



Georgia Institute
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PHATCAT

Power-Head And Thrust Chamber Analysis Tool

Submitted to:

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ACRONYMS AND SYMBOLS

c^*	characteristic velocity
C_F	Thrust Coefficient
c_p	constant pressure specific heat [Btu/(lbm-R)]
c_v	constant volume specific heat [Btu/(lbm-R)]
DP	Absolute Pressure Drop [psia]
$\Delta P/P$	Relative Pressure Drop
h	specific enthalpy [Btu/lbm]
HPFP	High-Pressure Fuel Pump
HPOP	High-Pressure Oxygen Pump
I_{sp}	Specific Impulse [sec.]
$I_{sp,sl}$	Sea-level Specific Impulse
$I_{sp,vac}$	Vacuum Specific Impulse [sec.]
JANNAF	Joint Army Navy NASA Air Force
LPFP	Low-Pressure Fuel Pump
LPOP	Low-Pressure Oxygen Pump
m_{dot}	Mass flow rate
MR	Mixture Ratio
NBS	National Bureau of Standards
NIST	National Institute of Standards
p	Static pressure [psia]
P	Total pressure [psia]
PHATCAT	Power-Head And Thrust Chamber Analysis Tool
P_{real}	Actual Power [HP]
Q_{dot}	heat rate [Btu/s]
s	specific entropy [Btu/(lbm-R)]
SCCREAM	Simulated Combined Cycle Rocket Engine Analysis Module
SCORES	SpaceCraft Object-oriented Engine Simulation

SSDL	Space Systems Design Lab
SSME	Space Shuttle Main Engine
t	Static temperature [R]
T	Thrust [lbf]
T	total temperature [R]
T_{in}	Inlet Temperature [R]
T_{out}	Exit Temperature [R]
T_{sl}	Sea-level Thrust [lbf]
T_{vac}	Vacuum Thrust [lbf]
W_{ideal}	Isentropic Work [Btu/lbm]
W_{real}	Actual Work [Btu/lbm]
η_{pump}	Pump Efficiency
η_{turb}	Turbine Efficiency
ρ	Density [lbm/ft ³]

1.0 Abstract

This document is intended to outline the reasoning, methodology, structure and results of a property-based liquid rocket engine analysis tool. As system-level space vehicle analysis requires that more detailed analyses be performed at the discipline level, it is necessary to create computer programs that are capable of producing the necessary inputs. These tools should provide the system-level designer with the necessary inputs to his or her analysis in a timely fashion while maintaining the accuracy and precision of the subsystem level analysis.

Current propulsion analysis capabilities within the Space Systems Design Lab (SSDL) include several in-house tools. SpaceCraft Object-oriented Rocket Engine Simulation (SCORES) was developed by David Way in 1996 to allow the vehicle designer to simulate a “rubberized” liquid rocket propellant engine [1]. For most applications, a “rubberized” engine model is sufficient enough to provide the vehicle analysis all of the necessary information. The code is also very easy to use and provides results almost instantly. However, there are several limitations to this code. First, the code does not account for regenerative heat loss through the nozzle walls. As such, the nozzle performance is not directly affected by cycle selection without the use of statistical data based on historical engines. More importantly, without heat regeneration, it is impossible to model the power head of the engine. This may put the user in a situation where the cycle requirements are infeasible considering the amount of energy present in the system. “Rubberized” engine models do not capture these limitations.

On the other hand, an industry standard power balance tool is available for rocket engine analysis. Rocket Engine Transient Simulation (ROCETS) provides a high level of fidelity to the propulsion designer. However, there are two major drawbacks to using ROCETS. First, ROCETS is written in the FORTRAN programming language. FORTRAN does not afford the programmer the benefits of object-oriented programming languages. As such, typical engine analyses require the code to be compiled multiple times, which may be very time consuming. While component modules are usually kept as functions in a standard library, many calculations are performed in the main code itself. This makes it difficult to quickly change engine

configurations. Secondly, the code is proprietary in its most robust form, therefore not readily available to the rocket engine enthusiast or student.

PHATCAT (*Power-Head And Thrust Chamber Analysis Tool*) is intended to provide the space vehicle designer a means of generating performance data relevant to the vehicle design process while capturing the physical limitations of different engine cycles. To do this PHATCAT uses a property-based component approach to feed system design. All calculations concerning the individual power-head components are made using basic textbook thermodynamic analysis and fluid property data, therefore the code can be made available to the public. Turbine analysis requires a model of the heat exchange between the thrust chamber of the rocket engine and the regenerative cooling flow. This nozzle analysis is performed using an incremental thermally perfect gas assumption with a numerical integration algorithm to calculate the overall change in flow properties. The regenerative cooling flow is analyzed using an industry standard empirical correlation based on thermodynamic properties. The code is structured to use input files wherever possible so that unwanted compile time can be kept to a minimum. The code is also written in the object-oriented C++ language allowing quick interchange between new components.

2.0 Introduction

Classes called by the top-level program, 'PHATAT.C', generate the main input output files and analyze the engine using 'engines.C'. The engine configuration class is constructed from multiple instances of the component classes arranged to simulate the flow path of a rocket engine. In addition to analyzing the engine, 'engines.C' is also used to generate derivative information for the Newton-Raphson root-finder. The class 'newtonraphson.C' is used to set the derivative and function information in a form usable to the solver algorithm. Once all this information is set the engine is iterated upon and solved in 'PHATCAT.C'. A top-level flow diagram of the tool is shown in Figure 1.

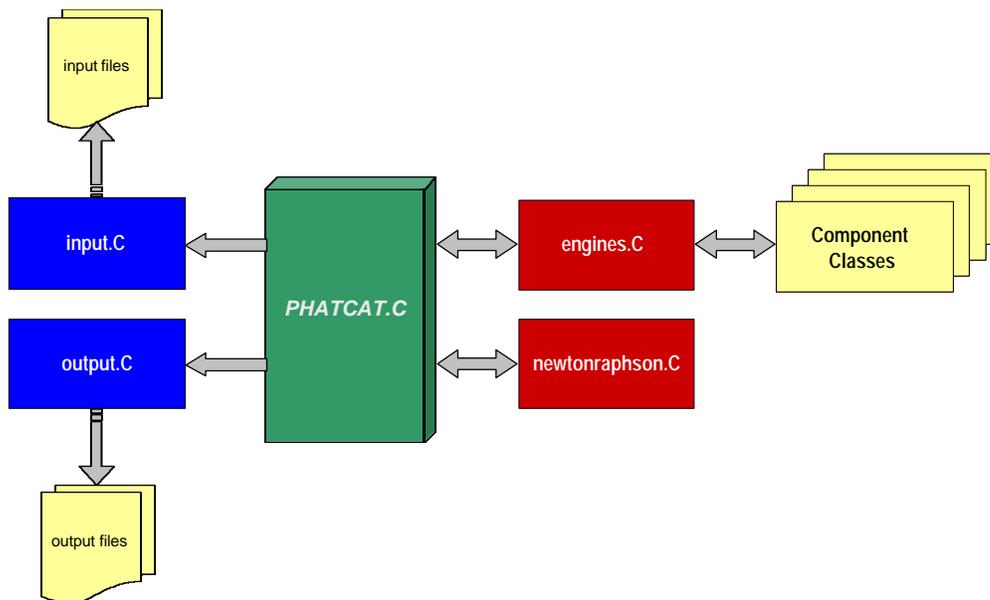


Figure 1. Flowchart of top-level classes.

Several cycles are pre-configured for use in PHATCAT. PHATCAT currently holds the capability to analyze a single turbine expander (RL-10), a gas-generator (Vulcain), and a fuel-rich dual-preburner staged combustion cycle (SSME). Additional engine cycles can be configured in the engine class on an ad-hoc basis. The user will need to know the flow path for the engine before configuring the model. Once the user has developed a schematic of the desired

engine system, the engine can be constructed using the generic component classes. The addition of new cycles requires that the program be recompiled.

PHATCAT uses a Newton-Raphson root finder to solve the engine for required values. This process is also called “balancing the engine.” Any engine cycle in PHATCAT may be run unbalanced to evaluate components at a specific point. However, for most purposes the engine should be run to match turbomachinery powers, match thrust, match I_{sp} , match combustion pressures or any combination thereof. The additional balances and their use will be described later in the document. PHATCAT currently allows up to 30 balances to be run simultaneously.

The component classes include the capability to analyze cold-flow components, hot-flow components, the engine nozzle, and performance metrics. Cold-flow components will be defined as those that use fluids that have not been used in a combustion process. Hot-flow components are any components that are used downstream from a combustor or preburner. This differentiation is necessary due to the use of two property databases. Cold flow components acquire property data from tables generated by the NIST Thermophysical Properties of Hydrocarbon Mixtures Database: Version 3.0. A linear interpolation code is used to evaluate the requested point. Hot flow components use curve fits based on the JANNAF Thermochemical Tables. A simple one-dimensional Newton-Raphson root-finder is used on the curve-fits where necessary to obtain independent variable values from an independent-dependent variable combination. Both databases contain hydrogen, oxygen, and kerosene (RP-1) data. The block diagram in Figure 2 depicts the interaction between the engine class and the component classes, and the interaction between the component classes and the property database.

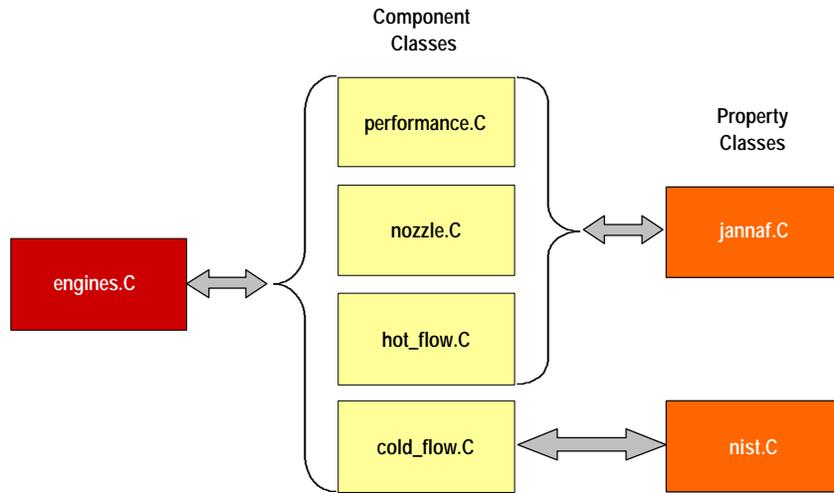


Figure 2. Engine, component and property class interaction.

3.0 Methodology

The characteristics of each of the classes used in the development of a liquid rocket engine model will be described in the following sections. The methods implemented in PHATCAT for component analysis will also be outlined.

3.1 Property Tables

The determination of fluid properties in PHATCAT requires two different databases. Components that are analyzed upstream of combustion processes use property data from the NIST Thermophysical Properties of Hydrocarbon Mixtures Database: Version 3.0 [2]. Components that are analyzed downstream of combustion processes use property data from the JANNAF Thermochemical Tables [3].

3.1.1 NIST Thermophysical Properties of Hydrocarbon Mixtures Database

The property tables based on NIST Hydrocarbon Mixture Database were generated using a PC based program, SUPERTRAPP. SUPERTRAPP is capable of calculating thermodynamic properties of mixtures containing as many of 20 different components. Of the 196 different components in the database the majority of them are hydrocarbons. Pure fluids such as hydrogen and oxygen are also included. SUPERTRAPP allowed tables of enthalpy, entropy, density to be created as a function of pressure and temperature. The data tables generated by SUPERTRAPP are valid from the vapor region of the fluid down to typical cryogenic operating points.

PHATCAT uses a two-dimensional linear interpolation routine to read the data tables. The dimensions, point increments and property limits of each table were specified within the data tables. This enabled the property lookup classes to find necessary data points in a quick and efficient manner. The basic table lookups require that a pressure and temperature be specified to read enthalpy, entropy and density. However, work and power calculations require that ideal enthalpy be determined as a function of pressure and ideal entropy. Such reverse table reading scenarios are accomplished by using a one-dimensional Newton-Raphson root-finder. The reverse lookup enables the program to find temperature as a function of pressure and enthalpy

and as a function of pressure and entropy. This Newton-Raphson routine typically solves for temperature in 8-10 iterations per point. A bisection routine was examined and was shown to converge in 30-35 iterations per point.

The properties of RP-1 (kerosene) were not readily available in SUPERTRAPP. However it is possible to enter new mixtures in the database. Approximate property data can be generated using only the mixture's average boiling point and API gravity. Generalized shape factors are used for petroleum fractions. More sophisticated methods of creating new properties are possible. The user may specify up to 20 components in the mixture. However, kerosene is comprised of 24 different components, and of those that are not listed in the database, their boiling point and API gravity are not readily available.

Arbitrary bounds have been placed on the Newton-Raphson root-finder for each fluid. The functions are uni-modal over the relevant range of pressures and temperatures, but the derivative changes signs at the low-pressure, low-temperature range of the tables. The use of Newton-Raphson would cause undesirable effects if the root-finder searched near the table endpoints.

3.1.2 JANNAF

Hot-flow devices require that property data come from the JANNAF Thermochemical Tables. Information from the JANNAF tables had previously been converted to curve fits for specific heat, and Gibbs' free energy. Molecular weights, enthalpy of formation and Gibbs of formation were also included. The 'jannaf.C' class was slightly modified to include entropy curve fits for turbomachinery calculations. The entropy curve fits were generated as a function of temperature from the JANNAF tables, which includes data on entropy at a reference condition (1atm). To obtain entropy information at a given pressure, the following relationship was used:

$$s = s^{\circ} - R * \ln\left(\frac{P}{P^{\circ}}\right) \quad (\text{Eq. 1})$$

where: s° : entropy at the reference pressure
 P° : reference pressure (1 atm)
R: specific gas constant

The entropy is returned in units of Btu/(lbm-R).

3.2 Engine Components

The analysis method used to determine the performance characteristics of each of the engine components will be described in detail below. General thermodynamic analyses were used [4]. Each engine component receives inlet inputs (typically pressure, temperature and flow) from the previous component. In the case of the first iteration, the input file sets an outlet parameter and a performance parameter. These may remain unchanged throughout the solver iterations or may be updated depending on the balance configuration.

3.2.1 Cold Flow Components

3.2.1.1 Pumps

The pump class is used to generate pump performance characteristics such as power, rotational speed, diameters, specific speed, suction specific speed, weight and outlet conditions. Power is the parameter of main importance since a balanced engine cycle requires that coupled components have equal powers. The required inputs are the inlet pressure and temperature, discharge pressure, mass flow rate and pump efficiency. The discharge conditions are calculated by comparing the performance of the real pump to performance of an ideal or isentropic pump.

The first step in the pump analysis is to calculate inlet enthalpy, entropy and density using pressure and temperature. The ideal exit specific entropy is then set equal to the inlet specific entropy. Using the exit pressure and ideal entropy, the ideal exit specific enthalpy can be found. The ideal work required to drive the pump is calculated using (Eq. 2). Once the ideal work is determined, the actual work is calculated using the user defined pump efficiency where:

$$h_{pump} = \frac{W_{real}}{W_{ideal}} \quad (\text{Eq. 2})$$

Given the real work required the actual exit enthalpy can be calculated. Using the exit pressure and enthalpy, the exit temperature can be found. The power required to drive the real pump can also be calculated using the following relation:

$$P_{real} = \dot{m}w_{real} \quad (\text{Eq. 3})$$

Other performance characteristics are evaluated using the method outlined by Humble [5]. The mass of the pump is estimated by using:

$$m_p = a \left(\frac{P_{real}}{N_r} \right)^b \quad (\text{Eq. 4})$$

where: N_r : pump rotational speed
 α : empirical coefficient (typical range 1.3-2.6)
 β : empirical coefficient (typical range 0.6-0.667)

The process to calculate the pump rotational speed is outlined as follows:

- Calculate the required number of stages

$$n = \text{int} \left(\frac{\Delta P_p}{\Delta P_{ps}} \right) \quad (\text{Eq. 5})$$

where: ΔP_p : calculated pump pressure rise
 ΔP_{ps} : allowable pressure rise over a single stage
 16 MPa for liquid H₂
 47 MPa for all others

- Calculate the pump rotational speed

$$N_r = \frac{N_s \left(\frac{H_p}{n} \right)^{0.75}}{\sqrt{Q}} \quad (\text{Eq. 6})$$

where: N_s : stage specific speed
 2.0 for liquid H₂
 3.0 for all others
 Q : volumetric flow rate
 H_p : pump head rise

The pump head rise is defined as:

$$H_p = \frac{\Delta P_p}{g_o \mathbf{r}_{ave}} \quad (\text{Eq. 7})$$

The pump may also be sized using the relations defined by Humble. The pump impeller tip speeds are calculated by using the following formula:

$$u_t = \sqrt{\frac{g_o H_p}{n \psi}} \quad (\text{Eq. 8})$$

where: ψ : pump head coefficient
 0.65 for liquid H₂
 0.55 for all others

The exit tip diameter is defined as:

$$D_{2t} = \frac{2u_t}{N_r} \quad (\text{Eq. 9})$$

and the inlet tip diameter is defined as:

$$D_{1t} = \sqrt[3]{\frac{(4/p)Q}{\mathbf{f} * N_r (1 - L^2)}} \quad (\text{Eq. 10})$$

where: ϕ : inducer-inlet flow coefficient (0.10)
 L : inducer-inlet hub-to-tip diameter ratio (0.3)

The correlations used by Humble require metric units. Conversions were made to use the correlations and the outputs were then converted back to English units.

3.2.1.2 Turbines

The analysis of the turbines is similar to the analysis of the pumps insofar that isentropic work relations and efficiencies are used. Again power is the parameter of main importance since a balanced engine cycle requires that all powers be balanced between coupled components. The required inputs are the inlet pressure, inlet temperature, mass flow rate and turbine efficiency. Instead of specifying a discharge pressure, a turbine pressure ratio is required. The discharge conditions are calculated by comparing the performance of the real turbine to performance of an ideal or isentropic turbine.

The process for finding the power generated by a turbine is similar to the power analysis used for a pump. The first step in the turbine analysis is to calculate the inlet specific entropy and specific enthalpy using pressure and temperature. The ideal exit specific entropy is then set equal to the inlet specific entropy. Using the exit pressure and entropy, the ideal exit specific enthalpy can be found. The ideal work required to drive the pump is calculated using:

$$w_{ideal} = h_{in} - h_{out,ideal} \quad (\text{Eq. 11})$$

The sign convention used for the turbine work allows turbomachinery power outputs to have the same sign in the engine solver. Once the ideal work is determined, the actual work is calculated using the user defined pump efficiency where:

$$h_{pump} = \frac{w_{ideal}}{w_{real}} \quad (\text{Eq. 12})$$

Given the real work required, the actual enthalpy can be calculated and therefore all other exit properties of the real pump. The power required to drive the real pump can also be calculated using the following relation:

$$P_{real} = \dot{m}w_{real} \quad (\text{Eq. 13})$$

Sizing calculations for turbines are currently unavailable in PHATCAT.

3.2.1.3 Heat Exchangers

Heat exchangers by definition exchange energy between several different flows. Heat exchange in rocket engine analysis is important in that it provides energy to the turbines to drive the pumps. The heat exchanger class in PHATCAT analyzes the cold flow in the regenerative cooling scheme. This energy is typically extracted from the thrust chamber but may also be extracted from other hot flows. Thrust chamber hot flow analysis is described in section 3.3 .

The analysis performed in the heat exchanger class uses an enthalpy balance and lumped parameter heat transfer as shown below.

$$h_{out} = \eta \left(\frac{\dot{Q}}{\dot{m}} \right) + h_{in} \quad (\text{Eq. 14})$$

where: η : user-defined heat exchanger efficiency

The heat exchanger efficiency compensates for heat transfer losses not accounted for in the lumped-parameter method. Based on test point correlations, a value of 0.912 is suggested.

The mass flow rate, inlet temperature and pressure are given by the previous component. The user specifies the heat exchanger pressure drop (as a ratio of inlet to exit pressure) and the baseline heat transfer rate. The heat transfer rate is adjusted using an industry standard relationship.

$$\dot{Q} = \dot{Q}_{base} \left(\frac{P}{P_{base}} \right)^{0.8} \quad (\text{Eq. 15})$$

This relationship is derived from Bartz's empirical correlations as outlined by Huzel & Huang [6].

3.2.1.4 Valves

Valves are considered to be isenthalpic flow devices that produce large pressure drops. The current analysis capability of the valve class allows the user to specify the amount of the pressure drop (DP) as the ratio of the inlet pressure to exit pressure. The inlet conditions to a valve are supplied by the previous component in the engine configuration class. Using the exit enthalpy and exit pressure, the exit temperature can be calculated.

3.2.1.5 Injectors

The injectors of the engine are currently analyzed valve analysis algorithm. This class was written to allow the user to differentiate between valves and injectors.

3.2.1.6 Flow Splits

The fluid does not incur losses by traveling through a flow node. The exit properties of the split are the same as the inlet properties. The amount of flow directed through each outlet is specified by a bypass percentage. The percentage is given on a scale of 0-1. This percentage determines the amount of flow to move through the first outlet. The flow split class can handle one input flow and two output flows.

3.2.1.7 Mixers

The fluid does not incur losses from mixing. This method is used to prevent backflow through any line. The mixer class can handle two input flows and one output flow. The exit pressure is taken to be the minimum pressure of the inlet pressures. The exit enthalpy of the mixer is evaluated by using the mass-weighted average of the inlet enthalpies as shown below.

$$h_{out} = \frac{\dot{m}_{in,1}h_{in,1} + \dot{m}_{in,2}h_{in,2}}{\dot{m}_{in,1} + \dot{m}_{in,2}} \quad (\text{Eq. 16})$$

3.2.2 Hot Flow Components

Hot flow components are analyzed classes that use property data from JANNAF to model performance characteristics. These components are downstream from any combustion processes. The following hot flow component analysis algorithms are the same as their respective cold flow counterparts.

- Turbines
- Heat Exchangers
- Valves
- Injectors
- Mixers

3.2.2.1 Combustors

The combustor and preburners of the engine cycle are modeled using the combustor code written by John Bradford for SCCREAM [7]. Bradford's code was selected for various reasons. First, the code was easily modifiable to handle extremely low mixture ratios such as those ratios characteristic of fuel-rich preburners. Typical mixture ratios for fuel rich preburners range from 0.6 to 2. Secondly, Bradford's combustion model is capable of varying the fuel and oxidizer inlet temperatures. This is essential considering the extremely low combustor inlet temperatures.

To account for low mixture ratios, the initial guesses for the combusted gas species was modified. The 'eq.C' class includes a protocol that selects different initial guesses based on equivalency ratio (ϕ) and propellants. The equivalency ratio was selected as the switch based on the difference in stoichiometric mixture ratio between hydrocarbon fuels and liquid hydrogen. For a detailed description of the algorithm use in the combustion model, refer to Gordon & McBride [8].

The combustor class can handle up to nine inlet flows. Three are reserved for cold fuel flow, three for cold oxidizer flow, and three for hot gas flow. The combustor produces one outlet flow. The mass flow rate of each species is calculated as well as combustion gas properties.

3.3 Nozzle Analysis

The nozzle analysis requires that heat loss be accounted for through the nozzle walls to supply energy to the turbines. Ideal nozzles are assumed to be adiabatic and isentropic. With this assumption, the basic isentropic flow relations can be used to calculate exit conditions from given inlet conditions. Because the nozzle in this code can no longer be assumed adiabatic, it also cannot be assumed isentropic. The introduction of mass addition to the flow presents another problem. This flow will be entering the main nozzle flow at different conditions. Therefore another analysis method must be used to find the exit conditions.

3.3.1 Convergent Section

The convergent section of the nozzle is analyzed using the isentropic flow relations. It is assumed that the flow is choked at the nozzle throat, hence the Mach number is 1. An isentropic flow class was written for this purpose. The isentropic relations used in the convergent section analysis are outlined below.

$$P_{throat} = \frac{P_{total}}{\left(1 + \frac{g-1}{2} M^2\right)^{\frac{g}{g-1}}} \quad (\text{Eq. 17})$$

$$T_{throat} = \frac{T_{total}}{\left(1 + \frac{g-1}{2} M^2\right)} \quad (\text{Eq. 18})$$

$$u_{throat} = M \sqrt{gRT_{static}} \quad (\text{Eq. 19})$$

Using the ideal gas law and the condition of continuity the throat area can be calculated with the following formula:

$$A_{throat} = \frac{\dot{m}RT_{throat}}{P_{throat}u_{throat}} \quad (\text{Eq. 20})$$

3.3.2 Divergent Section

The regenerative cooling flow passes through the nozzle wall and requires analysis that can compensate for energy loss in the divergent section of the nozzle. The method of potentials outlined by Zucrow is well suited for the type of analysis required in this scenario [9]. Simple flow methods (such as adiabatic, isentropic flow) have only one driving potential present. In a general, multiple steady one-dimensional flow driving potentials may be present simultaneously. The independent driving potentials determined to be relevant to this analysis are as follows:

1. Area change, dA : Expansion
2. Heat transfer, dQ : Regenerative Cooling
3. Mass addition, dm_{dot} : Gas Generator Flow Dumps
- 4.

Solving Zucrow's method for the potentials relevant to the analysis performed in PHATCAT results in a first-order differential equation of the form:

$$\frac{dM}{M} = \frac{\left(1 + \frac{g-1}{2}M^2\right)}{1-M^2} \left\{ -\frac{dA}{A} + \frac{(1+gM^2)}{2} \frac{dT}{T} + \left[(1+gM^2) - y g M^2 \right] \frac{dm}{m} \right\} \quad (\text{Eq. 21})$$

The equation (Eq. 21) requires the use of a numerical integration algorithm to find a solution. A fourth order Runge-Kutta numerical integration algorithm was implemented to solve for exit Mach number as a function of axial distance from the throat. The function to be integrated and the numerical integration scheme are shown in (Eq. 22a-e).

$$M_{n+1} = M_n + \frac{h}{6}(m_1 + 2m_2 + 2m_3 + m_4)$$

$$m_1 = f(x_n, M_n)$$

$$m_2 = f\left(x_n + \frac{h}{2}, M_n + \frac{h}{2}m_1\right) \quad (\text{Eq. 22a-e})$$

$$m_3 = f\left(x_n + \frac{h}{2}, M_n + \frac{h}{2}m_2\right)$$

$$m_4 = f(x_n + h, M_n + hm_2)$$

The displacement steps (h) are set in the integration class as a function of overall nozzle length. It was determined through several trial runs that 1/1000 of the nozzle length provides a decent trade between run time and accuracy. Mach number is typically accurate to the fourth decimal place.

Area functions have been produced following a method described by J.V.R. Rao [6]. For conical nozzles, the divergence angle is specified and the throat region is modeled as circular. The two regions meet where their derivatives are continuous. The continuous derivative constraint is upheld for bell nozzles with the upstream profile modeled as a parabolic function. The user may specify the length of the nozzle a percentage of a theoretical 100% conical nozzle. The nozzle code produces exit Mach number, temperature pressure, and other relevant gas properties.

3.4 Engine Performance

The rocket engine performance class produces an output deck of parameters to evaluate to overall characteristics of the rocket engine. These metrics are also considered to be the final result of PHATCAT and required inputs for the space vehicle designer. Many of these outputs can be directly calculated using an adiabatic assumption, while a few are adjusted for the real system modeled in PHATCAT.

The thrust produced by any control volume may be found by using the conservation of momentum equation. After derivation this may be expressed as:

$$T = \dot{m}_{exit} u_{exit} + A_{exit} (P_{exit} - P_{ambient}) \quad (\text{Eq. 23})$$

The exit properties include any adjustments made by the nozzle class for the addition of gas generator flow.

The specific impulse of the system may be expressed as:

$$I_{sp} = \frac{T}{\dot{m}_{in} g_c} \quad (\text{Eq. 24})$$

Here the inlet mass flow is the total inlet flow to the engine, not the inlet flow to the nozzle.

The characteristic velocity (c^*) is essentially a measure of the performance of the rocket upstream from the throat. This is calculated by using,

$$c^* = \frac{\sqrt{g \cdot R \cdot T_c}}{g \sqrt{\left(\frac{2}{g+1}\right)^{\frac{g+1}{g-1}}}} \quad (\text{Eq. 25})$$

where T_c is the combustion chamber temperature, γ is the ratio of specific heats of the combustion products and R is the universal gas constant (R) divided by the molecular weight of the combustion products. The nozzle coefficient of the engine cannot be calculated using isentropic relations due to the nature of the nozzle analysis. Instead, the formal definition of C_F , shown in below is used.

$$C_F = \frac{T}{A_t P_{chamber}} \quad (\text{Eq. 26})$$

3.5 Program Solver

The engine may be solved for multiple parameters using the Newton-Raphson root finding method. Newton-Raphson may be used for most any problem provided that each function is uni-modal, continuous, and differentiable everywhere in the domain and an equal number of variables and functions exist. If such a problem has been formulated, Newton-Raphson can solve the problem in an efficient manner in relatively few iterations. [Note: The functions in PHATCAT are not continuous due the minimum pressure function in the mixer classes and the combustor class. However, the solver seems relatively insensitive to these step functions.]

3.5.1 One-dimensional Newton-Raphson

The procedure for iterating on Newton-Raphson begins with evaluating the function at any point. The next step is to evaluate the function's derivative at the same point. The derivative may be numerical or analytical. Once the function value and its derivative has been obtained, the following equation is evaluated:

$$x_{n+1} = x_n - \frac{F(x_n)}{F'(x_n)} \quad (\text{Eq. 27})$$

This equation essentially solves for the x-intercept of the line tangent to the function at the evaluated point. A schematic diagram is shown below.

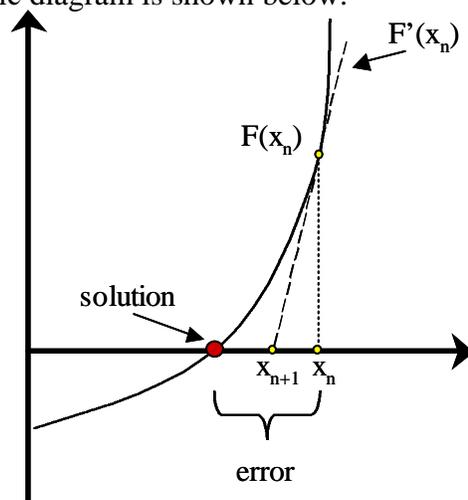


Figure 3. Sample Newton-Raphson iteration in one dimension.

The updated point x_{n+1} will be closer to the root than the previous point x_n . Subsequent iterations will come closer. The iteration procedure terminates once the convergence criteria have been met.

3.5.2 Multi-dimensional Newton-Raphson

The same procedure may be followed for multi-dimensional problems. The variable term x_n is replaced by:

$$\bar{x}_n = \begin{bmatrix} x_{n,1} \\ \vdots \\ x_{n,m} \end{bmatrix} \quad (\text{Eq. 28})$$

The function term is replaced by a matrix of functions:

$$\bar{F} = \begin{bmatrix} F_1 \\ \vdots \\ F_m \end{bmatrix} \quad (\text{Eq. 29})$$

The Jacobian (the matrix of partials with respect to each variable) replaces the derivative term:

$$\bar{J} = \begin{bmatrix} \frac{\partial F_1}{\partial x_{n,1}} & \dots & \frac{\partial F_m}{\partial x_{n,1}} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_1}{\partial x_{n,m}} & \dots & \frac{\partial F_m}{\partial x_{n,m}} \end{bmatrix} \quad (\text{Eq. 30})$$

Using these variables, the following equation can be solved.

$$\bar{x}_{n+1} = \bar{x}_n - \frac{\bar{F}}{\bar{J}} \quad (\text{Eq. 31})$$

The convergence criterion is usually based on the total sum-squared error.

3.5.3 Newton-Raphson in PHATCAT

The class ‘newtonraphson.C’ is used to convert the information from the balance file, the current function and its derivative information into a form that is easily manipulated by the solver routine in ‘PHATCAT.C’. This class interprets the balance file then builds the necessary matrices from the function and derivative data.

The first step is to calculate the current set of x 's. This matrix is built from the current inputs. Calling the engine class and using the current inputs generates the function data. To build the Jacobian, a finite-forward difference derivative is calculated for each function over the range of dependent variables. The engine configuration is analyzed once for each variable with each variable incremented by some Δx in turn. The generic form for a finite-forward difference is shown below:

$$F' = \frac{F(x + \Delta x) - F(x)}{\Delta x} \quad (\text{Eq. 32})$$

Since Newton-Raphson is used to find the point at which a function is equal to zero, each of the functions in PHATCAT are based on the difference of two values. For example a typical power balance function would be represented as:

$$F = P_1(x_{n,1}, \dots, x_{n,m}) - P_2(x_{n,1}, \dots, x_{n,m}) \quad (\text{Eq. 33})$$

where P_1 and P_2 may be any representative turbomachinery powers.

Once the function, Jacobian, and x matrices have been built, the Jacobian is inverted and the updated set of x 's is solved for. This calculation is shown below.

$$\bar{x}_{n+1} = \bar{x}_n - \bar{J}^{-1} \bar{F} \quad (\text{Eq. 34})$$

Once the x_{n+1} matrix has been evaluated, 'newtonraphson.C' replaces the engine parameters with the updated x 's. This process is continued over multiple iterations until convergence is reached.

3.6 Input/Output

The input and output files are the necessary interface between the program and the user. The input files allow the user to set system parameters and balance the engine. The output files provide the user with system performance values and a means of error checking the program run. Each of these files will be described in detail.

3.6.1 Input Files

There are two required input files in PHATCAT. The first input file configures the balance scenario. This file is used to set power balance parameters and overall engine system performance metrics. The second input file makes initial guesses on component performance parameters and gives the Newton-Raphson algorithm a starting point.

3.6.1.1 Balance Input File

The balance input file is required to set coupled turbomachinery power requirements equal to each other. It may also be used to match flow to thrust, flow to areas, mixture ratio to specific impulse, output pressures to chamber pressure, pressure ratios to exit pressures, or flow splits to temperatures, etc.

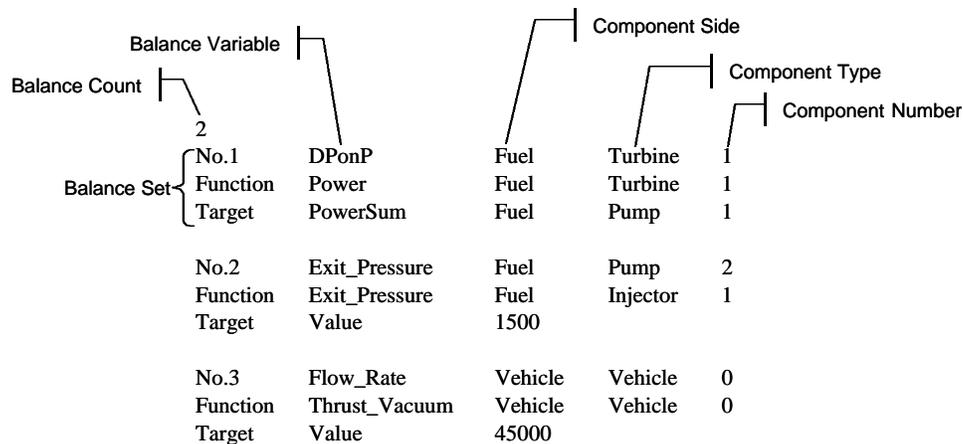


Figure 4. Sample balance input file

In Figure 4, the different components of the balance file are shown. The balance count refers to the number of balance sets that 'input.C' will look for. In this case only the first two balances will be read. Balance set 1 is an example of a typical set. The first line represents the variable and its component, the second line represents the function to be matched and the third line represents the target to be matched to. In a statement form, this set may be read as:

“Iterate on the pressure ratio of fuel turbine 1 until the power of fuel turbine 1 equals the power of fuel pump1.”

The second balance set may be read as:

“Iterate on the exit pressure of fuel pump 2 until the exit pressure of fuel injector 1 equals a value of 1500”

There are two exceptions to this form. The first is for sets of turbomachinery that are coupled with more than two components. An example is shown in Figure 5.

No.1	DPonP	Fuel	Turbine	1
Function	Power	Fuel	Turbine	1
Target	PowerSum3	Fuel	Pump	1
		Fuel	Pump	2
		Lox	Pump	1

Figure 5. Example of a balance of multiple coupled components.

Here the qualifier “PowerSum3” indicates that three target components are coupled with the function component. This statement should be read as:

“Iterate on the pressure ratio of fuel turbine 1 until the power of fuel turbine 1 equals the sum of the powers of fuel pump 1, fuel pump2, and lox pump 1.”

The second exception is used with vehicle balances. The third balance set in Figure 4 shows the use of the word “vehicle” and the number “0”. Although these values are not used in the solver routine the file reader requires them.

3.6.1.2 Engine Input Files

Each engine configuration requires a different input file. The first section of the input file specifies the cycle type and maximum number of iterations. The second section defines a component count so that the file reader knows how many components are present in the file. The fuel side inputs and lox side inputs are identical. The components are given in this order:

- Pumps
- Turbines
- Heat Exchangers
- Valves
- Injectors
- Mixers
- Flow Splits
- Initial Guesses (turbine only)

The hot side inputs include the components in the following order:

- Combustors
- Turbines
- Heat Exchangers
- Valves
- Injectors
- Mixers
- Splits

The final section of the input file defines vehicle and nozzle parameters.

All headers must be included in the input file regardless if any components exist or not. (i.e.: the expander cycle does not have a lox side heat exchanger, but the heat exchanger heading must exist) Spaces are not allowed between words, the underscore character is required. After each component an asterisk is required. Units are also required where necessary, but are only used for

reference. The list of parameters under each component in Table 1 shows the order in which the parameters must be specified.

Table 1. List of input file components and parameters.

Tank	Pumps	Turbines	Heat Exchangers	Valves	Injectors	Mixers	Splits	Initial Guesses	Combustors	Nozzle
Name	Name	Name	Name	Name	Name	Name	Name	Name	Name	Nozzle Profile
Fluid	Pexit	h	Qdot	DP/P	DP/P	*	% split	*	# Fuel Lines	Expansion Ratio
P	h	DP/P	Pcbaseline	*	*		*		# Lox Lines	Alpha
T	*	*	h						# Hot Lines	Theta
*			DP/P						*	Qdot throat
			*							Qdot nozzle
										Total Flow Rate
										Mixture Ratio
										*

Sample input files are shown in "11.0 Sample Input Files."

3.6.2 Output Files

There are two primary output files generated by 'output.C' in PHATCAT. The first output file relates to information used by the solver routine. The second file provides the user with engine performance data.

3.6.2.1 Solver Output

PHATCAT generates a history of all the data used to balance the engine. This data is stored in 'solver.out'. This information is extremely useful to check the convergence history of a program run to insure that the run has converged and to error check any program failures. A sample output file is shown in "12.0 Sample Output Files." The "Function" matrix lists the current iteration balance function values and the "Target" matrix lists the balance targets. The "Perturb" matrix shows how much each function changed by perturbing each variable by Δx . The "Jacobian" matrix is the difference of each column of the "Perturb" matrix and the "Function" matrix. [Note: This is not a true Jacobian. It has not been divided through by Δx]. The "Inverse Jacobian" matrix is the inverse of the "Jacobian" matrix (again, without dividing through by Δx). The "X_n" and "X_n+1" matrices show the current and new updated variables.

3.6.2.2 Engine Output

PHATCAT generates a file to view the results of a converged engine run. This information is stored in “engine.out”. All engine performance data is output to this file. Sample engine output files are included in “12.0 Sample Output Files.”

4.0 System Validation

Cycle data provided by Manski, et. al. for the Space Shuttle Main Engine (SSME) enables a fair comparison between PHATCAT and other cycle analysis codes [10]. Two sets of validations were performed. Enough data was provided by Manski to perform a cold flow component validation. The overall system performance results of PHATCAT were compared to the baseline results quoted by Manski as well. Manski did not provide enough information to complete a thorough evaluation of hot flow components. A cold flow component validation class was written into the 'engine.C' file.

4.1 Component Validation

The cold flow component validation of PHATCAT shows that performance calculations are extremely accurate. Property estimates using LOX components are accurate too. Although the property estimates for LH2 components are reasonable, there is noticeable error present.

Five pumps were evaluated with the component testbed. The results are shown in Table 2. These results show that PHATCAT performs exceptionally well in calculating the power requirements for the pumps with the exception of the Lox Pressure Fuel Pump. Although the power required by the LPFP is low compared to Manski's results, it is still acceptable. The output temperatures (which are a function of output entropy and enthalpy) are also very good for the Lox components. Examination of the output temperatures for the LH2 components shows undesirable error, but since the resultant powers are close this error can be tolerated.

Table 2. Turbopump validation results.

Component	Component Inputs					PHATCAT	Manski		PHATCAT	Manski	
	P _{in} (psia)	T _{in} (R)	P _{out} (psia)	m _{dot} (lbm/s)	η	T _{in} (R)	T _{in} (R)	%error	Power (HP)	Power (HP)	%error
LPFP	30.02	37.08	282.82	161.40	0.65	39.6	40.9	3.18%	3412	3694	7.63%
HPFP	282.82	40.86	7055.95	161.40	0.73	91.5	103.1	11.25%	77235	77497	0.34%
LPOP	99.93	163.98	430.76	968.66	0.63	166.0	166.1	0.06%	1864	1872	0.43%
HPOP1	430.76	170.64	4791.33	1151.79	0.67	195.3	196.0	0.37%	27494	27504	0.04%
HPOP2	4791.33	196.02	8103.42	111.25	0.80	209.5	210.2	0.35%	1698	1694	0.24%

There are two cold flow turbines in the flow path of the SSME. Those turbines were evaluated using the component testbed. Their results are shown in Table 3. The trends exhibited by the Low Pressure Oxygen Turbine are similar to those of the Lox turbopumps. Both the temperature calculations and power calculations yield low relative errors. The trend exhibited by the Low Pressure Fuel Turbine is different than those of the LH2 turbopumps. In this case the temperature calculations are accurate. The relatively large error in the power calculation is still acceptable for the purposes of PHATCAT's analysis.

Table 3. Cold flow turbine validation results.

Component	Component Inputs					PHATCAT	Manski		PHATCAT	Manski	
	P _{in} (psia)	T _{in} (R)	ΔP/P	m _{dot} (lbm/s)	η	T _{in} (R)	T _{in} (R)	%error	Power (HP)	Power (HP)	%error
LPFT	5011.06	455.04	1.3219	34.08	0.52	441.7	440.6	<i>0.25%</i>	3955	3694	<i>7.07%</i>
LPOT	4791.33	196.02	11.123	183.13	0.62	194.1	194.0	<i>0.05%</i>	1872	1872	<i>0.00%</i>

Analysis of the heat exchanger components illustrates the discrepancies between the hydrogen properties and oxygen properties. Both the relative and absolute errors in output temperature for LH2 heat exchangers are noticeably high compared to the Lox heat exchangers.

Table 4. Cold flow heat exchanger validation results.

Component	Component Inputs					PHATCAT	Manski	
	P _{in} (psia)	T _{in} (R)	ΔP/P	m _{dot} (lbm/s)	Q _{dot}	T _{in} (R)	T _{in} (R)	%error
Nozzle Regenerator	6719.90	106.38	1.074	63.69	98257	500.0	464.0	<i>7.76%</i>
Chamber Regenerator	6719.90	106.38	1.341	34.08	50389	494.1	455.0	<i>8.59%</i>
Lox Tank Repressurization	3646.69	1369.60	1.013	73.86	-427	1322.3	1367.1	<i>3.28%</i>
Lox Injector Flow	4791.33	196.02	1.157	1.6538	427	209.5	210.2	<i>0.35%</i>

The results from the cold flow valve analysis fare extremely well. These results are illustrated in Table 5.

Table 5. Cold flow valve validation results.

Component	Component Inputs				PHATCAT	Manski	
	P _{in} (psia)	T _{in} (R)	ΔP/P	m _{dot} (lbm/s)	T _{in} (R)	T _{in} (R)	%error
Main Fuel Valve	7055.95	103.14	1.050	161.42	105.3	106.4	1.03%
Nozzle Cooling Bypass	6719.90	106.38	1.074	63.69	109.3	110.5	1.09%
LH2 Tank Repressurization	3790.71	440.64	74.459	0.77	470.0	453.8	3.57%
Lox Tank Repressurization	4141.17	914.04	111.680	1.6536	893.8	889.2	0.52%

The mixers show the discrepancy between the hydrogen data and oxygen data. Output pressures for the oxygen mixers yield low errors while the hydrogen mixers yield reasonable yet high errors.

Table 6. Cold flow mixer validation results.

Component	Component Inputs						PHATCAT	Manski	
	P _{in,1} (psia)	T _{in,1} (R)	m _{dot,1} (lbm/s)	P _{in,1} (psia)	T _{in,1} (R)	m _{dot,1} (lbm/s)	T _{in} (R)	T _{in} (R)	%error
Nozzle Regenerator Bypass Mixer	6256.94	110.52	63.69	6256.94	464.04	63.69	276.2	293.9	6.02%
Lox Recirculation Flow Mixer	430.76	194.04	183.13	430.76	166.14	968.66	170.7	170.6	0.06%

These results show that PHATCAT is capable of producing reasonably accurate rocket engine component evaluations. Further development of the heat exchanger component should be explored as well as finding a remedy for the quality of the hydrogen data.

4.2 Cycle Analysis Validation

To validate the ability of PHATCAT to analyze entire engine systems, the results of four different scenarios were compared to SCORES and Manski's results. An expansion ratio of 78.78 was used. The turbomachinery powers were balanced in all scenarios. The main chamber

combustion pressure was allowed to vary. In the first scenario the engine model in PHATCAT was run at the baseline conditions. The vehicle mixture ratio and vehicle flow rate was set as constants. Because SCORES does not have an option for changing flow rate, the exit area was changed until the engine flow rate equaled that of the SSME. The results of this scenario are shown in below.

Table 7. Cycle analysis validation No. 1

	SCORES	PHATCAT	Manski
Vehicle MR	---	6.002	6.002
Vehicle Flow (lbm/s)	---	1130.1	1130.1
Engine MR	6.019	6.004	6.019
Engine Flow (lbm/s)	1127.7	1125.8	1127.7
Vacuum Thrust	507430	509570	511350
Vacuum I_{sp} (sec)	450.0	452.6	453.5
Exit Area (ft ²)	43.79	44.38	44.01
Throat Area (in ²)	80.05	81.12	80.45
Pc (psia)	3341.7	3313.7	3341.7

The second scenario made use of the thrust balance. The total vehicle flow rate was iterated upon until it matched Manski’s results. In SCORES, the “Designer Mode” was used to match thrust. These results are shown in Table 8.

Table 8. Cycle analysis validation No. 2

	SCORES	PHATCAT	Manski
Vehicle MR	---	6.002	6.002
Vehicle Flow (lbm/s)	---	1134.0	1130.1
Engine MR	6.019	6.004	6.019
Engine Flow (lbm/s)	1102.9	1129.7	1127.7
Vacuum Thrust	511350	511350	511350
Vacuum I_{sp} (sec)	450.0	452.6	453.5
Exit Area (ft ²)	44.13	44.38	44.01
Throat Area (in ²)	80.67	80.61	80.45
Pc (psia)	3341.7	3341.7	3341.7

The third scenario required that the vehicle mixture ratio be varied until the vacuum I_{sp} 's matched. This scenario was not possible in SCORES with out changing the nozzle expansion ratio.

Table 9. Cycle analysis validation No. 3

	PHATCAT	Manski
Vehicle MR	6.002	6.002
Vehicle Flow (lbm/s)	1130.1	1130.1
Engine MR	5.924	6.019
Engine Flow (lbm/s)	1125.74	1127.7
Vacuum Thrust	510530	511350
Vacuum I_{sp} (sec)	453.5	453.5
Exit Area (ft ²)	44.38	44.01
Throat Area (in ²)	80.61	80.45
Pc (psia)	3301.1	3341.7

The final scenario combined the balances in scenarios 2 & 3. Again, this process was not possible in SCORES.

Table 10. Cycle analysis validation No. 4

	PHATCAT	Manski
Vehicle MR	5.921	6.002
Vehicle Flow (lbm/s)	1131.9	1130.1
Engine MR	5.923	6.019
Engine Flow (lbm/s)	1127.6	1127.7
Vacuum Thrust	511350	511350
Vacuum I_{sp} (sec)	453.5	453.5
Exit Area (ft ²)	44.38	44.01
Throat Area (in ²)	80.61	80.45
Pc (psia)	3301.1	3341.7

The iteration times and total analysis times were recorded for each of the validation scenarios. This information should provide the user with an estimate on PHATCAT run times. On average, the user should expect run times of 1.4 sec/balance/iteration. Repeated use has shown that the

number of iterations on the SSME rarely exceeds 12. Considering the complexity of the SSME, these times are very conservative. The runtime data is shown in Table 11.

Table 11. SSME validation runtime data.

	Scenario			
	1	2	3	4
Elapsed Time	20	41	63	80
Iterations	4	6	9	10
Balance Count	4	5	5	6
Time/Iteration/Balance	1.25	1.37	1.40	1.33

5.0 *Web Interface*

One goal of the SSDL is to provide disciplinary design tools to the space vehicle design community. The World Wide Web is an excellent means of relaying information between parties. As such, hosting a web page about PHATCAT is an excellent way to bring attention to the design capabilities of the SSDL. But more importantly, PERL and CGI scripts can be used as a way to access the design tool directly through the web to run analyses.

The web interface enables the user to analyze three pre-configured cycles: a gas generator, a staged combustion, and an expander cycle. The inputs delivered to each of the models will be the same as those given by the command line version of PHATCAT. The user enters input information and initial guesses into a web form. The CGI script will convert this data into the engine input file and the PERL script will execute the code. Once the analysis has been completed, a dynamic web page is created containing links to the output files.

Upon opening the page, the user is prompted to select the cycle type. Once, forwarded to the appropriate page, labeled schematic diagrams of the three cycles are available. These schematic diagrams are shown in “10.0 Cycle Schematic Diagrams”. On the left side of the screen are the balance parameters. Only vehicle level balances are available. Power-head balances are inherently built into the CGI script. The right side of the web page enables the user to change any of the inputs and initial guesses in the input file. There is a “Set Up” button on each side of the screen. Pressing these buttons writes the balances and inputs to their respective input files. Once the user is satisfied with the inputs, the “Solve!” button is used to execute the program. A screen shot of this page is shown in Figure 6.

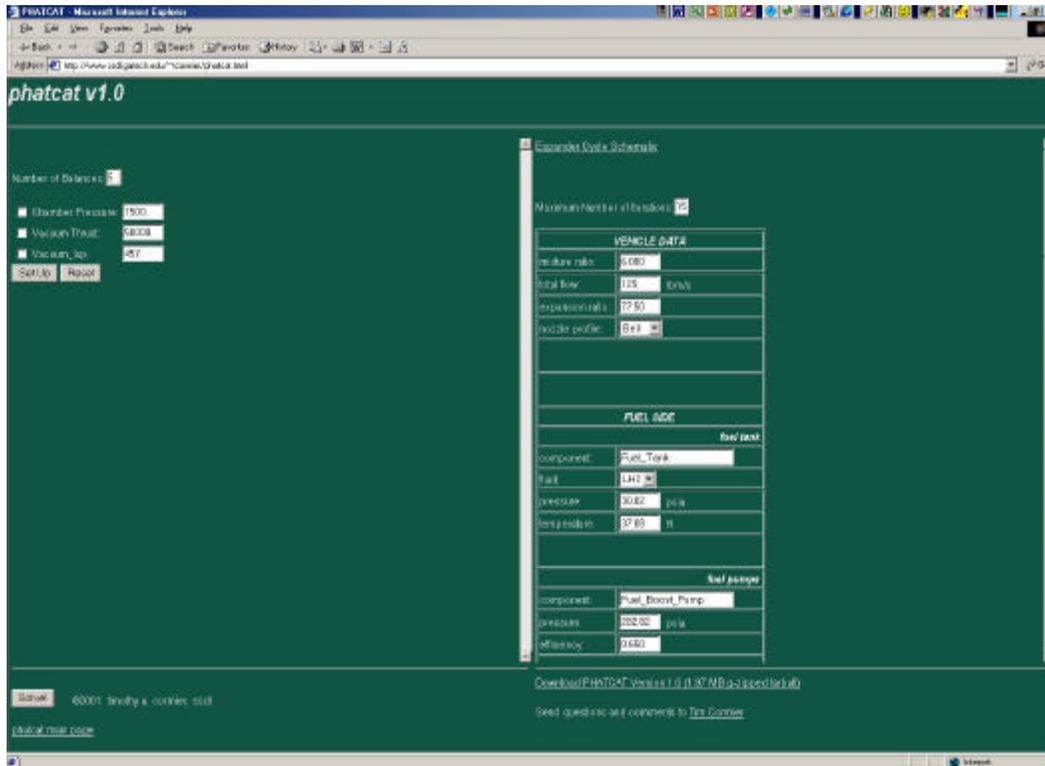


Figure 6. PHATCAT website input page.

Once the program has finished, a new web page appears allowing the user to select either the “solver.out” file or the “phatcat.out” file.

6.0 Lesson Cycle

This section is intended to provide a tutorial on using the command line version of PHATCAT. Several sample cycles will be analyzed in increasing order of difficulty.

6.1 Expander Cycle

Problem: Design an expander cycle capable of producing 50,000 lbs. vacuum thrust. The engine should operate at a combustion pressure of 1500psi, and have an I_{sp} of 462 sec. The nozzle is bell shaped with an expansion ratio of 90.

Solution Strategy: The first step in this analysis is to make a suitable input file. Copy 'expander.inp' to 'phatcat.inp' and 'expanderbal.inp' to 'balance.inp' in the working directory. By using "Designer Mode" in SCORES, the approximate flow rate for this engine can be found.

In SCORES set:

- Cycle: split expander
- MR: 6.1
- Pc: 1500 psi
- Area Ratio: 90
- Required Thrust: 50,000 lbs.

This yields a flow rate of 112.208 lbm/s. Modify the total flow rate in 'phatcat.inp' to this value, set the mixture ratio to 6.1 and the expansion ratio to 90.

Next, knowing that the desired chamber pressure is 1500 psi, you can calculate the approximate exit pressure of the lox pump by multiplying 1500 psia by the lox valve pressure ratio and the lox injector pressure ratio. It is approximately 2151 psi. Making a guess on the main fuel pump exit pressure is not so straightforward, since the turbine power is dependent on pressure ratio and the main pump exit pressure. Try using a pump exit pressure of 6000 psia and a turbine pressure ratio of 2. For now, leave all other variables in 'phatcat.inp' at the default settings, make sure that the balance count in 'balance.inp' is 0 and type 'phatcat' from the command line.

Now open the file 'phatcat.out'. The variables that were just set in the input file should still be at those values. The thrust is reasonably close to 50 klbs. and the chamber pressure is close to 1500 psi. However, notice that the sum of the pump powers differs from the turbine power by 661 HP. Open 'balance.inp' and change the balance count to 1. The first balance set will iterate on the turbine pressure ratio until the powers are equal. (see Figure 1). Now that the solver routine is going to be used, make sure that the maximum number of iterations in 'phatcat.inp' is set to 15. Type 'phatcat' in the command line again. Once it is finished, re-open 'phatcat.out'. Notice that the difference in powers is 0.1 HP and that the turbine pressure ratio is now 1.882. This PHATCAT run was fairly quick. Open 'solver.out' to find out how many iterations were required for this run. To converge the power head only three iterations were needed.

The next balance to consider is the combustion pressure. The lox injection pressure is 1500 psi, but the fuel injection pressure is 1851.4 psi. Turn on the pressure balances by changing the balance count to 3 in balance input file. Once the program is run again, re-open 'phatcat.inp'. The original guess for the main fuel pump exit pressure was 6000 psi. Now it is 4346.3 psi and its power has changed. But the sum of the pump powers still equals the turbine power (notice that the turbine pressure ratio has changed to 1.625) The injection pressures should now be equal as well. This PHATCAT run may have taken significantly longer than the previous one. By opening the 'solver.out' file it can be seen that the model converged in 8 iterations.

To fulfill the thrust requirements of the engine, change the balance count to 4 and change the value (not the word "value") in the fourth balance set to 50000. This run of PHATCAT should take 9 iterations. Now the thrust is 50klb and the flow rate is 108.97 lbm/s.

Finally, change the balance count to 5. The current I_{sp} of 458.85 is unacceptable. Change the value for the I_{sp} balance to 462 and run PHATCAT. By looking at 'phatcat.out' it is apparent that quite a few parameters have changed. All of the engine requirements have been fulfilled: thrust, I_{sp} , chamber pressure, and the inherent power balances. In addition to power changes, the flow rate has changed too. This illustrates the coupling between dependent variables and the ability of the solver routine to find the solution.

Congratulations! You have just completed your first PHATCAT engine analysis!

7.0 Conclusions

PHATCAT provides the user with a means of accurately analyzing liquid rocket engine systems. The program is recommended for engineers with a solid background in propulsion and thermodynamics. It is suggested that the beginner try the lesson cycle to become familiar with the operation of the program.

The property databases provide reasonably accurate information for the component analyses. This information enables the program to perform well in overall engine analyses. This has been validated with published industry information.

This program is a useful tool to be used in conceptual launch vehicle design. It contains the fidelity of detailed analysis while producing results in a time efficient manner. The model captures the limitations of different engine cycles by using simple thermodynamic relationships. Finally, the algorithms used were derived from textbook material and public resources, therefore PHATCAT can be made available to all who wish to examine rocket engine characteristics.

Note: Due to the size of the source code, it has not been included in this document. Please refer to the PHATCAT web sit to download the latest verson.

8.0 Acknowledgements

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10.0 Cycle Schematic Diagrams

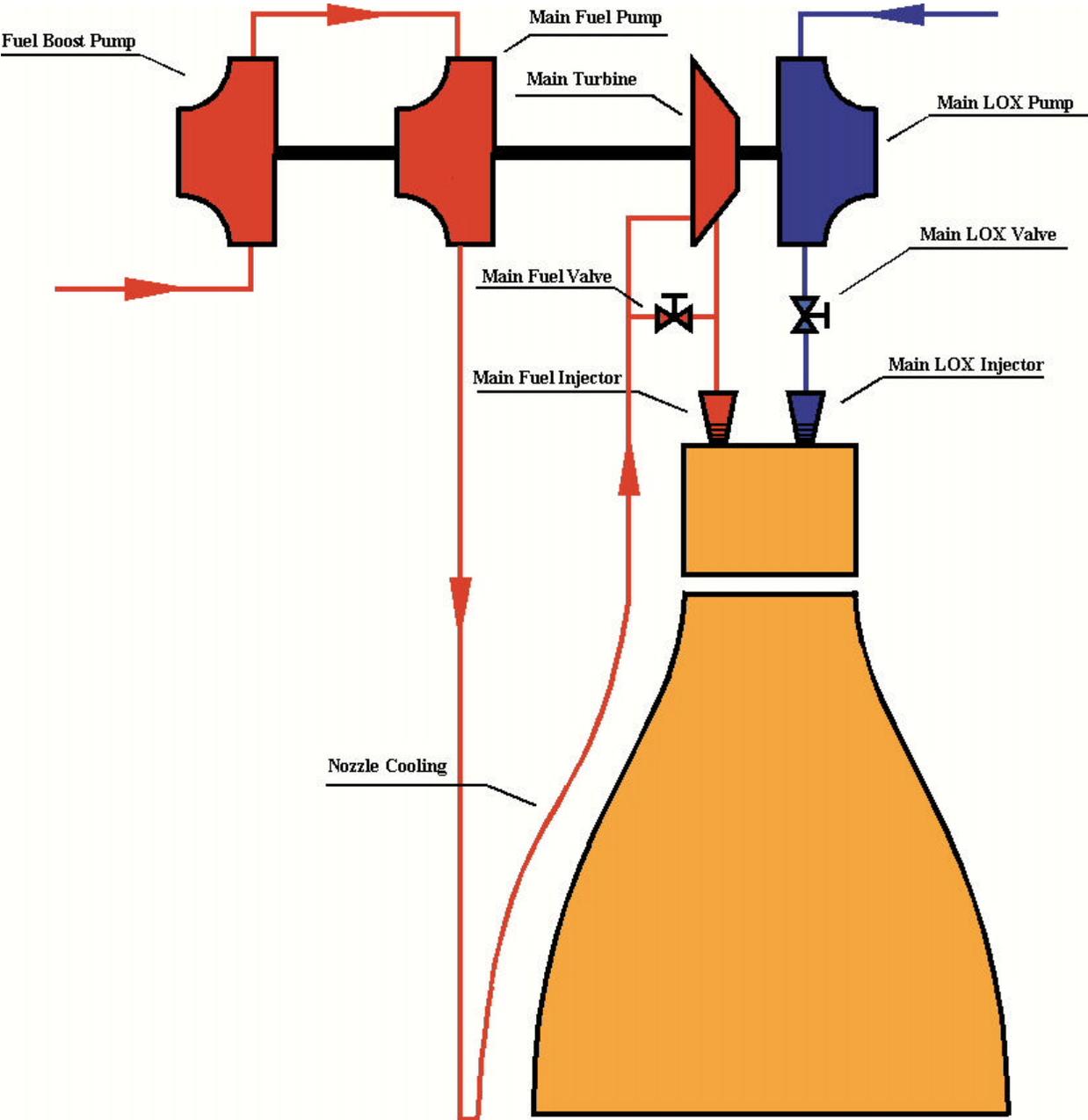


Figure 7. Expander Cycle: Single Turbine (RL-10)

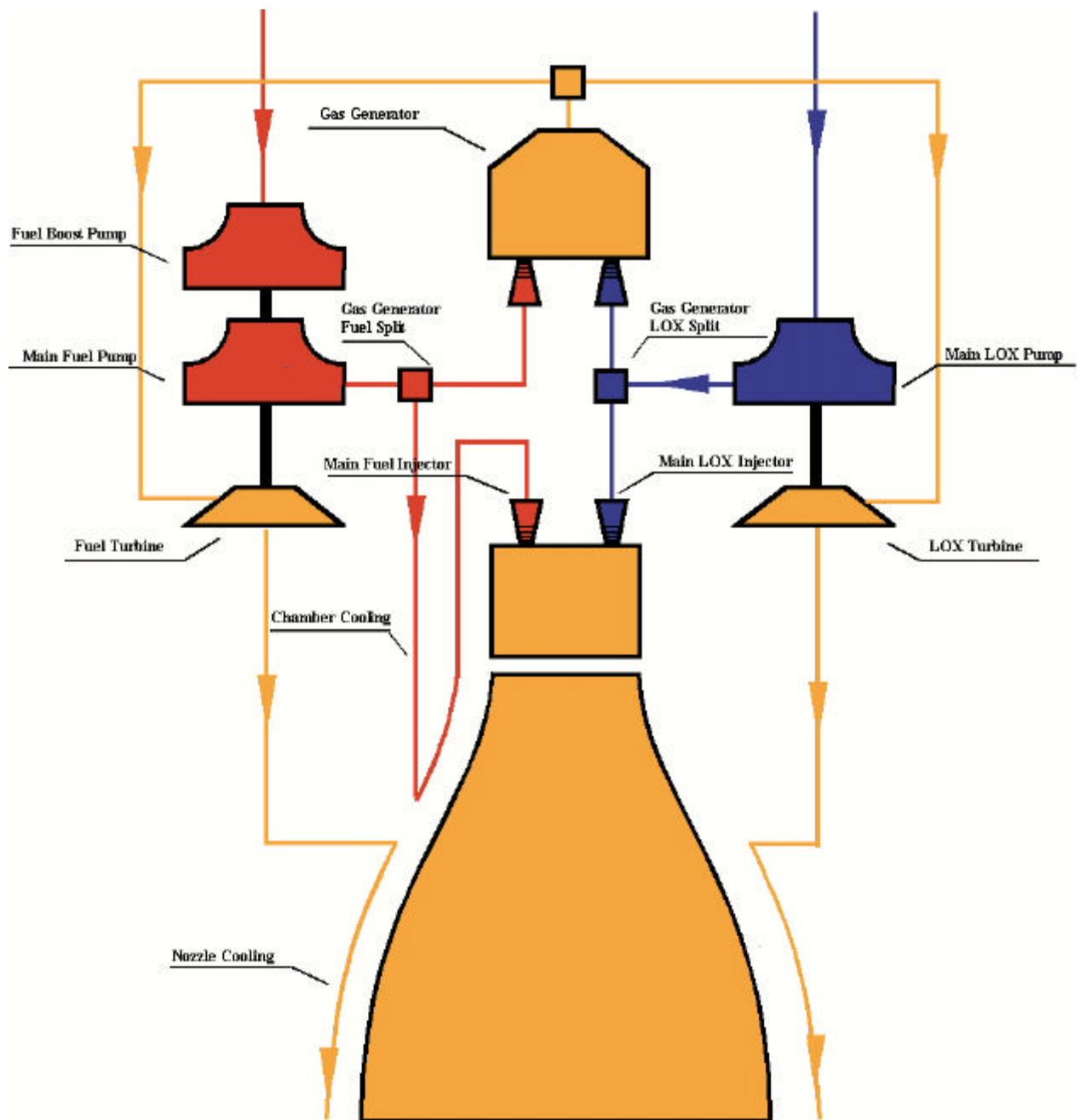


Figure 8. Gas Generator Cycle: Dual Turbine (Vulcain)

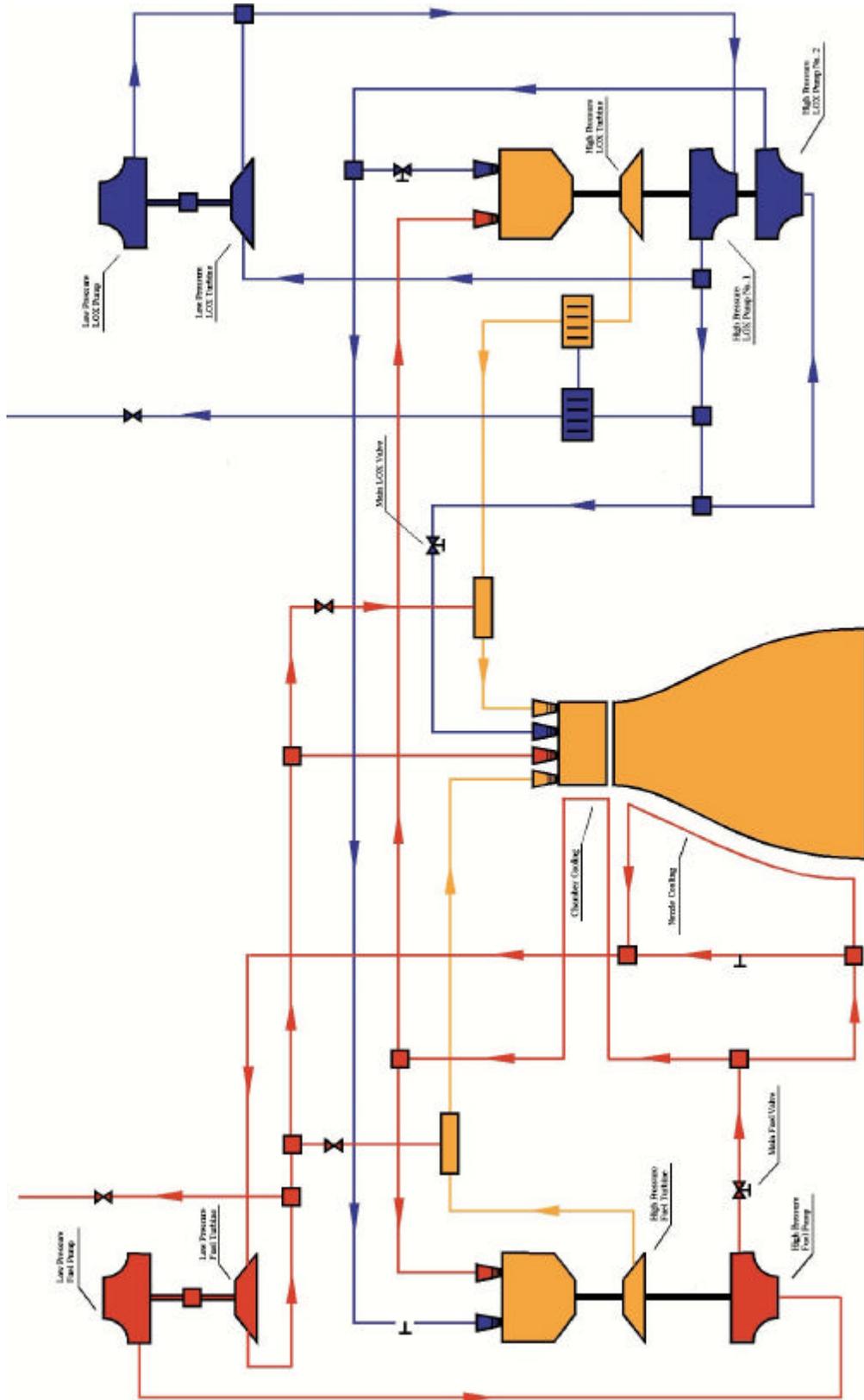


Figure 9. Staged Combustion: Dual Fuel-Rich Preburner (SSME)

11.0 Sample Input Files

11.1 Expander Cycle Input File

```
*****
***Solver_Parameters*****
*****
Maximum_Iterations      15
Cycle_Type              EXPANDER

*****
***Component_Count*****
*****
-----
                Fuel      Lox
-----
Pumps                2      1
Turbines              1      0
Heat_Exchangers      2      0
Valves                3      1
Injectors             1      1
Mixers                1      0
Splits                1      0
Initial_Guesses      0      0
*

                Hot_Gas
-----
Combustors            1
Turbines              0
Heat_Exchangers      0
Injectors             0
Mixers                0
Splits                0
*

*****
***Fuel_Side*****
*****
Component              Fuel_Tank
Fluid                  LH2
Pressure                30.02      psia
Temperature             37.08      R
*

---PUMPS---
-----
Component              Fuel_Boost_Pump
Exit_Pressure          282.82      psia
Efficiency              0.650
*
Component              Main_Fuel_Pump
Exit_Pressure          6000.00      psia
Efficiency              0.730
*

---TURBINES---
-----
Component              Main_Turbine
Exit_Pressure          0.520
Efficiency              2.000
*

---HEAT_EXCHANGERS---
-----
Component              Chamber_Cooling
Qdot                   49886      Btu/s
Pc_base                 1500.0      psia
Efficiency              0.912
```

```

DP                1.074
*
Component         Throat_Cooling
Qdot              25583      Btu/s
Pc_base           1500.0      psia
Efficiency        0.912
DP                1.341
*

```

```

---VALVES-----
Component         Main_Fuel_Valve
Pressure_Ratio 1.050
*
Component         Turbine_Bypass_Valve
Pressure_Ratio 1.23
*
Component         Fuel_Shutoff_Valve
Pressure_Ratio 1.100
*

```

```

---INJECTORS-----
Component         Main_Fuel_Injector
Pressure_Loss 1.134
*

```

```

---MIXERS-----
Component         Turbine_Bypass_Mixer
*

```

```

---FLOW_SPLITS-----
Component         Turbine_Bypass_Split
Split_Percentage 0.820
*

```

```

*****
**Lox_Side*****
*****
Component         Lox_Tank
Fluid             LOX
Pressure          99.93      psia
Temperature       163.98      R
*

```

```

---PUMPS-----
Component         Main_Lox_Pump
Exit_Pressure    2151      psia
Efficiency       0.800
*

```

```

---TURBINES-----

```

```

---HEAT_EXCHANGERS-----

```

```

---VALVES-----
Component         Main_Lox_Valve
Pressure_Ratio   1.163
*

```

```

---INJECTORS-----
Component         Main_Lox_Injector
Pressure_Loss    1.233
*

```

```

---MIXERS-----

```

```

---FLOW_SPLITS-----

```

```

---INITIAL_GUESSES-----

```

```

*****
**Hot_Components*****
*****

```

```

*****
---COMBUSTORS-----
Component           Main_Combustion_Chamber
Fuel_Lines          1
Lox_Lines           1
Mix_Lines           0
*

---TURBINES-----

---HEAT_EXCHANGERS-----

---INJECTORS-----

---MIXERS-----

---FLOW_SPLITS-----

*****
***Nozzle_Geometry*****
*****
Nozzle_Profile Bell
Expansion_Ratio     90
Alpha               15.00          degrees
Theta              30.00          degrees
Qdot_Throat        -50389          Btu/s
Qdot_Nozzle         0              Btu/s
Flow_Rate_in       112.208        lbm/s
Vehicle_MR         6.1
*

```

11.2 Gas Generator Input File

```

*****
***Solver_Parameters*****
*****
Maximum_Iterations  20
Cycle_Type          GENERATOR

*****
***Component_Count*****
*****

```

	Fuel	Lox
Pumps	2	1
Turbines	0	0
Heat_Exchangers	1	0
Valves	1	1
Injectors	2	2
Mixers	0	0
Splits	1	1
Initial_Guesses	0	0

```

*

Hot_Gas
-----
Combustors          2
Turbines            2
Heat_Exchangers     0
Injectors           0
Mixers              0
Splits              1
*

*****

```

Fuel_Side**

Component Fuel_Tank
 Fluid LH2
 Pressure 30.02 psia
 Temperature 37.08 R
 *

---PUMPS-----

Component Fuel_Pump_1
 Exit_Pressure 282.82 psia
 Efficiency 0.650
 *

Component Fuel_Pump_2
 Exit_Pressure 1575. psia
 Efficiency 0.730
 *

---TURBINES-----

---HEAT_EXCHANGERS-----

Component Chamber_Cooling
 Qdot 48500 Btu/s
 Pc_base 1500 psia
 efficiency 0.912
 DP 1.074

---VALVES-----

Component Main_Fuel_Valve
 Pressure_Ratio 1.050
 *

---INJECTORS-----

Component Gas_Generator_Fuel_Injector
 Pressure_Loss 1.102
 *

Component Main_Chamber_Fuel_Injector
 Pressure_Loss 1.134
 *

---MIXERS-----

---FLOW_SPLITS-----

Component Gas_Generator_Split
 Split_Percentage 0.075
 *

 Lox_Side**

Component Lox_Tank
 Fluid LOX
 Pressure 99.93 psia
 Temperature 163.98 R
 *

---PUMPS-----

Component Main_Lox_Pump
 Exit_Pressure 2150 psia
 Efficiency 0.800
 *

---TURBINES-----

---HEAT_EXCHANGERS-----

---VALVES-----

Component Main_Lox_Valve
 Pressure_Ratio 1.163
 *

```

---INJECTORS-----
Component          Gas_Generator_Lox_Injector
Pressure_Loss      1.221
*
Component          Main_Lox_Injector
Pressure_Loss      1.233
*

---MIXERS-----

---FLOW_SPLITS-----
Component          Gas_Generator_Lox_Split
Split_Percentage   0.075
*

---INITIAL_GUESSES-----

*****
***Hot_Components*****
*****

---COMBUSTORS-----
Component          Gas_Generator
Fuel_Lines         1
Lox_Lines          1
Mix_Lines          0
*
Component          Main_Combustion_Chamber
Fuel_Lines         1
Lox_Lines          1
Mix_Lines          0
*

---TURBINES-----
Component          Fuel_Turbine
Efficiency          0.780
Pressure_Ratio     1.600
*
Component          Lox_Turbine
Efficiency          0.780
Pressure_Ratio     1.495
*

---HEAT_EXCHANGERS-----

---INJECTORS-----

---MIXERS-----

---SPLITS-----
Component          Turbine_Split
Split_Percentage   0.5

*****
***Nozzle_Geometry*****
*****
Nozzle_Profile     Bell
Expansion_Ratio    45.0
Alpha              15          degrees
Theta              30          degrees
Qdot_Throat       -50389       Btu/s
Qdot_Nozzle       0           Btu/s
Flow_Rate_in      560.0       lbm/s
Vehicle_MR        6.2
*

```

11.3 Staged Combustion Input File

```

*****
***Solver_Parameters*****
*****
Maximum_Iterations      20
Cycle_Type              SSME

*****
***Component_Count*****
*****
                Fuel      Lox
-----
Pumps              2       3
Turbines           1       1
Heat_Exchangers   2       1
Valves             5       3
Injectors          3       3
Mixers             1       1
Splits            6       4
Initial_Guesses   0       1
*

                Hot_Gas
-----
Combustors         3
Turbines           2
Heat_Exchangers   1
Injectors          2
Mixers             2
Splits            0
*

*****
***Fuel_Side*****
*****
Component           Fuel_Tank
Fluid               LH2
Pressure            30.02      psia
Temperature         37.08      R
*

---PUMPS---
Component           Fuel_Pump_1
Exit_Pressure       282.82      psia
Efficiency          0.650
*
Component           Fuel_Pump_2
Exit_Pressure       7055.95     psia
Efficiency          0.730
*

---TURBINES---
Component           Fuel_Turbine_1
efficiency          0.52
Pressure_Ratio     1.2815
*

---HEAT_EXCHANGERS---
Component           Chamber_Cooling
Qdot               98257      Btu/s
Pc_base            3500      psia
efficiency         0.912
DP                 1.074
*
Component           Throat_Cooling
Qdot               50389      Btus/s
Pc_base            3500      psia
efficiency         0.912
DP                 1.341

```

*

---VALVES-----

Component Main_Fuel_Valve
Pressure_Ratio 1.050
*
Component Chamber_Cooling_Bypass_Valve
Pressure_Ratio 1.074
*
Component Fuel_Repressurization_Valve
Pressure_Ratio 74.45
*
Component Fuel-->FPB_HG_Valve
Pressure_Ratio 1.053
*
Component Fuel-->OPB_HG_Valve
Pressure_Ratio 1.053
*

---INJECTORS-----

Component Fuel_Preburner_Fuel_Injector
Pressure_Loss 1.102
*
Component Lox_Preburner_Fuel_Injector
Pressure_Loss 1.114
*
Component MCC_Fuel_Injector
Pressure_Loss 1.134
*

---MIXERS-----

Component Chamber_Cooling_Mixer
*

---FLOW_SPLITS-----

Component Regenerative_Cooling_Split
Split_Percentage 0.82
*
Component Chamber_Cooling_Bypass_Split
Split_Percentage 0.5000
*
Component Preburner_Fuel_Split
Split_Percentage 0.65478
*
Component Fuel_Repressurization_Split
Split_Percentage 0.022639
*
Component Fuel-->FPB_HG_Split
Split_Percentage 0.12574
*
Component Fuel-->MCC_Split
Split_Percentage 0.96445
*

Lox_Side**

Component Lox_Tank
Fluid LOX
Pressure 99.93 psia
Temperature 163.98 R
*

---PUMPS-----

Component Lox_Pump_1
Exit_Pressure 430.76 psia
Efficiency 0.630
*
Component Lox_Pump_2
Exit_Pressure 4791.33 psia
Efficiency 0.670

```

*
Component          Main_Lox_Pump
Exit_Pressure      8103.42      psia
Efficiency          0.800
*

```

```

---TURBINES-----
Component          Lox_Turbine_1
Efficiency          0.62
Pressure_Ratio     10.9290
*

```

```

---HEAT_EXCHANGERS-----
Component          Lox_Repressurization_Flow
Qdot               427.40      Btu/s
Pc_base            3500      psia
efficiency          0.912
DP                 1.157
*

```

```

---VALVES-----
Component          Lox_Preburner_Lox_Valve
Pressure_Ratio     1.182
*
Component          Fuel_Preburner_Lox_Valve
Pressure_Ratio     1.151
*
Component          Main_Lox_Valve
Pressure_Ratio     1.163
*

```

```

---INJECTORS-----
Component          Lox_Preburner_Lox_Injector
Pressure_Loss      1.221
*
Component          Fuel_Preburner_Lox_Injector
Pressure_Loss      1.240
*
Component          Main_Lox_Injector
Pressure_Loss      1.233
*

```

```

---MIXERS-----
Component          Recirculated_Flow_Mixer
*

```

```

---FLOW_SPLITS-----
Component          Recirculation_Split
Split_Percentage   0.1590
*
Component          Lox_Repressurization
Split_Percentage   0.0037638
*
Component          Lox_Pump_2_Split
Split_Percentage   0.115051
*
Component          Preburner_Lox_Split
Split_Percentage   0.268728
*

```

```

---INITIAL_GUESSES-----
Comonent           Lox_Turbine_1
Exit_Pressure      430.76      psia
Exit_Temperature   194.04      R
Mass_Flow          183.13      lbm/s
*

```

```

*****
***Hot_Components*****
*****

```

---COMBUSTORS-----

Component Fuel_Preburner
 Fuel_Lines 1
 Lox_Lines 1
 Mix_Lines 0
 *

Component Lox_Preburner
 Fuel_Line 1
 Lox_Lines 1
 Mix_Lines 0
 *

Component Main_Combustion_Chamber
 Fuel_Lines 1
 Lox_Lines 1
 Mix_Lines 2
 *

---TURBINES-----

Component High_Pressure_Fuel_Turbine
 Efficiency 0.780
 Pressure_Ratio 1.600
 *

Component High_Pressure_Lox_Turbine
 Efficiency 0.780
 Pressure_Ratio 1.495
 *

---HEAT_EXCHANGERS-----

Component Lox_Tank_Repress
 Qdot -427.40 Btu/s
 Pc_base 3500 psia
 efficiency 1.000
 DP 1.013
 *

---INJECTORS-----

Component Hot_Gas_Injector_1
 Pressure_Loss 1.077
 *

Component Hot_Gas_Injector_2
 Pressure_Loss 1.077
 *

---MIXERS-----

Component Hot_Gas_Manifold_FP
 Fuel_Lines 1
 Lox_Lines 0
 Mix_Lines 1
 *

Component Hot_Gas_Manifold_OP
 Fuel_Lines 1
 Lox_Lines 0
 Mix_Lines 1
 *

---MIXERS-----

 Nozzle_Geometry**

Nozzle_Profile Bell
 Expansion_Ratio 77.5
 Alpha 15 degrees
 Theta 30 degrees
 Qdot_Throat -50389 Btu/s
 Qdot_Nozzle 0 Btu/s
 Flow_Rate_in 1216.4 lbm/s
 Vehicle_MR 6.001
 *

11.4 Balance Input File

6

No.1	DPonP	Lox	Turbine	1
Function	Power	Lox	Turbine	1
Target	Power	Lox	Pump	1
No.2	DPonP	Gas	Turbine	1
Function	Power	Gas	Turbine	1
Target	Power	Fuel	Pump	2
No.3	DPonP	Fuel	Turbine	1
Function	Power	Fuel	Turbine	1
Target	Power	Fuel	Pump	1
No.4	DPonP	Gas	Turbine	2
Function	Power	Gas	Turbine	2
Target	PowerSum2	Lox	Pump	2
		Lox	Pump	3
No.5	Split	Fuel	Split	1
Function	Inlet_Temperature	Fuel	Turbine	1
Target	Value	479.76		
No.6	Flow_Rate	Vehicle	Vehicle	0
Function	Thrust_Vacuum	Vehicle	Vehicle	0
Target	Value	550000.		
No.7	Exit_Pressure	Lox	Pump	2
Function	Exit_Pressure	Lox	Injector	3
Target	Value	3350.		
No.9	Exit_Pressure	Fuel	Pump	2
Function	Exit_Pressure	Fuel	Injector	3
Target	Value	3350.		
No.10	Split	Lox	Split	4
Function	Exit_Temperature	Gas	Combustor	1
Target	Value	2050		
No.11	Exit_Pressure	Fuel	Pump	2
Function	Exit_Pressure	Fuel	Injector	1
Target	Exit_Pressure	Lox	Injector	2
No.12	Exit_Pressure	Lox	Pump	3
Function	Exit_Pressure	Lox	Injector	1
Target	Value	5600.		

12.0 Sample Output Files

12.1 Expander Output File

```

Vacuum Thrust          50000
Sea Level Thrust      -57166
Total Flow Rate       108.23
Generator Flow         0
Mixture Ratio         5.8746
Vacuum Isp            462
Sea Level Isp        -528.21
Exit Mach Number      4.9994
Exit Pressure         0.21764

```

```

Expansion Ratio       90
Throat Area          17.356
Exit Area            50.64

```

```

Regen Heat Rate      0

```

Component	Fuel Pump 1	Fuel Pump 2	LOX Pump 1
Inlet Pressure	30.02	282.82	99.93
Exit Pressure	282.82	4323.3	2151
Inlet Temperature	37.08	39.624	163.98
Exit Temperature	39.624	72.723	172.25
Mass Flow Rate	15.743	15.743	92.482
Power Required	332.8	4551.3	866.17
Efficiency	0.65	0.73	0.8

Component	Fuel Turbine 1
Inlet Pressure	2858.9
Exit Pressure	1771.6
Inlet Temperature	1298.1
Exit Temperature	1219.3
Mass Flow Rate	12.909
Power Required	5750.7
Efficiency	0.52

Component	Chamber_Cooling	Throat_Cooling
Inlet Pressure	4117.5	3833.8
Exit Pressure	3833.8	2858.9
Inlet Temperature	74.122	896.51
Exit Temperature	896.51	1298.1
Mass Flow Rate	15.743	15.743
Heat Transfer	49886	25583
Pressure Loss	1.074	1.341

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Main_Fuel_Valve	4323.4	4117.5	1.05	15.743
Turbine_Bypass_Valve	2858.9	2324.3	1.23	2.8337
Fuel_Shutoff_Valve	1871.1	1701	1.1	15.743
Main_Lox_Valve	2151	1849.5	1.163	92.482

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Main_Fuel_Injector	1701	1500	1.134	15.743
Main_Lox_Injector	1849.5	1500	1.233	92.482

Component	Main_Combustion_Chamber
Pressure	1500
Molecular Weight	13.003

```

Gamma          1.2205
Exit Cp        0.84544
Exit Temperature 6669.1
Total Mass Flow 108.23
H2      :4.4311
O2      :1.3381
H2O     :93.432
O       :0.73887
H       :0.38978
OH      :7.8949

```

12.2 Gas Generator Output File

```

Vacuum Thrust      2.4167e+05
Sea Level Thrust   1.8803e+05
Total Flow Rate    600.84
Generator Flow     46.055
Mixture Ratio      6.2
Vacuum Isp         402.22
Sea Level Isp      312.94
Exit Mach Number   4.4075
Exit Pressure      2.6983

```

```

Expansion Ratio    45
Throat Area        85.564
Exit Area          25.348

```

```

Regen Heat Rate    0

```

Component	Fuel Pump 1	Fuel Pump 2	LOX Pump 1
Inlet Pressure	30.02	282.82	99.93
Exit Pressure	282.82	1918.2	2151
Inlet Temperature	37.08	39.624	163.98
Exit Temperature	39.624	55.397	172.25
Mass Flow Rate	83.451	83.451	517.39
Power Required	1764.1	9980.8	4845.8
Efficiency	0.65	0.73	0.8

HOT Turbine 1	HOT Turbine 2
1514.7	1514.7
946.71	1252.5
6211.3	6211.3
5831.9	6055.1
23.027	23.027
11745	4845.8
0.78	0.78

Component	Chamber_Cooling
Inlet Pressure	1826.9
Exit Pressure	1701
Inlet Temperature	55.991
Exit Temperature	228.78
Mass Flow Rate	76.2
Heat Transfer	48500
Pressure Loss	1.074

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Main_Fuel_Valve	1918.2	1826.9	1.05	83.451
Main_LoX_Valve	2151	1849.5	1.163	517.39

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Gas_Generator_Fuel_Injector	1826.9	1657.8	1.102	7.2501
Main_Chamber_Fuel_Injector	1701	1500	1.134	76.2
Gas_Generator_LoX_Injector	1849.5	1514.7	1.221	38.804

Main_Lox_Injector 1849.5 1500 1.233 478.59

```

Component      Gas_Generator
Pressure       1514.7
Molecular Weight 12.425
Gamma         1.2206
Exit Cp       0.88431
Exit Temperature 6211.3
Total Mass Flow 46.055
H2      :2.3732
O2      :0.12125
H2O     :41.767
O       :0.079634
H       :0.10857
OH      :1.6052

```

```

Component      Main_Combustion_Chamber
Pressure       1500
Molecular Weight 13.848
Gamma         1.2116
Exit Cp       0.82106
Exit Temperature 6535
Total Mass Flow 554.79
H2      :17.987
O2      :7.5713
H2O     :487.5
O       :3.2462
H       :1.4751
OH      :37.008

```

12.3 SSME Output File

```

Vacuum Thrust      5.1135e+05
Sea Level Thrust   4.1907e+05
Total Flow Rate    1130.7
Generator Flow     0
Mixture Ratio     6.001
Vacuum Isp        452.24
Sea Level Isp     370.63
Exit Mach Number  4.8131
Exit Pressure     2.8012

```

```

Expansion Ratio    77.5
Throat Area       81.598
Exit Area         43.607

```

Regen Heat Rate 0

Component	Fuel Pump 1	Fuel Pump 2	LOX Pump 1	LOX Pump 2	LOX Pump 3
Inlet Pressure	30.02	282.82	99.93	432.01	4791.3
Exit Pressure	282.82	7055.9	430.76	4791.3	8103.4
Inlet Temperature	37.08	39.624	163.98	170.49	195.07
Exit Temperature	39.624	89.271	166.03	195.07	208.47
Mass Flow Rate	162.14	162.14	972.99	1156.9	111.52
Power Required	3427.6	76742	1871.9	27601	1700.7
Efficiency	0.65	0.73	0.63	0.67	0.8

Component	Fuel Turbine 1	LOX Turbine 1	HOT Turbine 1	HOT Turbine 2
Inlet Pressure	5011.2	4791.3	5677.7	5614.8
Exit Pressure	3983.2	438.53	3512	3747.3
Inlet Temperature	479.76	195.07	2031.9	1516
Exit Temperature	468.05	193.26	1850.8	1384.9
Mass Flow Rate	34.072	183.95	165.41	74.18
Power Required	3427.6	1871.9	76743	29300
Efficiency	0.52	0.62	0.78	0.78

Component	Chamber_Cooling	Throat_Cooling	Lox_Repressurization_Flow	Lox_Tank_Repress
Inlet Pressure	6720	6720	4791.3	3747.3
Exit Pressure	6256.9	5011.2	4141.2	3699.2
Inlet Temperature	91.567	91.567	195.07	1384.9
Exit Temperature	483.82	479.76	508.17	1382.2
Mass Flow Rate	64.033	34.072	3.6621	74.18
Heat Transfer	98257	50389	427.4	-427.4
Pressure Loss	1.074	1.341	1.157	1.013

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Main_Fuel_Valve	7055.9	6720	1.05	162.14
Chamber_Cooling_Bypass_Valve	6720	6256.9	1.074	64.033
Fuel_Repressurization_Valve	3983.2	53.502	74.45	0.77136
Fuel-->FPB_HG_Valve	3983.2	3782.7	1.053	4.1872
Fuel-->OPB_HG_Valve	3983.2	3782.7	1.053	1.035
Lox_Preburner_Lox_Valve	8103.4	6855.7	1.182	29.969
Fuel_Preburner_Lox_Valve	8103.4	7040.3	1.151	81.553
Main_Lox_Valve	4791.3	4119.8	1.163	857.81
Lox_Repress_Valve	4141.2	3560.8	1.163	3.6621

Component	Inlet Pressure	Exit Pressure	Pressure Ratio	Mass Flow
Fuel_Preburner_Fuel_Injector	6256.9	5677.8	1.102	83.855
Lox_Preburner_Fuel_Injector	6256.9	5616.6	1.114	44.211
MCC_Fuel_Injector	3983.2	3512.5	1.134	28.079
Lox_Preburner_Lox_Injector	6855.7	5614.8	1.221	29.969
Fuel_Preburner_Lox_Injector	7040.3	5677.7	1.24	81.553
Main_Lox_Injector	4119.8	3341.3	1.233	857.81
Hot_Gas_Injector_1	3512	3260.9	1.077	169.6
Hot_Gas_Injector_2	3699.2	3434.7	1.077	75.215

Component	Fuel_Preburner
Pressure	5677.7
Molecular Weight	3.9764
Gamma	1.3448
Exit Cp	1.9476
Exit Temperature	2031.9
Total Mass Flow	165.41
H2	:73.58
O2	:0
H2O	:91.828
O	:0
H	:0
OH	:0

Component	Lox_Preburner
Pressure	5614.8
Molecular Weight	3.3824
Gamma	1.3677
Exit Cp	2.1837
Exit Temperature	1516
Total Mass Flow	74.18
H2	:40.435
O2	:0
H2O	:33.745
O	:0
H	:0
OH	:0

Component	Main_Combustion_Chamber
Pressure	3260.9
Molecular Weight	13.562
Gamma	1.2118
Exit Cp	0.83793
Exit Temperature	6622.9
Total Mass Flow	1130.7
H2	:41.548
O2	:7.4333
H2O	:1019.2
O	:3.5258

H :2.4303
OH :56.553

12.4 Solver Output File

Iteration Number 1
Function

9942.850646855337
8547.127575270229
1499.324606566763
1231.612032356911

Target

9020.397705347445
4514.281148122704
1500
1500

Perturb

9942.85457829557 9942.850646855337 9942.850646855337 9942.850646855137
8547.130968528154 8547.128026834167 8547.127575270229 8547.127575270069
1499.324606566763 1499.324606566763 1499.324606588815 1499.324606566763
1231.612032356911 1231.612032356911 1231.612032356911 1231.61203238164
225590.615365752 225590.6188729953 225590.6188729953 225590.6188729573

Jacobian

0.003931440232918249 0 0 -2.000888343900442e-10
0.003393257924471982 0.0004515639375313185 0 -1.600710675120354e-10
0 0 2.205251803388819e-08 0
0 0 0 2.472825144650415e-08

Inverse Jacobian

244.7369028888969 0 0 -14.58712819923513
-1911.083174729239 2214.525822117149 0 -0.6257164286762689
0 0 45346295.53247824 0
-2.909465853048846e-09 0 0 40439575.84964508

X_n

0.075
1.495
2150
1575

X_n+1

0.06225234191603753
1.268490384071324
2150.968497820734
1918.217665904039
