Out (psi)	6,940	7,054
HPOTP Pressure Out (psi)	4,681	4,790
HPOTP-S2 Pressure Out (psi)	7,970	8,101

Table 4. REDTOP-2 SSME Weight and Geometry Predictions.

Parameter	REDTOP-2 Value	Actual Value
Weight (lbs)	6,988	7,000
Vacuum T/W	73.13 : 1	73.05 : 1
SLS T/W	59.81 : 1	59.92 : 1
Overall Length (ft)	13.02	13.78

B. Centaur RL10A-3-3A

The RL10A-3-3A engine is built by Pratt and Whitney to power the Centaur upperstage on the Atlas and Titan launch vehicles. This very efficient, altitude engine is a LOX/LH2 expander cycle. As mentioned previously, a detailed flowpath description is not readily available for this engine. An assessment for a similar thrust-class engine was performed using REDTOP-2. This engine featured a dual-shaft/turbine configuration in series with no gearing required. Table 5 provides the engine specifications used to obtain the REDTOP-2 results.

The sizing mode selected was to target the specified vacuum thrust value of 16,500 lbs. at a 100% throttle setting. The maximum and operating throttle was then set at 100%. Execution time was approximately 15 seconds on a dual 1.8Ghz G5 PowerPC with 1.5GB of RAM. Table 6 summarizes the key output parameters from REDTOP-2 for this engine and compares them with performance values available publicly.

Table 5. RL10A-3-3A Engine Specifications.

Parameter	Value
Propellants	LOX/LH2
Vacuum Thrust (lbs)	16,500
Mixture Ratio	5.5
Chamber Pressure (psi)	475
Nozzle Area Ratio	61: 1

Table 6. RL10-3-3A Engine Results.

Parameter	REDTOP-2 Value	Ref. Value
Tank Supplied Flowrate (lbm/s)	37.2	37.1
Vacuum Isp (s)	443.85	444.4
Vacuum T/W	52.2 : 1	53 : 1
Weight (lbs)	316	310
Length (ft)	5.6	5.8

C. J-2S

The J-2S engine was built by Rocketdyne in 1970 to investigate a more reliable version of the J-2 that powered the upperstages of the Saturn V[4]. This novel engine is a LOX/LH2 tap-off cycle and has improved performance and a simpler flowpath compared with the J-2 gas-generator cycle. An assessment for a similar thrust-class engine was performed using REDTOP-2. A number of assumptions regarding the flowpath were required do to a lack of engine detail. Less aggressive material and technology factors were utilized in this arrangement. Table 7 provides the limited dataset used to obtain the REDTOP-2 results.

The sizing mode selected was to target the specified vacuum thrust value of 265,000 lbs. at a 100% throttle setting. The maximum and operating throttle was then set at 100%. Execution time was approximately 30 seconds on a dual 1.8Ghz G5 PowerPC with 1.5GB of RAM. Table 8 summarizes the key output parameters from REDTOP-2 for this engine and compares them with performance values available publicly.

Table 7. J-2S Engine Specifications.

Parameter	Value
Propellants	LOX/LH2
Vacuum Thrust (lbs)	265,000
Mixture Ratio	5.5
Chamber Pressure (psi)	1,200
Nozzle Area Ratio	40: 1

Table 8. J-2S Engine Results.

Parameter	REDTOP-2 Value	Ref. Value
Tank Supplied Flowrate (lbm/s)	607.6	607.8
Vacuum Isp (s)	436.1	436
Vacuum T/W	73.39 : 1	69.7 : 1
Weight (lbs)	3,610.5	3,800
Length (ft)	10.5	9.7

D. Delta-IV RS-68

The RS-68 engine is built by Rocketdyne and used on the Delta IV EELV[5]. This engine, capable of generating just over 750Klbs of vacuum thrust, is a LOX/LH2 gas-generator cycle with parallel flow turbines. The expendable engine also features a regeneratively cooled chamber and an ablative nozzle. An assessment for a similar thrust-class engine was performed using REDTOP-2. Table 9 provides the limited dataset used to obtain the REDTOP-2 results.

The sizing mode selected was to target the specified vacuum thrust value of 751,000 lbs. at a 100% throttle setting. The maximum and operating throttle was then set at 100%. Execution time was approximately 30 seconds on a dual 1.8Ghz G5 PowerPC with 1.5GB of RAM. Table 10 summarizes the key output parameters from REDTOP-2 for this engine and compares them with performance values available publicly.

REDTOP-2 appears to overpredict the Isp of the RS-68 by about 1.4 seconds. This performance difference could be easily attributable to differences in the GG mixture ratio and turbine pressure ratio. These engine details are not available for comparison, thus values were assumed in REDTOP-2. Since this is an open cycle design, the GG performance will directly impact the specific impulse. The weight differences are likely attributable to similar assumptions regarding the flowpath details and the nozzle. The length differences are due to the relatively long powerhead arrangement on the RS-68[5]. An examination of just the nozzle geometry revealed a nozzle length and diameter very similar to the RS-68 (approximately 7 ft long and 8 feet wide).

Table 9. RS-68 Engine Specifications.

Parameter	Value
Propellants	LOX/LH2
Vacuum Thrust (lbs)	751,000
Mixture Ratio	6.0
Chamber Pressure (psi)	1,420
Nozzle Area Ratio	21.5: 1

Table 10. RS-68 Engine Results.

Parameter	REDTOP-2 Value	Ref. Value
Tank Supplied Flowrate (lbm/s)	1,772	1,836
Vacuum Isp (s)	410.4	409
SLS Isp (s)	359.1	357
Vacuum T/W	55.1 : 1	50.88 : 1
SLS T/W	48.2 : 1	44.44 : 1
Weight (lbs)	13,620	14,761
Length (ft)	10.3	17.1

IV. Sensitivity Analysis

REDTOP-2 was utilized to perform a multi-variable sensitivity study for a LOX/LH2 staged-combustion cycle with a single, fuel-rich preburner. Parameters investigated included the vacuum Isp, sea-level Isp, vacuum T/W, and overall length sensitivity to changes in chamber pressure, nozzle expansion ratio, and mixture ratio. All engines were sized to obtain 600,000 lbs. of vacuum thrust at 100% throttle condition. For this exercise, pump and turbine efficiencies, preburner mixture ratio value of 0.7, and nozzle equilibrium-to-frozen flow fraction, were held constant for all cases examined.

Tables 11, 12, and 13 contain the results of the sensitivity analysis for a mixture ratio of 6:1. Trends indicate that the higher Pc results in higher vacuum and sea-level specific impulses, but a plateau is reached around 3,000 psi. for the vacuum performance. This improvement was more pronounced for the lower area ratio case. Furthermore, as expected the larger area ratio cases resulted in a significantly higher vacuum Isp of approximately 10 seconds. This improvement came with a massive decrease in SLS Isp.

The higher chamber pressure also resulted in lower engine T/W ratios due to higher system pressures needed to obtain the desired Pc. Note that because the entire engine is being resized to meet the Tvac of 600Klbs, the propellant flow rate will vary, thus some system components, like the nozzle, are smaller as a result of the higher Pc. These effects offset some of the weight increase due to the higher pressures.

The sensitivity analysis was repeated at a mixture ratio of 7:1. Tables 14, 15, and 16 contain the results of this examination. In general, the higher mixture ratio cases showed lower Isp values but higher engine T/W ratios.

Table 11. Vacuum and SLS Isp (s) Sensitivity for MR=6.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	446.5/359.4	446.9/377.2	446.5/388.6
	100	456.4/281.5	456.6/316.8	456.8/340.3

Table 12. Vacuum T/W Sensitivity for MR=6.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	80.6	79.2	76.9
	100	68.1	70.6	69.9

Table 13. Engine Length (ft) Sensitivity for MR=6.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	14.2	12.9	11.9
	100	19.2	17.4	16.1

Table 14. Vacuum and SLS Isp (s) Sensitivity for MR=7.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	438.1/353.9	438.7/371.3	438.6/382.5
	100	448.7/279.5	449.3/313.9	449.8/337.1

Table 15. Vacuum T/W Sensitivity for MR=7.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	82.1	81.1	79.0
	100	69.1	72.5	72.1

Table 16. Engine Length (ft) Sensitivity for MR=7.

		Chamber Pressure (psi)		
		2,000	*2,500*	*3,000*
Expansion Ratio	*50*	14.1	12.8	11.9
	100	19.1	17.3	15.9

V. Case Studies

REDTOP-2 can be incorporated and utilized in almost any vehicle or propulsion system design study. The flexibility of the tool and quick execution times, combined with the numerous interface methods, allow for fast and simple integration. REDTOP-2 has been utilized in numerous design studies conducted at SEI. Typical uses of the code have included: engine design and Pareto sensitivity trades on mixture ratio, chamber pressure, nozzle expansion ratio, and component efficiencies for a variety of propellant combinations; uncertainty analysis on engine performance and weight; propulsion uncertainty analysis coupled with a vehicle closure model in automated framework; and engine parameter optimization to maximize an overall evaluation criteria (OEC) coupled with component-level uncertainties.

A. Airbreathing, Two-Stage Launch Vehicle Design

SEI has been conducting research into the design of a two-stage to orbit (TSTO), reusable launch vehicle. This first stage of this vehicle features a combination propulsion system (CPS) with turbines, scramjets, and multiple liquid rocket tail-engines. The second stage system features a single liquid rocket engine for main propulsion. The design of this very advanced vehicle was performed in a collaborative environment using a distributed analysis framework called ModelCenter© by Phoenix Integration. The vehicle performance closure model features disciplinary analysis (trajectory, aeroheating, mass properties, etc.) executing on four different computing platforms, including a Mac, two PCs, and an SGI workstation.

REDTOP-2 was incorporated into this closure model to predict the first stage tail-rocket and second stage engine's performance. REDTOP-2 was hosted on a Mac running OS X and Analysis Server 4.0 from Phoenix Integration. The interface to the closure model, ModelCenter©, was hosted on a PC running Windows XP. This closure model is shown in Fig. 5.

While the details of this vehicle design and specific engine performance results will not be presented in this paper, the utilization of REDTOP-2 and process will be elaborated upon. The 'Converger' script resolves any coupling issues between disciplinary analysis via a fixed point iteration scheme. The primary or coupling variables iterated upon to obtain system closure are: the mass ratio and mixture ratios for each vehicle stage, engine T/Ws for each stage, average TPS unit weight on first stage, and the first stage flyback mass ratio. The Converger script makes initial guesses for each of the coupling variables and the disciplinary analysis are then executed using these guesses. This results in a new vehicle size and weight from the mass properties model. The rocket system thrust requirements from the mass properties model are fed to the REDTOP-2 models. Each REDTOP-2 instance assesses the engine characteristics at the specified thrust conditions for the respective stage. The engine performance (thrust, Isp, exit area) are then utilized in the trajectory simulation run and predicted engine T/W is passed through the Converger script as a coupling variable with the mass properties model. This process is repeated until all the guesses made by the converger match the resultant values for each discipline. System closure generally requires about 10-15 iterations, with each iteration taking approximately 20 minutes. It is worth noting that in this model, the original REDTOP tool is also utilized for reaction control system thruster performance predictions. REDTOP was hosted locally.

This very tightly coupled modeling approach to vehicle design allows for the propagation of very low-level vehicle system parameters to the vehicle architecture level. For example, using REDTOP-2 a designer could assess the impact to the vehicle GLOW and dry weight due to a 5% improvement in an engine turbopump efficiency or 100 psi. increase in chamber pressure. REDTOP-2 would capture both the performance (thrust/Isp) and the engine T/W impacts of these variables. These impacts would then be propagated through the system and iterated upon until system closure is obtained again.

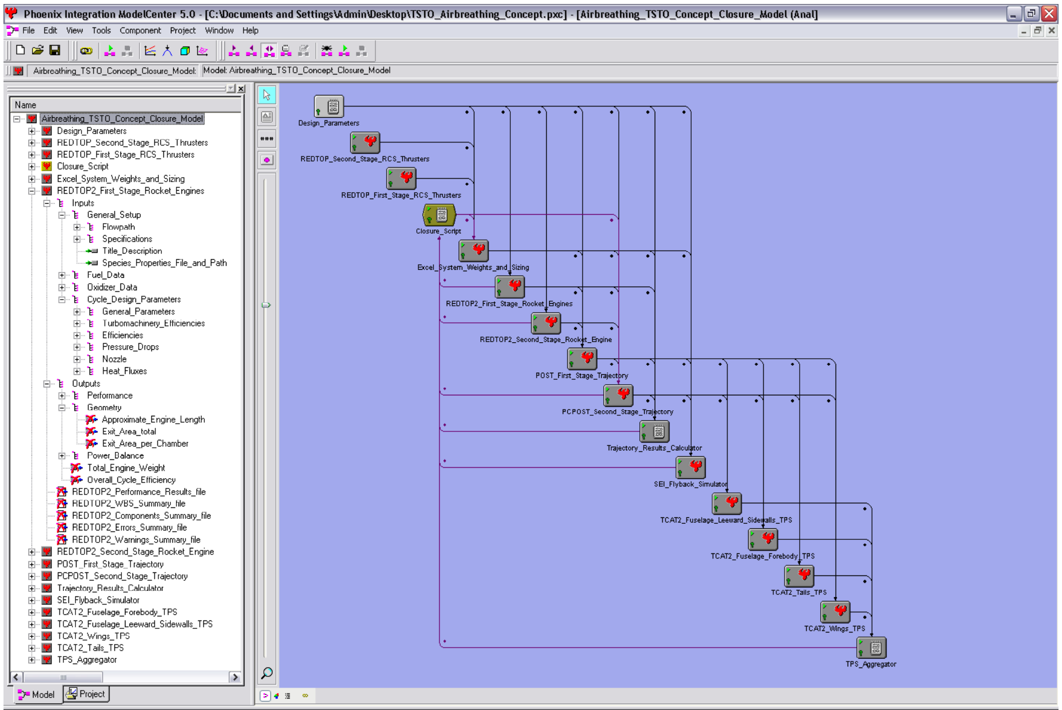

Figure 5. Airbreathing TSTO Vehicle Closure Model with REDTOP-2 for Rocket Propulsion.

B. All-Rocket SSTO Vehicle with Uncertainty

REDTOP-2 was utilized in a collaborative design environment to close a reusable, all-rocket launch vehicle design concept. The tool was coupled with the following disciplinary analysis: trajectory simulation, mass properties, aerodynamics, non-recurring cost, economics, safety, and operations.

For this examination, REDTOP-2 will be used to design and analyze an engine to be used on a specific space vehicle design, an all-rocket Single-Stage-To-Orbit (SSTO) wing-body configuration capable of taking off vertically and landing horizontally. Referred to as the All-Rocket Winged Body (ARWB) vehicle, the reference mission includes cargo or passenger delivery to a 100 nmi. circular orbit at 28.5^{o} inclination. The nominal payload is 15 klbs to this Low Earth Orbit (LEO) with an Orbital Maneuvering System (OMS) ΔV of 600 ft/s. The vehicle is designed to be human rated and to fly un-piloted with crew/passenger survivable abort capability, having no capability to make its nominal mission with one or more engines out, and possessing a cross range capability of several hundred nautical miles.

The original concept design studied by Dan Levack at Boeing/Rocketdyne during NASA's Highly Reusable Space Transportation (HRST) study, utilized the Advanced Concept Rocket Engine (ACRE), with a sea-level T/W of 92:1[6,7]. The authors at SEI have subsequently continued to examine this particular vehicle airframe and propulsion system combination as a testbed for demonstrating a variety of systems integration and vehicle design processes.

This ARWB concept contains advanced technologies in multiple areas. These technologies are assumed to be substantially better than those used on the current Space Shuttle with an estimated technology freeze date of 2020. Propellants used on the vehicle include LOX / LH2 for the Main Propulsion System (MPS), LOX/LH2 for the Orbital Maneuvering System (OMS), and a Gasified H2 (GH2) / Gasified Oxygen (GOX) Reaction Control System (RCS). Airframe lifetime is anticipated to be 1,000 flights with a 500 flight lifetime on each individual propulsion unit.

A deterministic vehicle closure model was constructed for the ARWB concept in ModelCenter©. This closure model features a design variable controller script, a Weights and Sizing (W&S) model created in Excel, a POST (Program to Optimize Simulated Trajectory) ascent simulation model with appropriate aerodynamics database for the ARWB concept[8], an instance of REDTOP-2 for main propulsion system modeling, and a fixed-point iteration

(FPI) converger script. The FPI script that ensures the vehicle's available mass ratio matches the trajectory results required mass ratio. Additionally, engine T/W convergence is required in the closure process, with REDTOP-2 providing the actual value and a guess being specified to the W&S model. The vehicle mission and system technologies are based on the ARWB assumptions discussed previously. The vehicle outer mold line (OML) is scaled photographically during the closure process. This eliminates the need to perform an in-the-loop aerodynamics assessment. Table 17 provides a brief summary of key engine design parameters and performance at nominal operating conditions (no uncertainty) utilized for the design of the vehicle and analysis in REDTOP-2. It should be noted that for this study, the engine cost values are from the NAFCOM based model.

For the probabilistic ARWB vehicle closure process, the ProbWorks© approximate Monte Carlo technique known as Discrete Probability with Optimal Matching Distributions (DPOMD) driver was introduced into the deterministic closure model (see Fig. 6). Eight uncertainty parameters were linked from REDTOP-2 to the DPOMD driver. These uncertainty parameters include: high-pressure pump efficiencies, turbine efficiencies, and main propellant valve pressure drops. The closure model is constructed such that for each pass of the iteration process, the DPOMD component mimics the Direct Monte Carlo simulation (performed in a fraction of the time) and instead of designing the ARWB with overly optimistic engine performance parameters (Isp, T/W, exit area), more conservative results based on a 90% certainty value are utilized instead. This inevitably results in a larger vehicle, but represents a significant reduction in overall program risk and a more robust vehicle design.

Using the deterministic closure model, the ARWB concept was closed with the uncertainty parameters set to their mean values. A non-optimized vehicle liftoff T/W ratio of 1.15 was held constant by resizing the 5 main engines of the ARWB system using REDTOP-2 to achieve the total sea-level thrust requirement. The deterministic closure of the ARWB concept required approximately 10 iterations of the complete analysis process, with each iteration requiring approximately 1.5 minutes (total of 15 minutes). The mass ratio and engine T/W difference was driven to a tolerance of 1x10-3. The probabilistic closure process took significantly longer than the deterministic process, but by utilizing the DPOMD technique, the vehicle closure process was still accomplished in a timeframe suitable for conceptual and preliminary design studies. Approximately 8 iterations were necessary to obtain convergence, requiring approximately 2 hours of CPU time. Table 18 contains a listing of the vehicle-level metrics for both the deterministic results and the probabilistic results. For the probabilistic analysis, the engine T/W at sea-level decreased from an optimistic 64.1:1 to 62.8:1, while the vacuum specific impulse decreased by approximately 0.3 seconds. The more conservative performance estimates resulted in both the vehicle gross weight and dry weight increasing by approximately 11%, representing a 198,600 lbs increase in GLOW and 18,000 lbs increase in dry weight.

Table 17. ARWB Engine Specifications.

Engine Parameter	Value
Fuel / Oxidizer	LOX/LH2
Engine Health Monitoring	Yes
SLS Thrust (lbs)	375,338
Chamber Pressure (psi)	3,500
Tank Supplied Mixture Ratio	6.0
Expansion Ratio	60.0
Preburner Mixture Ratio	0.85
Preburner Chamber Temperature (R)	1,718
Nozzle Shape	Bell
Length Factor (% of cone)	80.0
Conical Half Angle (deg)	15
Nozzle Efficiency (%)	98.8494
Nozzle Surface Area (ft^2)	117.96
Engine Length (ft)	11.908
Exit Area (ft^2)	33.259
Fuel Turbine Pressure Ratios	2.695
Oxidizer Turbine Pressure Ratios	2.693
High Pressure Fuel Pump Power (hp)	115,648
High Pressure Oxidizer Pump Power (hp)	29,989
Overall Reliability	99.942512
Overall Safety	99.998011
Total Development Cost (FY2003$M)	1,534.8
First Unit Cost (FY2003$M)	39.386

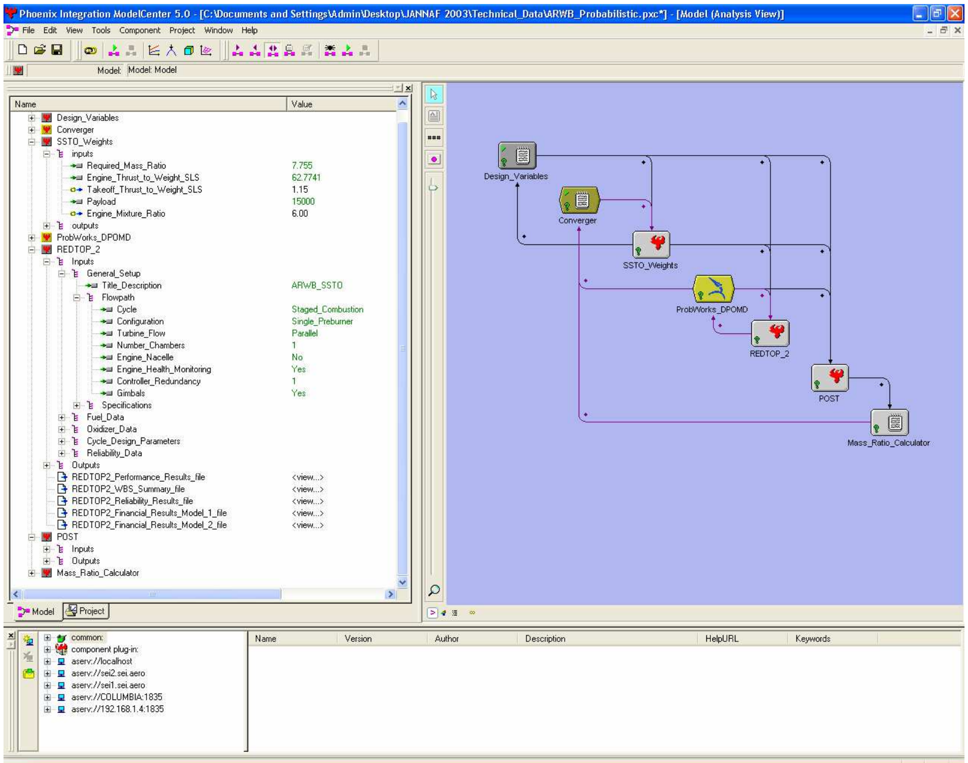

Figure 6. ARWB Concept Closure Model with REDTOP-2.

Table 18. ARWB Deterministic and Probabilistic Closure Results.

Item	Deterministic	Probabilistic [DPOMD]
GLOW (lbs)	1,631,900.00	1,830,510.00
Dry (lbs)	166,671.00	184,651.00
Mass Ratio	7.61	7.76
Isp, vac (seconds)	453.73	453.46
T/W)sls	64.07	62.77
Vacuum Thrust (lbs)	445,708.00	481,938.00
Weight (lbs)	5,863.72	5,992.46
Engine Length (ft)	11.8	11.91

VI. Future Work

The capabilities of REDTOP-2 will continue to be expanded upon. Enhancements currently being developed include:

1) Implementing a more detailed heat-transfer model to allow for option of specifying the heat flux rates or to utilize internal tool predictions based on the hot and coolant flow conditions, heat exchanger geometry, and material properties.
2) Continue to add additional cycles, including monopropellant and tripropellant configurations.
3) Refinement of specific component analysis and improved execution speeds.
4) Incorporating a bottom-up reliability model based on individual component/hardware items, safety factors, and flowpath details.

VII. Conclusion

A unique analysis tool has been introduced to the space propulsion community to assist in the design of liquid rocket engines for ETO and in-space applications. This tool, a commercially available product from SpaceWorks Engineering, Inc. (SEI), has been executed and shown to be in good agreement with a number of actual liquid rocket engines. Included for comparison were the SSME, RL10-3-A3, J-2S and RS-68 engines. Results indicated good overall agreement in terms of vacuum Isp, length, and weight predictions from REDTOP-2 with published performance parameters. The usefulness of REDTOP-2 was illustrated in a number of different case studies. These studies ranged from using REDTOP-2 to perform engine sensitivity analysis on mixture ratio, chamber pressure, and nozzle expansion ratio, to analyzing the main propulsion rocket engines on a TSTO airbreathing system, and performing probabilistic engine assessments for an all-rocket RLV closure model.

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